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HUMAN FACTORS IN AIR TRAFFIC CONTROL

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# Human Factors in Air Traffic Control




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NORTH ATLA' 'REATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARDograph No.275

# HUMAN FACTORS IN AIR TRAFFIC CONTROL

by

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This AGARDograph was prepared at the request of the Aerospace Medical Panel of AGARD.

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## PREFACE

This volume attempts to relate human factors to air traffic control. There are several ways in which this might be done: the most obvious is perhaps to read and distill all the relevant literature, give an interpretative account of it, and allow it to mirror what has been achieved. Perhaps as an enterprise this is no longer practical, because thousands of items would have to be reviewed; such a passive approach also smacks of complacency, for which there is no justification; the recounting of forgotten findings in the interests of completeness seems a profitless exercise, a guarantee of dullness. I have therefore not followed this approach.

Instead I have made some effort to break new ground, rather than fit the mould of other texts or rehash familiar material. I have tried to provide some ideas to serve as a stimulus or starting point for myself and for others, and to question conventional wisdom on appropriate and even inappropriate occasions. Perhaps, having pointed out traps for the unwary, I have still been caught in them.

Many major references and sources are not specifically mentioned, though I believe they are covered indirectly by citations in the references given. Where possible I have tried to give recent references. Many accounts of human factors work in air traffic control are not written for a human factors readership, and do not contain the essential data by which the validity of the findings might be judged in human factors terms. To paraphrase conclusions could invite their unwarranted generalisation; even recourse to the original source does not always suffice to establish the applicability of the findings to a new problem, but it offers the best prospects of doing so.

The terminology associated with man-machine systems gives rise to difficulties and to unfounded charges of bias. A human-machine system would seem to be a kind of robot, so I have ruled that out as a useful concept. To use 'man and woman', or 'his and hers', throughout a text of this length is initially cumbersome and eventually infuriating. Conceptually and linguistically, 'man' embraces 'woman', and is used throughout to include both. Other terms, such as controller, supervisor, assistant, monitor and operator, are also intended to refer to both men and women. With the exception of references to anthropometric data, no distinction between men and women is made or intended in this text. What a pity it is that such impartiality, that could until recently be taken for granted, now has to be spelt out.

Many friends and colleagues in human factors have lent their willing assistance. With the single exception of Dr E.P. Buckley, to whom my special thanks are due, it would be invidious to give names: to imply that others endorse views that they may not agree with is no way to repay their kindness. The sponsorship and patience of the Aerospace Medical Panel of AGARD, and the support of the Royal Air Force Institute of Aviation Medicine and the United Kingdom Civil Aviation Authority, are gratefully acknowledged: my views are not necessarily their views.

I wish to thank Mr A.J. Hopkin who compiled and drew Figures 1, 2 and 3, the United States Federal Aviation Administration for Figures 6 and 7, and the United Kingdom Civil Aviation Authority and Ministry of Defence for Figures 4, 5, 8 and 9. My wife and family have supported my self-imposed labours with forbearance, tolerance and quietness. Mrs M. Fawcett has contributed staunch clerical support and much tireless fetching and carrying. My thanks also to Mrs N. Mitchell who has done all the typing, of the text itself and of all the other material associated with it.

CONTENTS

LIST OF FIGURES

# CHAPTER 1

# INTRODUCTION

## 1a AIR TRAFFIC CONTROL

The purpose of air traffic control is to ensure the safe, orderly and expeditious flow of air traffic. To achieve this traditional objective, numerous functions, employing diverse facilities and aids, are fulfilled collaboratively by air traffic controllers (who in some countries are called air traffic control specialists or journeymen). Except near airports, controllers cannot see the aircraft under their control; they must rely on indirect information, provided before the flight, sensed by ground-based installations, transponded from aircraft, computed from collated data, or spoken by aircrew or by other controllers. This information has to be stored and sustained. It must be presented to the controller, or accessible to him, in a form that he can use.

A modern air traffic control system is a complex man-machine system, always in operation. As air traffic continues to increase, air traffic control must evolve to handle it, often by introducing innovative technology. The role and functions of the air traffic controller may change accordingly. The capabilities of the controller and of technology must be harnessed to accomplish their shared objective.

The interest of AGARD in air traffic control and its problems has steadily increased, as reflected in AGARD meetings and publications. A comprehensive two-volume survey of modern air traffic control has appeared[1], and three major conferences on air traffic control have attracted large numbers of submitted papers and high attendances[2,3,4]. Several AGARD meetings devoted to other technical, specialist or human factors themes have included papers on air traffic control or drawn examples from it[5,6]. Human factors aspects of air traffic control were considered in detail some twelve years ago[7]. All these AGARD publications include papers or chapters on human factors.

These AGARD activities typify the increased world-wide interest in air traffic control, for which several reasons may be adduced, such as increased densities of air traffic and its consequent regulation and restriction, delays imposed on the travelling public by air traffic control in the interests of safety, rare but widely publicised aircraft accidents with air traffic control implications, and the occasional involvement of air traffic controllers in industrial disputes. As a result, air traffic controllers and their functions now receive much more publicity, both favourable and unfavourable, than they once did. The general public has become more conscious of air traffic control, more inquisitive about it, and more eager for reassurance that it is safe.

There is no simple non-technical introduction to the principles and procedures of air traffic control to meet the needs of the enquiring layman. From time to time, descriptions of air traffic control, usually at a particular place, have appeared in popular magazines: though often well illustrated, most of these accounts are unbalanced and over-dramatic. Comprehensive textbooks, notably those of Gilbert[8] and of Field[9], presume some existing interest and knowledge on the part of the reader. Other texts are unsuitable as general introductions because they were never intended to serve that purpose or to be self-sufficient: examples are manuals in use in various countries for the professional training of controllers, and texts which form part of a more general course[10]. A comprehensive, self-contained, well-illustrated and inexpensive introduction to air traffic control would meet a real need. It is beyond the scope of this volume and the purview of its author to attempt to provide it here.

## 1b HUMAN FACTORS

The increased interest in air traffic control has its counterpart in a more general acknowledgement of the importance of human factors. In the past, when the value of human factors was often queried, the burden of proof rightly lay with the human factors specialist to show that he had a worthwhile contribution to make. This was true in air traffic control and also in other applications of human factors. Nowadays, human factors are respectable, to the extent that conferences on many topics include a section on human factors and dwell on their importance. However, this avowed concern for human factors often remains more nominal than actual, and in only a few instances has it taken the practical form of a commensurate increase in resources and funding for human factors work in air traffic control. To insist that a proportion of every contract should be devoted to human factors represents progress of a kind, but cannot guarantee the relevance or value of the work that is done. It may imply, wrongly, that every human factors problem must have a solution.

Skilled, experienced human factors effort that can be devoted to air traffic control problems is in short supply. A planned and progressive expansion of the available effort is needed: a sudden gross expansion could outstrip existing resources and impair the quality of what is achieved. Many fundamental human factors issues have been neglected in favour of simpler questions amenable to quantitative experimental methods. This experimental approach has often been expedient because others expect human factors data to be factual and specific. Unfortunately, some human factors problems do not lend themselves to experimental methods, and studies of them cannot yield such data.

Human factors problems in air traffic control offer a challenge at the present time. The advent of computer assistance and the prospect of further technological advances encroach upon the traditional roles of man in the air traffic control system, and broaden the questions which human factors specialists must tackle. Some of the human factors problems which new technology brings may be encountered for the first time in air traffic control contexts. Any untoward consequences of proposed system changes must be foreseen and forestalled well in advance, because most air traffic control systems are too complex to be changed readily after they have become operational, even to remove major deficiencies. As air traffic control systems evolve, they continue to pose new human factors problems, and to present old problems in new guise.

## 1c THE STRUCTURE OF THE TEXT

The main objectives of this text are the following:

(1) To define the topics that lie within the province of human factors, to demonstrate their relevance to air traffic control and to indicate what is known about each. The detailed 'List of Contents' is intended to go some way towards fulfilling the first part of this objective.

(2) To show how the application of human factors knowledge can benefit air traffic control, and to suggest practical forms which this help can take. Human factors should be able to assist everyone concerned with air traffic control in some way.

(3) To examine the content and methods of human factors as a whole, and hence to provide a perspective for the assessment of past and future applications of human factors to air traffic control.

(4) To relate the human factors problems in air traffic control to those in other systems, so that problems can be classified as general or as specific to air traffic control, and treated accordingly, and to define outstanding human factors problems.

(5) To consider psychological aspects of existing and envisaged air traffic control tasks in relation to human capabilities and limitations and to current psychological constructs, and to deduce the roles which man could fulfil efficiently in air traffic control systems.

This text is not intended to be a literature survey or a handbook. A comprehensive review of the literature would have to cite thousands of references, many of which are obscure and system-specific. To quote their conclusions would invite the unwarranted generalisation of their findings. In any case, the literature as a whole does not represent the relative importance of problems, but reflects rather the ease with which they can be studied experimentally. Most of the references mentioned in the text contain bibliographies.

A handbook of human factors data would be larger, more detailed, yet narrower in its scope than this volume. The uncritical use of handbook data has led to many errors and misunderstandings in the past, and should not be encouraged. Human factors handbooks[11,12] do contain much data applicable in principle to air traffic control, but these data cannot be applied validly without specialist human factors knowledge on their interpretation and generality, any more than engineering data can be used properly by those with no knowledge of engineering.

The application of human factors data also involves interdisciplinary collaboration. The relations between human factors and other disciplines should remain flexible in the interests of harmonious working. Part of the expertise of the human factors specialist is to know how far handbook recommendations and experimental findings can be compromised to meet the requirements of others, and when they must not be.

It is necessary in all human factors texts including this one, to classify the subject matter under various topic headings. These are intended to impose a coherent structure on the contents, help the reader to find what he is looking for, and ensure that all topics are covered without undue repetition. This classification, though exigent, is foreign to human factors, which are essentially interactive. The full ramifications of any human factors problem, even the simplest, always extend to several topics and are never confined to a single one. Any division of the subject matter of human factors into topics is therefore potentially misleading because, by separating intrinsically related factors, it underplays the importance of the interactions between them. Since the division is imposed rather than natural, it may also seem arbitrary: there may not be one best way to structure the subject matter.

This text considers first air traffic control systems and human factors in relation to them. Man as a system component and the relevance of various human attributes are then discussed. Man's functions in air traffic control are described, together with desirable characteristics of his physical working environment. Having considered what controllers do, their facilities and their working environment it is possible to suggest how they should be selected and trained, what might be desirable attributes in controllers, and what they need to know. The relevance of various aspects of their conditions of employment is examined, together with characteristics of the controller as an individual. Questions of measuring controllers and of conducting human factors research on air traffic control problems are then discussed. The human factors aspects of other functions within air traffic control systems are briefly examined, and the text concludes with suggestions for progress in applying human factors to air traffic control.

# CHAPTER 2

# THE AIR TRAFFIC CONTROL SYSTEM

## 2a PRINCIPLES OF AIR TRAFFIC CONTROL

Air traffic control seeks to maximise or improve the efficiency with which aircraft in flight fulfil their objectives. The notion of efficiency includes safety, orderliness, expedition and further factors. The relative importance of such factors depends on the objectives: the paramount importance of safety may be easier to reconcile with civil than with military requirements.

In most contexts, air traffic control achieves its objectives by keeping aircraft apart, and its efficiency can be gauged by its success in doing so without excessive or unnecessary disruptions or penalties. One principle is to allocate separate regions of airspace to different kinds of user: civil aircraft may be confined to designated routes or airways, while military aircraft fly in the regions between these routes. Aircraft of different types, designed to meet different objectives, need to fly at different heights and speeds. Air traffic control formalises this, so that some categories of user, for example supersonic transport aircraft, are separated en route from other traffic primarily by height.

Air traffic control also keeps aircraft within the same region of airspace safely separated. How far apart they must be depends on international rules and agreements, which in turn depend on factors such as the quality of navigational information available. The permissible minimum separations between aircraft are very different for traffic in mid-ocean with no radar coverage and for traffic over a land region with good radar coverage and other navigational aids. Separation minima are given in terms of flight levels (heights), lateral separations (distance between parallel routes), and longitudinal separations (between consecutive aircraft at the same height on the same route, usually expressed as distances with radar coverage and as times without it). Separation is maintained strategically by pre-planning the traffic flow before and during flights, and tactically by instructing the pilot of a specified aircraft to change to a different given heading, speed or height.

Air traffic control achieves its objectives by issuing instructions to pilots, acceding to their requests where possible. Pilots vary greatly in their knowledge of air traffic control. Many will have an understanding of common radio aids to navigation[13] which provide data for them and for air traffic controllers, and some may have read an account of air traffic control written primarily for pilots[14], but many amateur pilots in particular do not have a comprehensive understanding of air traffic control, its procedures or its facilities.

Even under favourable conditions, the pilot can seldom see much of the other air traffic around him. He may glean some notion of it by listening to transmitted conversations between air traffic controllers and other pilots in the same region and tuned to the same frequency, and this knowledge may be put to practical use in very heavy traffic near airports or in regions with an inadequate air traffic control service. In the future he may have a cockpit display of the air traffic around him[15]. If the air traffic control system is to remain safe, the pilots of aircraft under control must never initiate unexpected manoeuvres without warning. The successful planning of the future flow of air traffic is based on the assumption that each aircraft in the flow will behave predictably in accordance with its known intentions. Air traffic control in its present form relies on the centralised direction of the air traffic under control within a region.

In some flight regions, particularly around airports and at the higher levels within airways, air traffic control is mandatory, in that the pilot must notify the controller of his intention to enter the region, obtain his agreement, and accede to his instructions, within the limit that the ultimate responsibility for the safety of the aircraft remains with the pilot. In other flight regions, notably at lower levels and away from airways and airports, air traffic control may provide an advisory service to those who request it, and help to those who become lost or encounter emergencies in flight: in these regions there may be some ambiguities about the nature of the air traffic control service which is being provided.

The role of air traffic control depends on the phase of flight. For an aircraft flying along airways, the main phases of flight in air traffic control terms include the following:

(1) Manoeuvres within the confines of the airport and its immediate vicinity, including take-off and landing.

(2) The departure from an airfield and the final approach to it.

(3) Manoeuvres within the terminal area around the airport.

(4) The transition, usually involving climbing or descent, between the terminal area and cruising flight level.

(5) Cruising en route, normally at constant height and speed.

For air traffic control purposes, airways are divided into sectors. On a long journey, an aircraft may fly through many sectors, each of which is the responsibility of a different controller or team of controllers, sometimes at different centres and in different countries. Outside radar coverage, for example over oceans, air traffic control is based primarily on procedural methods where each aircraft is allocated a time slot at a particular level on a given route, and the pilot reports progress periodically to the controller. New sources of navigational information, from satellites for example, may lead to revised air traffic control procedures for such regions in the future[16].

For much military and general aviation traffic off airways, air traffic control is different in certain respects. On and around airfields and sometimes while transiting to a mission area, air traffic control may remain comparable, but mandatory and tight control over air movements may not be exercised thereafter, and indeed would be incompatible with the objectives of certain military flights.

Air traffic control must achieve its objectives within numerous constraints. Internationally agreed rules, procedures and agreements must be observed. Problems must be solved within the information and facilities provided, which sometimes are very limited. Air traffic control must eschew solutions which are not impartial, or which incur penalties, delays, disruptions to scheduling, erratic traffic flows, excessive noise levels, fuel penalties, etc. Air traffic control contains a hierarchy of decisions[17], and the solutions of any problem at a given decision level must not violate decisions higher in the hierarchy. Constraints are introduced by the design of the system, by the provision of the information for it, by the agreed procedures to be followed, by the extent of preplanning and by the feasibility of ad hoc solutions in terms of aircraft manoeuvrability and available airspace.

As aviation prospers, the number and variety of aircraft increase. The demand for air traffic control grows, along with the competition among different airspace users for the finite airspace available. If more aircraft are handled safely within the same time and airspace, they tend to be in closer proximity, better navigational information is required about all of them, and the air traffic control problems which they pose assume greater urgency and have less flexible and more constrained solutions. Automated aids therefore tend to rely on enhanced sensing and processing of navigational information, which is then employed to increase the amount of air traffic that each controller can handle. Automated aids may take several more specific forms, including the collation of information, the computation of proposed solutions to problems, and the prediction of future states of the traffic under control. These in their turn can lead to a reappraisal of the planning and executive roles of controllers, of the kinds of manual assistance and supervision of controllers which could still be provided, of the structure and functions of teams of controllers, and of the roles, if any, which controllers should fulfil in highly automated systems.

## 2b INFORMATION INFLUENCING THE AIR TRAFFIC CONTROL SYSTEM

Many kinds of general information are pertinent to the purposes and procedures of air traffic control, and to the ways in which air traffic is, or can be, controlled. Although they can be distinguished, the various kinds of information are not wholly independent of each other. It is desirable to be aware of this general information when considering human factors problems in air traffic control, since it provides the context within which the man-machine interface must be considered and air traffic control tasks are done.

Some of the main classes of information are the following:

(1) General rules and conventions. These cover international agreements and standards on air traffic control, the rules of the air, some divisions of responsibility, and some legal rights and obligations. Conventions include methods for classifying traffic, such as eastbound, westbound or crossing, and en route or off route; methods for dividing airspace, such controlled or open, and upper, middle or lower; methods for describing the type of air traffic control service provided or offered, such as procedural or radar, and aerodrome or area; and methods for designating separations, such as lateral, longitudinal or height, and distance or time. These all influence the form and content of air traffic control, as do the principles for initiating, maintaining and monitoring a flow of air traffic.

(2) Specific widely adopted practices. In addition to general principles, there are numerous particular ones. One example is the vertical separation of aircraft on designated routes by 1,000 foot intervals up to 29,000 feet, and by 2,000 foot intervals thereafter. Another is the comparatively recent lateral separation of aircraft traffic on North Atlantic routes by 60 nautical miles. Under this heading of specific widely adopted air traffic control practices comes much of the language of air traffic control, the ICAO alphabet, the wording of identification messages, the format and content of messages giving positional data or predicted times, and so on. A further example is the design of the flight strip, on which standardised information about each aircraft under control is entered. These and other practices influence some of the training standards for air traffic control.

(3) Characteristics of aircraft and of aircraft users. Different types of aircraft have different flying characteristics, in terms of manoeuvrability, endurance, speeds, optimum climb and descent rates, and navigational and other facilities normally carried on board. Their physical interactions with following aircraft, in the form of vortices, also differ. Airlines may have different policies and preferred practices. Various categories of user, such as subsonic or supersonic, fixed wing or rotary, powered or unpowered, are subject to different air traffic control regulations and priorities regarding which categories of user give way to others.

(4) Geographical regions. Air traffic control is influenced by the geographical pattern of land and water, the structure of the terrain, population densities and distributions, and land based transportation and communications systems which collectively affect the route structure and the nature and density of air traffic. Political divisions and boundaries may bring a need for air traffic control activities by determining where responsibility for controlling air traffic should be transferred. Terrain characteristics may put limits on the control which can be exercised, on the data which can be sensed, on the location of airports, and on the length and orientation of runways.

(5) Air traffic control centres and towers. A centre serves a geographical region, and a tower an airport. The number of centres and towers, their locations and facilities, the communications between them, and the extent to which they are integrated or autonomous influence the air traffic control procedures and practices within a region. Towers may be categorised according to the types of traffic which the airfield can handle (commercial, military, general aviation, etc), the mix and densities of traffic, and the facilities they possess (e.g. radar). The provision of suitably equipped centres and towers, together with the geographical

characteristics of the region, determines the kind of air traffic control service which can be provided. A chart for each major airfield gives standardised information about it, including routes, procedures, aids and restrictions[18].

(6) Air traffic control policy. Generally this is a national matter, though influenced by agreed international standards, and sometimes combined across groups of nations, particularly if they are geographically adjacent and small in area. Policy concerns the national resources devoted to air traffic control, the planned capacity and expansion of airports, and the location and provision of new airports. It is influenced by estimates of future traffic demands and requirements. Decisions on airports and traffic demands affect policies on airspace, routeing, traffic flows and facilities. It is in relation to the formulation and implementation of policy that ecological factors, such as noise abatement and fuel conservation, may have greatest influence on air traffic control practices and procedures. There are policy guidelines on matters such as manning levels, rosters, and general conditions of employment within air traffic control.

(7) Air traffic control system design. The system is designed within the constraints and objectives set by defined policies. The design covers the detailed specification of the route structure, off route regions, arrangements for military and civil traffic, divisions of airspace, the provision and location of navigation aids and facilities installed on the ground, together with a clear statement of the assumptions, for example of traffic demands and mixes, of the expected performance of envisaged equipment and facilities and of the provision and functioning of communications, on which the specification is based. The design includes concepts of the ways in which the system is intended to function, and these concepts are developed into recommended procedures and instructions.

(8) The nature and functioning of navigation aids. Examples of aids are non directional beacons, area navigation, VHF omni-range equipment (VOR), and direction measuring equipment (DME). Further information sources can include doppler VOR, aircraft inertial navigation systems, and data derived from satellites. There may be data links for the automatic transmission of data between the aircraft and the air traffic control system, and in future aircraft may have in the cockpit a display of the air traffic pattern around them. The air traffic control system may use primary radar or secondary radar information with transponders giving squawk identity (IFF) or mode C height[19]. The methods for integrating navigational information from various sources for air traffic control purposes are also relevant.

(9) Facilities at the workspace. These include its planned capacity for handling traffic; communications resources; facilities for receiving, storing and using data; the means for displaying, updating and modifying information, and for denoting information states; and the specification of facilities for use by the controller in performing his task.

(10) Short term or temporary information. Instructions on temporary restrictions and their duration, regularly updated sources of information such as certain charts, notifications to airmen and other relevant regulations, and serviceability states and official hours of use of equipment items, can be listed under this heading. Various job aids or facilities may be provided for temporary usage or for evaluation purposes. Meteorological information, and much data from flight service stations and flight information services, also come under this heading.

(11) Current dynamic transient information. This refers to information within the air traffic control system about the aircraft with which the system is currently concerned, and to specific data about those aircraft. Its basis is data from schedules, flight plans, missions or exercises used to anticipate traffic loadings, to plan air traffic control procedures, to anticipate and forestall air traffic control tactical problems, and to control and regulate the traffic flow. The flight plan or mission information is updated according to the actual departure time of aircraft, and thereafter the position and location of each aircraft in relation to its route are continuously updated by means of data sensors on the ground, transponded or transmitted messages from the aircraft, computed or manual extrapolations, and speech. The controller, himself, in terms of his training, skills, experience and knowledge, is a major source of information in the system in relation to current information.

## 2c INFORMATION AVAILABLE TO THE CONTROLLER

The particular information sources, to which the individual air traffic controller has access while performing his tasks, depend on his planned role in the air traffic control system and on the facilities with which he has accordingly been provided. The latter reflect the nature, variety and density of his expected traffic, and also to some extent the national policies towards air traffic control of the country within which he works.

Much of the human factors work on air traffic control has concerned the performance of tasks by the controller, that is, aspects of the usage by him of current dynamic information. The role of his background knowledge and experience about air traffic control in general and about the particular air traffic control system he is concerned with has received far less attention, yet is of crucial importance. Anyone who lacks the controller's knowledge and experience cannot do his tasks or make much sense of the information on his displays.

The main information available to the controller at his workspace, as distinct from information entering the air traffic control system or inherent in the system design, can be categorised under the following headings:

(1) Information provided at a specific operating position. This covers the general information needed for designated tasks and responsibilities at that position, and the methods chosen for its depiction. Such information may be represented in various ways. It includes data on the

geographical area of control responsibility and on related parts of adjacent areas, and on their structure and boundaries, in the form of maps, radar displays or job aids. It deals with routes, reporting points, danger zones, restrictions in force, and navigation aids. It covers frequencies allocated for contact with pilots and other controllers, and procedures and facilities for liaison, co-ordination, acceptance, acknowledgement and handover. It includes control devices and other equipment items, and their labelled functions, with the responsibilities which their provision implies.

Information for the controller is inherent in the evidence of the planned traffic handling capacity of the control position which is implied by the size, format and layout of electronically generated tabular information displays or flight strip boards. There is further information implicit in the categories of aircraft information chosen for depiction, and in the relative importance of those categories as reflected in their sequence, coding, visual prominence, and method of depiction, and in the layout and blocking of displayed information which may also hint at the degree of association between information categories. Additional information is provided by the detailed contents of displays, by the provision, or lack of, a primary and/or secondary radar display or of electronically generated labels, by electronic, printed or hand written tabular displays of data, and by the extent to which pending as well as actual traffic is or can be shown. The controller may also have various manuals, instructions and job-aids, the interpretation and relevance of which vary with his operating position.

The controller's immediate workspace shows not only the information sources which are available to him but also those which are or could be in use, in the forms of facilities selected or unselected and of serviceability states. Occasionally there may be some implicit indications of the quality or reliability of the information portrayed, for example in the precision of the units in which digital information is expressed, or in the visual appearance of the echoes on a primary radar display.

An experienced controller can tell a great deal about the functions that are possible at a specific operating position, and the timescale for doing them, simply by examining in detail the sources of information, equipment and facilities that are provided there. Their provision or absence is itself a major source of information to him about what is expected and what is possible at that position.

(2) General information about the air traffic. This covers the traffic within a region or pending, information on whether it is under control or not, the type of control service being given, the controller responsible for it, the divisions of responsibility for traffic among controllers, and facilities and aids in use. It also includes less direct but still general information about the traffic, such as its density, distribution, mix of aircraft types, bunching, smoothness of flow, and loading on the system. Under this heading it is also appropriate to consider information relevant to the control of all aircraft within the region at a particular time, for example information about meteorological conditions.

(3) Specific information about each flight. This category contains two kinds of information, about the aircraft and about the flight. Details of the aircraft itself are its broad classification, such as civil or military, its airline or air force if applicable, its type, its identity and callsign, and navigational facilities carried on board. Details of the particular flight cover its flight plan, point of departure, planned route and destination, current status, and points along the route at which up to date information is expected.

(4) Dynamic information. Information about each flight under control is maintained automatically or manually. It may be brought up to date or renewed regularly or intermittently, at designated times or locations, or whenever it changes. Such information includes the current position of the aircraft, its height, heading and speed and planned or agreed changes in height, heading or speed, its proximity to other aircraft and its relationship to aircraft which are crossing or flying in the opposite direction. Information on its position [illegible] lated to the airway if applicable, to the traffic flow, to navigational sensors and a[illegible] [illegible] controller responsibilities such as acceptances and handovers.

(5) Information derived from computers. This may take the form of data which are kept up to date on the controller's displays automatically or are presented to him automatically. Data which have been sensed and stored may be used for computations forming the basis of various aids, such as conflict detection, conflict resolution, auto alert, and predictions of future traffic states. Information from computers may also be available to the controller on request, if he has appropriate facilities for its selective retrieval and display.

(6) Information from direct viewing of aircraft. Such information is generally available only to controllers in towers at airports, mainly in daylight. Nevertheless the controller may be able to see the aircraft using an airport while they are in the control circuit, on the final approach, landing, taxying, taking-off or departing, or he may see aircraft transitting the airport's control zone.

(7) Information in the form of speech. The controller converses with pilots, with his fellow controllers, with other members of the same control team such as supervisors or assistants, and sometimes with people fulfilling different roles within the same system such as technical and maintenance staff. Speech may be direct face to face conversation, speech by telephone or speech by R/T links. It may be an alternative to, or replaced by, information transmitted by other means. In the future there may be automated speech synthesis and recognition.

(8) Information from the controller's colleagues. As well as giving and receiving information by speech, the controller's colleagues may convey information to him by their actions, their attitudes, their proficiency, their procedures, and the standards of performance associated

with each watch, supervisor, or team of controllers. Each controller obtains much incidental information which conveys to him what his colleagues expect of him.

(9) Temporal information. The controller normally has a clock, and often makes plans in terms of the expected timing of future events. He is also influenced by broader categories of temporal information which he is aware of but are not displayed to him, such as expected times of peak traffic flows, the pattern of his work-rest cycles, and the time of the end of his watch when he is due to hand over his responsibilities to another controller.

(10) Individual ability and knowledge. The professional knowledge, ability, experience and skill of the individual controller constitute the largest single source of information available to him at his workspace, and the basis on which he interprets all the other information. Although in emergency or system failure, safe air traffic control may continue for a time in the absence of certain kinds of information, the controller's own professional knowledge is indispensible.

2d CLASSES OF USER

The users of air traffic control can be categorised in several ways. The main practical distinction is perhaps that between commercial, military and general aviation traffic. This classification overlaps to some extent with that between aircraft within controlled airspace and aircraft outside it. A further distinction, normally applicable only outside airways, is between aircraft which are receiving an air traffic control service and those which are not. Among the practical differences in air traffic control according to class of user are the type of control exercised, its legal status, the purposes of flight, the types of equipment commonly installed in aircraft, and the probable knowledge of the pilot about air traffic control facilities and procedures. A further related distinction in air traffic control concerns the maximum number of aircraft under the control of a single controller concurrently: this number is generally much higher in commercial and general aviation than in military aviation, where the roles and procedures of air traffic control are different.

Air traffic control of commercial passenger-carrying flights along airways between major airports is most familiar to the general public and has received most attention in research and evaluations. Pilots of commercial aircraft are usually familiar with air traffic control procedures and fly aircraft relatively well equipped to use on-board or ground-based navigation aids. They are also familiar with air traffic control communications, although some may have difficulty in speaking or understanding English, the international language of air traffic control. Normally, commercial aircraft follow air traffic control instructions, but the controller has relatively little time to devote to each in busy traffic, and has the further tasks of keeping aircraft safely separated, maintaining a smooth traffic flow, ensuring that the information on aircraft is kept up to date, and minimising delays. Although the pilots of commercial aircraft, particularly near airports with which they are unfamiliar, may not always have full knowledge of appropriate procedures and routings, nevertheless from an air traffic control point of view their responses to instructions are relatively similar and predictable: it is therefore possible for the controller to provide a uniform air traffic control service for all such aircraft under his control.

General aviation covers a great variety of aircraft flights. At one extreme are aircraft equipped to full commercial standards with experienced pilots following air routes. At the other extreme are aircraft fitted with the minimum permissible aids, and pilots who are inexperienced or lost and unfamiliar with air traffic control procedures and with the terrain over which they are flying. The controller of general aviation traffic may have a high workload in that he has to control a large number of aircraft and must not act on presumptions about serviceable facilities in the aircraft or experience and uniformity of responses among the pilots. The controller may have no knowledge about some general aviation aircraft in his airspace, or may know of their presence but be unable to contact them or to ascertain their intentions. The controller of general aviation traffic may have an advisory role, and the initiative may lie with the pilot as to whether he wishes to have an air traffic control service. Sometimes the pilot may make incorrect assumptions about the nature of the air traffic control service he is receiving. While the pressures to expedite general aviation traffic may be less than those for commercial aircraft, a larger variety of problems for the controller can arise with general aviation aircraft. The nature of general aviation traffic, and the locations of the air traffic control facilities for controlling it, make it less likely that the controller will have access to automated aids when dealing with it. Certain kinds of traffic pose their own air traffic control problems. Examples are agricultural aircraft, emergency flights and flights by helicopters.

The controller of military air traffic is usually responsible for fewer aircraft but is providing them with a different kind of air traffic control service. He may have the advantage of considerable standardisation of pilot behaviour in certain types of mission and manoeuvre and this predictability may sometimes facilitate pre-planning. However, certain missions require freedom of manoeuvre. Much military traffic does not follow airways or designated routes but has to be co-ordinated with other traffic with a minimum of interference with its mission. The variety of military roles does not permit close control of military aircraft at all times for air traffic control purposes. The military controller may be concerned with the limits of a region within which one or more military aircraft may manoeuvre freely and also with the current positions of those manoeuvring aircraft so that safe separations between them and other traffic can be maintained.

The competing requirements of different classes of user are partly allowed for by pre-planning and by the allocation of regions of airspace for different purposes and users. However, these differing requirements cannot be reconciled entirely by pre-planning; from time to time the individual controller may have to resolve conflicting claims between different classes of user in the airspace under his control, and show impartiality in doing so, within the constraints of the generally acknowledged priorities and orders of precedence accorded to different classes of user. The existence of different classes of user, with different air traffic control procedures and requirements, carries the implication that sometimes aircraft in the same airspace may be under the control of different controllers, with the consequent reliance on effective liaison between controllers, and on complete freedom from ambiguity in all messages and procedures, in order to ensure the safe separation of the aircraft.

## 2e AIR TRAFFIC CONTROL AND THE PILOT

The relationship between air traffic control and the pilot has begun to change considerably in recent years and seems likely to continue to do so. As long as spoken messages between the controller and pilot formed the main basis for agreed actions and manoeuvres for air traffic control, each treated speech as the primary means of conveying information to the other. Now and in the future, much of the information about the aircraft needed for air traffic control purposes can be transponded directly from the aircraft to the ground, without direct participation by the pilot or the controller. Neither therefore may know it without looking at appropriate displays. This transponding saves speech workload for both, but means that the incidental advantages of speech as a memory aid have been lost. There are also fewer spoken messages for the pilot and controller to overhear about other traffic: each may need to glean information about the general traffic situation from other sources.

The role of the pilot in relation to air traffic control would also change in the event of the installation of a display in the cockpit showing the pilot the other air traffic near him. This is technically feasible and raises the questions of what should be depicted on it[20], and of where the initiative for making manoeuvres and the responsibility for manoeuvres should lie.

At the present time, the pilot, particularly the international commercial pilot, recognises that the air traffic control service he receives varies greatly in different parts of the world, according to the expertise of controllers, the facilities installed on the ground and their serviceability, the traffic densities which the air traffic control system is designed to handle, and the relative status and importance assigned to air traffic control and controllers in terms of the allocation of national resources. To some extent the pilot therefore learns to adapt to the kind of air traffic control service he expects to receive, and pilots may themselves facilitate the smooth flow of air traffic, mainly by listening to R/T transmissions, and deducing traffic patterns from them.

The controller also adapts to the pilot. He becomes acquainted with the different priorities, policies, and procedures of various airlines. He acquires considerable knowledge of the pilot's task, so that he has some insight into the consequences of his instructions for the pilot, and may be able to adjust the timing of some of them to avoid periods when the pilot is likely to be most heavily loaded. National policies differ on whether the air traffic controller should himself be a pilot, and on the amount of experience of the cockpit environment and tasks which the air traffic controller should possess. There are also some anomalies: the pilot ultimately has legal responsibility for the safety of his aircraft, yet the safety and efficiency of the air traffic control system and the smooth flow of traffic presume that each pilot will obey air traffic control instructions. Without the willingness of pilots to follow instructions it would not be possible to plan air traffic control or to provide a safe air traffic control service.

Different classes of user have different air traffic control requirements, and therefore the relationship between the air traffic controller and the pilot varies. Most studies have been of commercial aviation, but the needs of the military pilot can be very different, and so can many of the needs and control practices associated with general aviation. The closest interactions between the controller and most pilots occur near busy airports. For example, if a pilot requests special clearance to overfly the control zone of the airport itself at low level, and this request is granted, the pilot is being given an individual service by the controller, rather than being treated as one of many similar pilots with aircraft in the same traffic flow.

In present systems, pilots and controllers can make assessments about each other based on speech. These informal assessments may be of such factors as competence, confidence, and helpfulness. The pilot makes judgements on the quality of the air traffic control service which he receives and on the apparent competence of the controllers who are providing it. The controller makes judgements of the apparent experience of the individual pilot, of the extent to which he appears to be familiar with the region in which he is flying and with the relevant air traffic control procedures, and of his propensity to behave unpredictably, and the controller treats the pilot and his aircraft according to these judgements. Whether or not such assessments are in fact correct, they do have an influence on the content and pace of spoken messages[21], and on the attitudes of controllers and pilots to each other.

Normally when air traffic control is studied, particularly by real-time simulation methods, pilots are simulated, but not by professional pilots. Similarly, when studies are conducted of pilots, in flight simulators for example, and it is necessary to simulate the air traffic control aspects of their tasks, controllers are simulated, but not by professional controllers. In both cases therefore, part of the simulation is in some respects unrepresentative and not fully realistic. It is rare to find full scale simulations of a single synthesised system, with real pilots and real controllers both fulfilling their actual roles.

Just as the air traffic controller may be considered as an element or component of the air traffic control system, so the pilot may be considered as an element of the man-machine system constituted by an aircraft in flight. Individual pilots and aircraft may also be treated as elements of the larger system comprising the air traffic pattern within a region. Much research has been done on the extent to which the pilot can be modelled as a system component[22], but comparable efforts have not been made to model the air traffic controller. The characteristics of the pilot as a system component have primarily been related to the efficiency with which he performs the tasks of flying the aircraft and to the kinds of descriptions which can help to explain how he behaves in that role, rather than to the ways in which he relates to the air traffic control system or responds to air traffic control instructions.

Vagaries in the organisation of and facilities for research have emphasised the divisions between ground based air traffic control systems and the pilot's role in the air. Research and evaluation facilities tend to be concerned either with air traffic control systems or with cockpits. This has led to the comparative neglect of the interactions between real, as distinct from simulated, air traffic controllers and pilots, because of the practical difficulties of conducting such studies and of considering in detail the aircraft and the tasks within them at the same time as the corresponding tasks of controllers on the ground.

A major concern of pilots is with the effects of air traffic control on air safety[23]. Their misgivings centre on the consequences for the pilot of errors by the controller, who is a main source of the rare system errors which occur[24], and on the occurrence of system induced errors. These illustrate that a specific human error can often be attributed to a flaw or limitation in the system design, that insufficient effort has been devoted to the study of the aetiology and prevention of system induced human errors, and that broad policy decisions are often taken either in ignorance of their known human factors implications or with a refusal to accept them[25,26]. Not only do "many human factors people harbour a hard-earned skepticism toward anyone who claims that any system is going to automate human error away"[26], but many pilots and controllers share this view on evidence which is equally hard-earned.

## 2f NATIONAL AND REGIONAL VARIATIONS

There are major international, national and local variations in the problems and practices of air traffic control, to the extent that these are often the main determinants of the particular forms in which human factors problems arise. The quality of air traffic control is far from uniform throughout the world, and there are major differences in the status of controllers and in their conditions of employment[27].

One source of variation is the amount of traffic. Air traffic control systems are intended to meet a demand. Manning levels, installed equipment, the information available in the system, and the methods for organising and conducting air traffic control all depend on what the demand is, what its peak is likely to be, how it is distributed during the day and seasonally, and what other services related to air traffic control are provided.

A related source of variation is the mix of traffic. In some countries, the concern is mainly with scheduled commercial aircraft on air routes. In others where general aviation thrives, the preponderance of air traffic is general aviation traffic. The nature and requirements of air traffic control therefore differ. The extent to which commercial and general aviation traffic are mixed influences the air traffic control procedures, particularly the co-ordination and integration of information from different sources.

Nations vary in the extent to which they integrate civil and military air traffic, and this has a major effect on the air traffic control system design and on the way the system is intended to function. At one extreme, the civil and military traffic are kept apart, each in designated regions of air space, and integration between the two has to be arranged by co-ordination between civil and military controllers on an ad hoc basis: the methods and procedures for controlling civil and military air traffic may be quite separate and there may seem no need to make them fully compatible. At the other extreme, the civil and military control systems are fully integrated; either a civil or a military aircraft may be controlled by either a civil or a military controller, depending for example on where it is geographically, on how it is equipped, on its route or on its height. Civil and military controllers may function side by side, their skills may be nearly interchangeable, and for many purposes they are treated as equivalent. Between these two extremes lie the air traffic control practices of many nations, where a certain amount of civil and military co-ordination and liaison of air traffic is taken for granted, but civil and military requirements are viewed as competitive in their demands for air space. Also certain military manoeuvres may have no civil equivalent in air traffic control terms, and vice versa. In such circumstances civil and military air traffic control skills and procedures are often seen by the controllers themselves as different rather than as similar, whereas to those outside air traffic control civil and military control are considered to be essentially similar to the point of permitting common procedures to be followed and being in some respects interchangeable. In recent years, particularly when there has been an industrial dispute between civil air traffic controllers and their management or national authorities, this issue has become both emotionally charged and politically sensitive.

A major local variation depends on characteristics of the route structure and of the terrain in relation to traffic demands. Whereas the principles of en route sectoring and of oceanic control may be fairly standardised over large regions, many of the problems of air traffic control near a particular airport tend to be specific to that airport. Numerous factors tend to make the problems specific. They include the number and orientations of airways leading to the airport, the size and shape of the terminal area and the routeings through it, the locations of holding positions for aircraft inbound to that airport, the number and orientation of the airport runways, the position in relation to the airport of high land, obstructions and areas of dense population, the noise level regulations, the distribution and mix of air traffic, the typical level of experience of the users of the airport, the facilities with which the airport is equipped and its radar coverage, the separation standards in force near it, etc. Whereas human factors findings and procedures about en route and oceanic control may generalise, those for terminal areas, approaches, ground movements and departures may be specific to an airport and inapplicable elsewhere. However the claimed uniqueness of the problems at each airport sometimes seems to be exaggerated. For example the numerous variations in the designs of air traffic control towers, which after all perform basically similar functions in most places, seem hard to justify in human factors terms. It would seem possible in principle to have quite a small number of good standard designs for towers, which would meet most requirements with minor modifications.

From the point of view of the pilot, international, national and regional variations in air traffic control can be tolerated only to a limited extent. It cannot be either in the interests of efficiency or safety for the air traffic control service which the pilot receives to vary greatly in its nature, its quality and its competence according to the part of the world in which he is flying. In long distance transit, pilots are entitled to expect that the procedures to be followed will largely be standardised wherever they are. The same considerations apply to variations in procedures associated with airports. Although each airport may have its particular problems, a limited range of solutions to them should be sought so that the pilot does not have to conform to a totally different set of procedures for each airport. Such variability seems bound to constitute a safety hazard, and a source of confusion particularly to pilots unfamiliar with a particular airport and its problems.

# CHAPTER 3

## HUMAN FACTORS CONTRIBUTIONS TO AIR TRAFFIC CONTROL SYSTEMS

### 3a THE BASIS OF THE HUMAN FACTORS CONTRIBUTIONS

This chapter considers the human factors contributions that could and should be made rather than those that have been or are made to air traffic control. Among the reasons why the actual contributions fall far short of the ideal are the following:

(1) Many of those concerned with air traffic control remain unaware of the contributions which human factors could make, do not understand them, or do not accept them.

(2) The practical experience of operational controllers may be preferred to human factors advice or be thought of as a substitute for it, though the two are not at all the same. Both are needed, and it is a mistake to equate them.

(3) There is a fundamental ignorance and confusion about what automation and computer assistance in complex man-machine systems are trying to achieve, about the consequences of automation for individual efficiency, and about the individual controller's perception of its consequences for him[28].

(4) There is a reluctance to concede that a technological advance may bring problems rather than benefits in human factors terms.

(5) Often human factors advice is sought for the first time too late during system evolution, when many decisions which generate human factors problems have already been taken.

(6) Insufficient time is generally allowed to gather and interpret the data needed to provide adequate human factors advice.

(7) There is a serious shortage of competent human factors specialists with a knowledge of air traffic control.

(8) Practical human factors effort has to be properly organised and requires appropriate facilities, support and funding, which may not be forthcoming.

(9) There can be a lack of adequate co-ordination of the various disciplines contributing to the air traffic control system, with human factors and with each other.

(10) Human factors findings may carry politically unwelcome or administratively unpalatable implications.

As a consequence of this shortfall, the initial contribution of human factors towards air traffic control must often be an educative one, so that those concerned with air traffic control know enough to recognise when human factors advice would be useful, and have realistic expectations when they seek such advice.

The human factors specialist should possess a knowledge of the principles and theories of man-machine systems, should know where to seek further knowledge, and should be able to appraise the applicability and relevance of psychological principles and theories to the practical problems he is facing. He needs an understanding of the main concepts of his discipline, how they have evolved, and what their limitations are. If he does not start with a thorough understanding of air traffic control, he must be prepared to acquire it or to work in close day-to-day interdisciplinary collaboration with those who possess it. His initial frame of reference is to treat air traffic control as an example of a large complex man-machine system. His general knowledge of the human factors problems typical of such systems should enable him to foresee many of the problems which may arise in air traffic control, to understand their origins and to formulate possible solutions to them. On the basis of this general knowledge he can recognise each human factors problem in air traffic control as specific to air traffic control or as widespread throughout large man-machine systems, and treat it accordingly as a specific or a general problem. It is therefore important that the human factors specialist working on air traffic control problems does not become over-specialised and out of touch with more general developments in man-machine systems, particularly because applications are often sought in air traffic control for technological innovations not originally developed for air traffic control.

A tradition in dealing with man-machine systems has been to allocate functions to man or machine. It is possible to make man-machine comparisons only about functions which could conceivably be done either by a machine or by a man. The list of such functions expands as technology advances but not as human needs and aspirations alter. Some human factors problems can be traced to limitations in the concepts deemed to be relevant to man-machine systems. In particular, there has been a tendency to describe human functions in machine terms - to say that the man functions like an amplifier, for example. This approach has been partly responsible for the biases in human factors towards ignoring some purely human attributes with no machine equivalents, considering others as more machine-like than they are, and making man-machine comparisons in line with advancing technology rather than with changing human requirements. Recently, examples of the opposite approach, describing machine functions in human terms as in artificial intelligence, have introduced other confusing biases.

In addition to his knowledge of man-machine systems, the human factors specialist possesses knowledge of human capabilities and limitations, much of which is derived from the findings of basic psychological research and from theories and concepts formulated from those findings. The traditions of experimental psychology, whereby facts gathered in laboratory experiments are used to formulate theories from which hypotheses are deduced for testing in further laboratory experiments, influenced many of the first human factors studies of man-machine systems, to the extent that it was not enough to take practical decisions in accordance with their findings but almost obligatory to give an explanation or interpretation of the findings according to a currently prevailing theory[29]. Efforts are still being made from time to time to link human factors findings and psychological theory in air traffic control[30], but not with such doggedness. Theories and practical findings can be mutually supportive. A theory based hitherto solely on evidence from the confined world of the psychological laboratory may appear more general or at least more widely applicable when evidence from a real life context is fully compatible with it. Similarly, findings from human factors studies have better prospects of generalising beyond their systems contexts if they rest on sound theoretical bases. The human factors specialist's knowledge about psychological theories and concepts may therefore offer prospects for demonstrating that findings may generalise and for providing explanations of them at a more fundamental level.

The generality of findings is gauged not only by their theoretical implications but also by their compatibility with existing evidence, as summarised in handbooks and reported in the human factors literature. Rarely can human factors guidelines be stated unconditionally in absolute terms. Normally an expert interpretation of them is necessary in any applied context. Numerous pertinent factors may invalidate the recommendations even of standard human factors handbooks. The interpretation of data in the light of specialised knowledge is one of the most important human factors contributions to air traffic control systems.

This combined knowledge of man-machine systems and of human abilities and limitations is used by the human factors specialist to evaluate what is known in relation to the applied problems he is dealing with. It may mean that a practical problem is treated as an example of a more general kind of problem or of a particular theoretical law or principle. Human factors may have to define and make explicit the implications for the controller of proposed air traffic control systems and tasks. This entails an evaluation of problems, a review of existing evidence, a distillation of relevant findings, and their interpretation in relation to the practical problems which arise. It is important not only to recognise what knowledge exists but also to appreciate what further knowledge would be helpful if it were available. Thus, gaps in existing knowledge are revealed, research needs are identified, and research can be conducted to close the gaps.

The extent to which existing findings generalise, their probable validity, and the need to reinterpret them for different practical applications are all human factors preoccupations which require assessments of whether the human factors evidence is likely to be context-dependent and is sufficiently reliable and valid to be trusted. Critical differences between the context in which the evidence was originally gathered and that in which it is now being considered therefore need to be understood.

Human factors can act as a catalyst in relation to the functions of others which can often remain compartmentalised and be fulfilled without much reference to what else is being done. Because human factors are essentially both interactive and interdisciplinary, the human factors worker may inadvertently fulfil an integrative role because he has to know more than most other specialists about the purpose of the whole system before he can do his own job properly. This can give the misleading impression that the human factors specialist can, and wants to, do everything, but his contribution, like that of his fellow specialists in other disciplines, is confined within the limits of his own professional knowledge and expertise.

To reveal the full human factors consequences of a proposal usually requires comprehensive measurement, and an important contribution of human factors concerns the measurement of people in systems contexts. Human factors can appraise the whole range of possible measurements, which normally extend far beyond measures of task performance, but which are needed to reveal the effects of a proposal in full. This aspect of human factors work is often of particular importance in that it will not be done at all unless the human factors worker does it. The reason is that proposals are usually advanced by those with a knowledge of their advantages rather than their limitations, and without independent guidance about appropriate measurements those which are favoured may confirm the expected advantages yet fail to reveal the limitations, which may not become apparent until the system becomes operational and it is too late to change them. The initial contribution of human factors, therefore, is often to bring a broad perspective to bear on man-machine systems, the tasks in them, the effects of the man on the system, and the effects of the system on the man. The human factors specialist knows how these effects can be demonstrated and measured, can provide concepts to describe and interpret them, can put the findings into a psychological or systems context, and can appraise not only the human factors work which has been done but the work which has not been done but should have been.

## 3b PLANNING

Most of the procedures in relation to the planning and conduct of air traffic control systems have human factors implications. Human factors principles can validly be applied not only to the product of planning but also to the processes of planning.

The fewer the firm decisions already taken when human factors advice is obtained, the more efficacious the advice can be. Advice available during the early stages of formulation and planning of the system can therefore in principle be the most effective and useful human factors advice of all.

Even if the planning of a future air traffic control system has progressed no further than the broad outline and discussion of proposals and possibilities, it is feasible to state the main human factors implications, to identify any major intractable problems, to cite sources of relevant human factors information and summarise what they recommend, and to indicate topics on which existing human factors data provide an insufficient basis for advice, so that further data should be gathered.

A key role of the human factors specialist in the formulation and planning of the air traffic control system is the identification of problems. Any which he fails to identify may remain unrecognised until the system becomes operational, when there may no longer be practical solutions to them. Problems are of two main types. Firstly, are those typical of large man-machine systems, described in the human factors literature and perhaps familiar from their own experience to some of the participants in planning.

Secondly, are problems specific to the system, associated in particular with changes, advances and innovations. Examples of general problems are the aggravation of the problem of boredom by progressive automation, the difficulty of indicating on displays of digitised information how trustworthy the information is, and the provision of means for effective supervision when many of the interactions are between individual operators and machines. Ex ..es of specific problems are the derivation and proving of appropriate training for new devices, the reconciliation of innovations with existing skills and practices, and the acquisition of knowledge about how a new facility can fail.

The role of the human factors specialist during planning is to bring out the human factors implications of what is being contemplated. He is there to collaborate and assist. He must not appear obstructive, intransigent or over-critical of the proposals of others on human factors grounds. Any system plan raises many human factors issues. He must identify and state them and their implications, so that the decision on whether to proceed with the plan is as fully informed as it can be in human factors terms, and the resulting operational system will not bring unpleasant surprises in the form of human factors consequences which could have been foreseen but were not. With innovations, he may be able to deduce their human factors problems but not offer solutions, though guidance should be possible on whether solutions are attainable or not. System planners unfamiliar with human factors may reach some decisions similar to those in previous systems which led to difficult human factors problems. Again a role of human factors is to draw attention to this and to any solutions which proved successful before. A human factors problem may apparently have been ignored in the past, not because it was unrecognised but because it could not be solved. An example is the fragmentation of team functioning under high workload.

In offering guidance, the human factors specialist must know the strength of the evidence on which his recommendations are based. System planning has to reach compromises, since operational, financial, technical, human factors, and other considerations would each individually point to different solutions, but a single solution has to be found. In reaching compromises, the human factors specialist must know what his recommendations should be but also should take account of the extent to which they could be modified without serious consequences. He needs to know the detailed nature of the supporting evidence. A simple example may clarify this important point. Suppose a handbook recommends 450 mm. as the viewing distance for a display. The interpretation of this depends on what 450 mm. was originally compared with - perhaps 440 mm, or 420 mm, or 400 mm, or even 350 mm. It also depends on the amount of data gathered about each alternative and on the statistical significance and operational importance of the differences. If 450 mm. was compared with 440 mm. and the difference between them was significant statistically and large in terms of task performance, such evidence suggests that the planned viewing distance should be 450 mm. and that it would be difficult to justify even small changes from this value. However, if, as is more likely, 450 mm. was compared with 400 mm. and the difference between them, though statistically significant was small in absolute terms of performance, for example with many tasks being unaffected and small decrements being observed on a few, then human factors evidence to insist on 450 mm. does not exist and the optimum may not be 450 mm. but some intermediate distance that has never actually been measured. In such circumstances the human factors recommendation is much less firm, and the human factors specialist must accordingly be much more willing to compromise. His specialist knowledge must cover not only the recommendation itself but the nature and strength of the supporting evidence, which handbooks do not give.

It is important to emphasise the interacting nature of human factors evidence, and to ensure that the full range of interactions and their consequences is appreciated as planning progresses. A choice which seems simple, cheap and effective but which would ultimately engender high rates of labour turnover and perhaps industrial unrest, may in the long term be the wrong one. When notions of cost effectiveness and reliability are discussed, the cost of recruitment, selection, training, high attrition rates, and similar notions should not be ignored, and if the system is not functioning because its human components are on strike this may constitute a major form of system unreliability. Many decisions taken during planning determine not only the safety and efficiency of the air traffic control system, but the well-being, the job satisfaction and the morale of those who operate it.

Part of the human factors frame of reference in viewing proposals and plans for new air traffic control systems concerns corresponding functions in existing systems and comparable functions in other large man-machine systems, such as air defence, nuclear power plants and chemical processing. This body of knowledge may influence the grouping of tasks and functions in the proposed system, the planned flexibility of the system for handling wide variations in traffic demands, and the methods for transmitting information intended for the controller's use. When the allocation of functions between man and machine is discussed, this experience of functions successfully or unsuccessfully performed in other systems[31] may be set against the pressures of advancing technology for more functions to be fulfilled automatically.

At the planning stage advice on specific system details is seldom required or appropriate. Human factors contributions are therefore general, and concern principles, known evidence, the compatibility of human factors and other requirements, and the relevance of problems which have arisen elsewhere and have proved difficult to solve[32]. Numerous other roles, supervision, assistance, monitoring, management and maintenance for example, should also be considered in the system plans in terms of their human factors consequences.

Often the human factors specialist is expected to put forward proposals of his own. It is not helpful to others participating in planning if their proposals are stated to be incompatible with human factors requirements, yet no attempt is made to formulate alternative proposals which would meet human factors requirements. Part of the role of human factors is often to formulate such proposals for discussion, just as the role of other disciplines may be to formulate ideas which satisfy their requirements. For his formulated proposals to be sensible, the human factors specialist relies on interdisciplinary collaboration during the planning stage.

Human factors as a discipline may be less entrenched than others, and therefore more of the burden of proof may rest with it to demonstrate why its recommendations should be accepted. The human factors specialist may be among the first to detect incompatibilities among the proposals of others, since he has to examine all of them to judge their human factors consequences. It may be in the interests of human factors and of system planning alike if human factors becomes a focal point for resolving such incompatibilities which affect the controller, wherever the formal organisation of the system planning does not include such a role, but it is vital to remember that the resolution of incompatibilities is still essentially a total planning team function and not a human factors one. The knowledge of the human factors specialist is a combination of his own professional expertise with a smattering of that of his colleagues participating in planning, just as their knowledge covers their own professional contribution in depth and contains a smattering of human factors knowledge. Smatterings of knowledge usually contain many inaccuracies and inadequacies, no matter whom they belong to. They allow common problems to be discussed with some glimmerings of their implications, but greatest reliance must always be placed on those who possess the most thorough relevant professional knowledge.

The role of human factors in relation to the planning of air traffic control systems does not have a single universally applicable description. It varies according to:

(1) The role assigned to human factors.

(2) The experience and knowledge of the human factors specialist.

(3) The stage at which human factors evidence is first contributed.

(4) The number and disciplines of other participants in planning.

(5) The methods of management and organisation employed for the planning process.

(6) The interpretation of the objectives of planning.

An essential human factors contribution at the planning stage, or even before, should be to identify relevant research needs. Normally the time needed to organise and conduct research to provide essential data to guide subsequent design stages is quite long. If problems are not identified until the design stage there is seldom sufficient time to conduct experimental research on them. Human factors advice should be given on the problems which are amenable to research, on the research effort which would correctly reflect their relative importance, on the conduct of the research itself and on the reliability, validity and interpretation of the research findings. It is desirable to have continuity of research effort which is not too system specific but which ultimately can provide a sound body of knowledge, so that the human factors contributions at the planning stage come to depend more on that established body of evidence and less on the identification of problems yet to be tackled. From this it follows that those best placed to give human factors advice during the planning of an air traffic control system are human factors specialists with a detailed knowledge of air traffic control, of aviation, of interdisciplinary collaboration, of large man-machine systems, and of the whole range of implications for the man of the progressive introduction of automation or computer assistance into his working environment. General purpose human factors consultancy, though successful in many fields, tends to be less satisfactory in air traffic control and in other systems of comparable complexity. The main failing and imbalance in current human factors work on air traffic control concerns the comparative neglect of research to understand the roles and thought processes of the air traffic controller in general terms. Such research covers systems concepts, principles for information portrayal, man-machine function allocation, the experimental exploration of alternative ideas, and particularly interactions between the man and flexible adaptable software. The resources devoted to human factors research intended to facilitate planning decisions have not kept pace with technological advances.

At the planning stage, the main functions of the human factors specialist are the following:

(1) The maintenance of his own professional knowledge, particularly about basic and applied psychology, to ensure that his advice is based on sound and up-to-date evidence, constructs and techniques.

(2) The acquisition of a reasonable knowledge of the proposed air traffic control system being planned.

(3) The appraisal of the practical relevance for the air traffic control system of human factors knowledge and particularly of recent advances in it.

(4) Participation in planning meetings at which proposals for the air traffic control system, or parts of it, are discussed and decisions taken.

(5) The formulation and explanation for participants in planning of the relevant human factors evidence that is available.

(6) The identification of human factors problems on which there seems too little relevant evidence to offer firm guidance.

(7) The deduction and statement of human factors research needs to meet the objectives of the proposed system.

(8) Advice on how, where and with what resources the proposed research should be done.

(9) Participation in relevant research and supervision of research to ensure that it meets planning needs.

(10) The interpretation and dissemination of human factors research findings.

(11) The provision of relevant solicited or unsolicited human factors advice to ensure that others are aware of it, and the professional interpretation of that advice in relation to the planned system.

(12) Active liaison with fellow specialists, for example in occupational health or lighting engineering, to ensure that solutions to problems meet their needs as well as those of human factors.

3. SYSTEM DESIGN

At the design stage, when the detailed facilities and procedures needed to achieve the planned objectives of the air traffic control system are formulated, the main human factors contribution is the interpretation and practical application of existing relevant knowledge. As in the planning stage, human factors advice during system design must not be rigid and intransigent, but should consist of recommendations with guidance on the strength of the supporting evidence, on the probable penalties of failing to meet the recommendations fully, and where possible on known limits within which solutions must be found to avoid serious consequences for efficiency or well-being.

It is important that all human factors recommendations are made with an understanding of how the system as a whole is designed and intended to function. Recommendations about any specific item, such as a display, a control, or a communications facility, must not concern human factors in isolation, but also consider the practicalities of implementing them. It is futile for the human factors specialist to make a proposal which is sensible in human factors terms but both wrong and naive in engineering terms, since this may suggest to others that the human factors specialist does not understand what they are doing or the limits in which they are working. However, the human factors specialist often has to contend with simplistic human factors suggestions by others, which betray their ignorance of human factors and their misunderstanding of his role. He needs forbearance when his colleagues from other disciplines make human factors suggestions which are naive and wrong to him. As people themselves, they believe they understand others, and they think of human factors as a combination of this understanding with experience and commonsense, which they also possess. The falsity of this view of human factors is immediately apparent to anyone who reads a textbook on the subject, or examines a handbook of human factors data, but many never do.

In system design, human factors contributes to decisions on how the broad aspects of tasks envisaged during the planning stage should become a practical reality. One contribution centres on the best methods for conveying information to the controller, usually by means of visual displays. This entails some knowledge of the human factors implications of modern display technology and of computer programming, as well as of the tasks to be done. Recommendations can be made on the type of display, on appropriate formats for portraying the information on it, and on its physical positioning in relation to the users and to other displays. More detailed recommendations cover the content and layout of displayed information, suitable principles for its depiction (such as alphanumeric, symbolic, pictorial or graphic), and choice of coding dimensions, such as colour, shape, size, brightness and contrast for information in symbolic form. The relationship of the display to the controls for it, to the physical environment in which it is used, and to the characteristics of the controllers who operate it, must also be considered. In the present state of automation and man-machine relationships, a display may have to do more than convey information, and human factors recommendations may be added on its suitability for these further functions, such as acting as a memory aid. Information should be displayed in a logical order derived from decision tree analysis, to facilitate task performance. The human factors specialist should emphasise that in drawing up the detailed specifications about displays, decisions are being taken, incidentally and perhaps unwittingly, on the kinds of error which can be made when the displays are read.

What appears automatically on a display is determined by the system design, and relates to sensors, to hardware, and to software. A very small portion of the information sensed and stored in a modern air traffic control system is presented to the controller on his displays, and that portion has been processed, collated, selected, smoothed, summarised, and converted to a level of detail appropriate for the tasks and for human information processing limitations. The display is the main means for conveying from the system to the man the limited information which the system has selected for his use.

Controls are the corresponding means for conveying information from the man to the system, and for allowing the man to select information for his own use. Therefore human factors advice is given on appropriate types and sensitivities of control for the envisaged tasks, on their location in the workspace, and on their relationship to the displays with which they are associated. General principles can be used to predict efficiency of performance, but again the choice of controls has a large influence on the kinds of error which are possible. Controls, particularly keyboards or their equivalents, also determine to a considerable extent the functions which the controller can fulfil in the system. It seems trite, but nevertheless must be spelled out by the human factors specialist during the design stage, that the controller can fulfil only those functions for which the means of fulfilment are provided in the form of input devices. The flexibility of the controller, and his power to innovate and compensate for any system inadequacies or deficiencies, are determined by the facilities and particularly the controls, with which he is provided. Ultimately he can do only what the system lets him do.

At the detailed design stage human factors advice is given on the methods of gathering information and transmitting it within the system. Machine to machine communications are generally of only peripheral interest to human factors, but all other communications, machine to man, man to machine, and man to man, come directly within the province of human factors. The first two concern the man-machine interface, and its effects on tasks and system performance. Man to man communications relate to speech and other forms of communication between people. With the advent of automated speech synthesis and recognition, the hitherto clear distinction between man-machine and man-man communications is in some respects becoming more blurred.

Often the gathering and transmission of information are seen as self-justifying activities, successfully achieved when it can be shown that all the data have been gathered and all the information transmitted[33]. The reasons for gathering information are relatively few and straightforward, and should determine what is gathered, how often it is gathered and what is done with it. Information may be gathered to meet a legal requirement, or gathered to be stored, or gathered to be fed into a computer and used as a basis for calculations, or gathered for the controller to use in order to take decisions and control air traffic. Once the purpose of gathering the information is defined, the form that it should take becomes more clear. The information needed for legal requirements can usually be clearly defined.

information for computation purposes can be specified, and will differ grossly in its quantity, rate of presentation, forms of coding and selectivity from information gathered for human use. In this last instance, gathering information for its own sake can be a pointless and self-defeating exercise, since in quantity, in rates of transmission, in formats and in codings it must be tailored to the tasks which the controller must do and to human limitations of attention, information processing, memory and understanding. If there is a need for a semi-permanent record of information, this suggests visual rather than auditory information transmission. On the other hand, speech is inherently more flexible than any keyboard. As with the choice of displays and controls, the methods of communication determine the sources of degradation which are possible as part of the transmission of the information and the sorts of error which will be made by the users of the information transmitted.

The detailed design must also consider the physical environment of the parts of the system where human operators will work. This covers the ambient environment, such as lighting, heating, and ventilation, and the layout of the workspace, including consoles, suites and accessability. If it is envisaged that an operational suite will be used for training, so that space must be found for an additional trainee, or that, when traffic is light, it may sometimes be operated by one man instead of by a team, then provision must be made for such flexibility in the design, otherwise it cannot be achieved efficiently. Various techniques, such as scale models, may be used to confirm the practicality of the physical design recommendations, though it should be possible from first principles to predict all the glares, reflections and accessability problems which will arise, and prevent them. Various colourings and surface textures within the environment can be used to enhance its appearance and to foster the practicality of the recommended design to achieve basic human factors requirements, particularly those related to vision. The design should also be influenced by anthropometric data. If both men and women will use the workspace, then the range of body sizes to be accommodated comfortably is much larger than for men or women only, and the design of furniture must take account of this.

Certain human factors aspects of the physical environment are more difficult to design for towers than for centres. In an air traffic control centre, it is usually possible to specify an optimum for the positioning, lighting and layout of facilities since the physical lighting environment is intended to be constant. With a tower, where the visual environment may range from exterior darkness to bright direct sunlight, a different approach may be necessary since equipment and facilities must tolerate a large range of ambient lighting and glare sources, and the solutions to human factors problems may therefore be quite different.

In theory, there should be no serious delays during the design stage because of lack of human factors evidence. If the planning has been properly conducted, there will have been ample forewarning of the kinds of evidence needed, and time to gather it from existing sources or to conduct experiments to obtain it. In practice, human factors problems are often not identified at the planning stage, and the necessary research is not done, with the result that evidence is not available when it is needed at the design stage, and hasty experimentation has to be conducted or human factors advice given on inadequate evidence. Although the role of human factors research at the design stage should be very limited, in practice there is therefore a considerable need for it.

In the past, at the design stage the operational equipment for the system did not yet exist, and therefore fidelity of its representation did not arise as a practical issue. What was needed was a quick check to ensure that any novel function would not introduce insuperable human factors problems caused by inherent human limitations. There was no point in embarking on ambitious experimentation to provide answers too late to affect the design. In the future, this will change: the above constraints refer to hardware, not software, and as systems come to rely more on software it becomes more feasible to try them out during their design.

Another human factors function during the design stage is to alert designers to the implications for selection, training or retraining which their detailed design recommendations may entail. These implications may not simply cover the novel aspects of the system but may also include functions which are apparently similar to those performed hitherto in existing systems, but in fact would require different skills and abilities and might therefore lead to difficulties, particularly for older controllers, in learning to adapt to them. The policy on other relevant human factors should also be considered during the design stage, including the needs for challenge, effort and interest in the job, for responsibilities and status, for careers and job satisfaction, and for knowledge of results and morale.

During the design the need may emerge for further evaluation, probably by real-time simulation methods using a prototype system, to resolve and clarify uncertainties and to confirm feasibilities. It may be necessary to devise new procedures and instructions, to explore the implications of a proposed design change for the rest of the system, to establish the levels of task performance likely to be achieved, and to confirm that communications and information transmission problems can be overcome. There may also be questions over manning, divisions of responsibilities, the information which is essential, optional or unnecessary, the amount of processing and collation of information which is desirable, the division between automated and manual functions, and the methods for keeping the controller sufficiently involved to participate actively when required even when fulfilling a normally passive role. Many of these problems can of course be identified at the planning stage and be studied in general terms then, but their particular form in the system may only become apparent during the design, when it becomes necessary to study their detailed implications for the specific system.

One problem in design which has often not been successfully resolved in the past is that of communication between the designer and the user. There is the perennial complaint, often with considerable justification, that the designer does not understand the user's needs. Less often heard, but equally cogent, is the designer's complaint that the user does not understand what he is trying to achieve, but criticises him for failing to design what he never intended or for inadequacies which are not design faults but technological, financial or legal constraints. The human factors specialist should know enough both of the designer's intentions and of the user's needs to be able to resolve some at least of the incipient misunderstandings between them, perhaps through devising suitable training, since training represents an intermediate stage between design and use. Otherwise systems and facilities may be designed which would work properly if the controller knew how they were intended to function, but he never has a chance to gain this knowledge. As systems become technologically more complex, there is more information about the designer's intentions to convey to the user, but with visual displays and appropriate software the materials are available for adaptive training of the controllers in the use of the system. The emphasis on software offers the advantage that it become possible to conduct real-time simulation studies as part of the design process, not to verify decisions already taken, trace their implications and quantify their consequences, but to try, by means of feasibility studies, to determine what the design decisions should be. This approach has the further advantages of allowing prospective users to participate in design decisions, and of evolving some training procedures, since the participants in simulation studies to aid design nevertheless need to be trained in the use of the simulated system.

The human factors specialist has to be alert to the labelling of jobs and functions during the detailed system design. Effective supervision does not become possible just because it is done by someone called a supervisor. Similar considerations apply to concepts such as assistant, monitor, and manager. A job done by more than one person is not necessarily done by a team unless specifically designed to be. The conditions for effective supervision, assistance, monitoring, or teamwork have to be built into the system design: they do not arise fortuitously.

At the system design stage, the main functions of the human factors specialist are the following:

(1) The maintenance of current and relevant professional knowledge of human factors.

(2) The evaluation of the generality of human factors data sources and the applicability of their findings to the specific air traffic control system design.

(3) Active participation in the system design processes.

(4) The presentation and interpretation of relevant human factors data and the demonstration of its relevance.

(5) The statement of the human factors implications of design decisions as they are made, particularly of some of the less obvious implications.

(6) The definition, where possible, of the optimum human factors design decisions and of the human factors limits within which decisions should be reached.

(7) The definition of human factors issues which can be recognised as problems but on which adequate human factors guidance cannot be given.

(8) The specification of what is needed to obtain adequate human factors evidence where it is lacking and on the best practical compromises to obtain adequate information within timescales available.

(9) The active seeking of effective practical compromises which meet human factors requirements.

3d IMPLEMENTATION AND TESTING

The most widespread application hitherto of human factors to air traffic control has been in the implementation and testing of system or task designs, often by attempted simulation or replication of some aspects of the system or the tasks. The role of human factors when applied to air traffic control in this way does not differ markedly from corresponding applications of human factors principles in other contexts. Use is made of the human factors knowledge of human abilities and limitations, of methods of measuring people while they are performing tasks, and of the principles for the design and analysis of experiments. Recently there has been some change of emphasis towards conducting experiments to verify design decisions but in general experiments during implementation and testing serve some of the following purposes:

(1) To confirm that the design is feasible.

(2) To discover and resolve any unforeseen difficulties which the design may lead to.

(3) To verify that procedures and instructions are practical and achieve the desired aims.

(4) To settle fine points of detail in the design in relation to already agreed principles.

(5) To examine the allocation of functions to individuals and teams and to study the associated communication and liaison problems.

(6) To provide empirical checks that the system will function as planned.

(7) To indicate whether the envisaged operational benefits are likely to be achieved.

(8) To work out methods of training and familiarisation.

There tends to be an imbalance between those aspects of the systems implemented without being tested and those implemented after they have been tested. The main reason for this imbalance is that a great deal of detailed thinking about how the system will function, what facilities should be provided, and how they should be integrated, is essential in order to set up the testing process. Without the stimulus of testing, such thinking in such detail may never be done. Often the process is so thorough that many of the findings of implementation and testing are known in general terms before the testing is actually done from the planning necessary for testing. The process of testing may rely on simulation methods and empirical measures or may be a logical progression through different system states, where the functioning of the system is discovered or deduced and the results are correlated with changes in the system states.

This latter procedure may be analogous to modelling the system, one purpose of which may be to select the most crucial topics and conditions for empirical testing and verification. If the system as designed is built without adequate testing, some of its inherent flaws may not become apparent until it is too late to change them: in such circumstances, an effective human factors contribution has to be based on a very substantial body of well established knowledge covering every aspect of the envisaged system and applied at the design stage, a contribution rarely attainable in the present state of knowledge. Therefore, the processes of simulation and testing may both verify the existence of suspected human factors problems and reveal unsuspected ones. Testing should also provide solutions, if they exist, to human factors problems in time for them to be implemented for operational use.

Often the human factors specialist, by training and inclination, is fundamentally research minded. It is essential that he does not treat the processes of implementation and testing as research, since by this stage in the evolution of the system it is far too late to conduct research which will influence the form of the system in a major way. It follows that it is not always appropriate to use the same experimental methods and experimental designs for testing and implementation as would be used for research. In particular, once a procedure or function is found to be satisfactory there may be no justification for gathering further quantitative data about it. Such data are often suspect since the equipment being used, whether hardware or software, will not necessarily be identical to that in the final operational system but merely a representation of it within available technology and finance. Also the operators or controllers participating in the testing lack full familiarity with the system and with the potential traffic demands. Therefore to conduct research-like studies seeking definitive guidance on system or human capacities, on workload or on stress is not likely to be productive or valid at the testing stage. The system has been designed. The aim of implementation and testing is to ensure that it functions in accordance with the design intentions, and to make any possible changes to achieve or enhance the planned objectives. Implementation and testing do not constitute an exclusively human factors exercise: many others have an interest in confirming that the system will work as envisaged, and their questions, as well as human factors ones, have to be answered during testing.

A further human factors contribution concerns the methods of training to use the system. Although air traffic controllers can be trained in principles and procedures using relatively simple simulations and demonstrations, and although experienced controllers will already possess a great deal of relevant knowledge before they come to a new air traffic control system, the first practical training specific to an air traffic control system cannot usually take place until the stage of implementation and testing has been reached. Then it is not merely desirable to begin training so that when the system becomes operational the controllers will be able to use it, but it is essential to devise training so that the system can be tested. Sometimes the same simulation facilities are used for evaluation and for training, although this is not ideal since the objectives are different and each is served best by purpose-built equipment. Also the traffic samples used for training are seldom ideal for testing and evaluation. In order to test the system it is necessary to train people to use it: in order to train them it is necessary to devise their detailed procedures and instructions.

In implementing the system, human factors guidance is often desirable on the level of training which should be achieved before the system is tested. Two distinct approaches are possible. One is to set a standard or criterion which must be reached by controllers before the system can be tested, and to persist with training until that standard has been attained. This can be administratively cumbersome and presupposes that the standard is attainable, but it does mean that the level of performance of participants can be clearly specified. The alternative approach is to give a fixed training schedule or amount of training, at the end of which training is deemed to be over and the testing is conducted. This gives some indication of individual differences and of whether the system could continue to function adequately with poorly trained controllers, although the results may not be typical of those in the final operational system.

To test the system properly, controllers or other operators must be trained to acquire the necessary operating skills. Some may prove unable to do so, and either additional selection procedures for controllers are entailed to pick them out, or changes in the facilities or training methods must be devised to remove the need for the skills or to acquire them by other means. It is vital to discover difficulties of this kind before the system becomes operational. Normally the purposes of implementation and testing will not reveal much about individual differences between controllers. Although some inkling of individual controllers' learning difficulties may emerge, there will not normally be a good indication of how prevalent these difficulties may prove to be. The emphasis in testing is on making the system work rather than on assessing the controllers and their individual differences.

Data gathering during implementation and testing may be misleading in terms of the capacity of the system or the workload of the tasks. Among the reasons for this are that controllers have insufficient experience, that their errors while inexperienced may not be typical of their errors when the system becomes operational, that the equipment is not an adequate representation of the operational equipment, or that those concerned with the maintenance and data integrity of the system are also learning their tasks, and may take some time to trace, diagnose and solve problems correctly. Sometimes the role of the controller in testing is little more than to exercise the equipment, although the opportunity should be taken to make whatever valid human factors assessments are possible.

The feasibility of a procedure may initially be established during testing by a simplified form of task or with light and predictable aircraft traffic. An important aspect of human factors advice is to specify how realistic the simulation must be to obtain valid data for various purposes from tests. One inclination is to opt for a very complex simulation and elaborate testing to try to assess every aspect of the system at once. Such an approach may yield human factors findings which cannot be interpreted and which fail to provide a clear guide on capacities or manning levels. Excessive complexity can make it impossible to disentangle the different effects of various factors or to reach general conclusions.

The role of the human factors specialist during implementation and testing is always interdisciplinary, and sometimes subsidiary. Unless and until the system or equipment can be made to function properly, and the technical teething troubles have been resolved, there is no point in taking human factors measures since the evidence obtained will be representative of nothing but a system with teething troubles.

The interactive human role however may become very important during implementation and testing. It is then that the first attempts are made to set the equipment into an appropriate physical environment, to check the interactions between the environmental factors, the physical workspace and the system functioning, to test the designed man-machine interface and its functioning and the typical errors which it will generate, and to ensure that all the information and facilities are in usable form. A modern air traffic control system is so complex that even with full human factors participation during the earlier stages of the evolution of the system, some human factors problems are likely to emerge for the first time during implementation and testing. Displays may have to be modified in format or content, the quantity of information may have to be changed to fit the limitations of human understanding and the rates of information assimilation, other software changes may be needed, and controls may have to be modified.

Modern techological systems have already changed the role of human factors in relation to implementation and testing of the air traffic control system, and are likely to change it more in future. Most existing systems contain a great deal of fixed hardware, originating from the design stage and difficult to modify. When these systems were originally implemented and tested, the aim was to ensure that the hardware was usable. It was not generally possible to modify the hardware grossly during or after implementation and testing, even if major deficiencies were found. In the future, when more functions will rely on software, in principle far more inherent system deficiencies can be resolved by rewriting the software, without entailing major costly hardware modifications. The human factors implications of this for training have not yet been fully appraised. In particular it is clear that an inherent source of error may be introduced if the hardware remains constant, but, as a result of different software, existing familiar keys or controls have new functions. In the future the human factors specialist will need to know more about the flexibility and limits of possible software changes, and the effort entailed in making them, if he is to give the best human factors advice on the modifications that should be made in the interests of system efficiency and safety.

At the implementation and testing stage, the main functions of the human factors specialist are the following:

(1) Participation in the planning of testing to ensure that it can produce relevant evidence to answer human factors problems if required.

(2) The provision of advice on aspects of testing which can yield meaningful results in human factors terms and particularly of cautionary advice about themes such as workload, capacities and stress, where findings from testing may be spurious.

(3) The explanation of appropriate levels of complexity in testing for obtaining valid human factors evidence, where tests that are too simple may be invalid because they are too far removed from operational conditions, and tests which are too complex may be invalid because the complexity obscures all explanations and interpretations of the findings.

(4) Advice on appropriate experimental designs for feasibility studies or for the systematic exploration of variables.

(5) The definition of appropriate measures of human behaviour and experience in testing and of the amount of information necessary to yield findings from which confident generalisations can be made.

(6) The application of general knowledge about human capabilities and limitations to the envisaged air traffic control tasks and variables in testing.

(7) Recommendations on the nature and amount of suitable training which should precede testing and on the criteria for judging whether sufficient training has been given.

(8) The provision of advice on the level of realism or fidelity of the testing conditions and of the traffic samples necessary to obtain valid human factors conclusions.

(9) The specification of the minimum physical environmental conditions which should be met if these conditions are not to invalidate any findings.

(10) The appraisal of human factors aims in relation to the aims of others so that the testing as a whole may achieve all its objectives.

(11) The interpretation of errors and omissions during testing in relation to their implications for system efficiency and for software or hardware changes.

(12) The identification of human factors problems not tackled directly in the testing but revealed by it.

## 3e OPERATIONAL USE

The first contributions by human factors specialists to air traffic control are normally made to an air traffic control system in operational use. This is not because contributions to operational systems are generally the most effective way of using human factors effort, but because human factors problems are recognised first as such in systems in operational use and the normal first contact of the human factors specialist with air traffic control occurs when he is asked to solve such problems. Often the constraints already built into the system mean that he can offer only palliatives which help to resolve the symptoms of the problem but do not tackle its root cause. In giving whatever help he can, he usually makes it clear that he could have made a much more effective contribution if he had been consulted earlier before the system became operational.

The extent to which an effective human factors contribution is necessary in systems in operational use should depend on the quantity and quality of the human factors contributions during the planning, design, implementation and testing of that system, and on the terms of reference of the human factors specialist as the system evolved. The greater his contributions at earlier stages, the less should be the need for human factors intervention during operational use. There will always however be some need for human factors contributions to operational systems as there are usually a few problems which no-one could foresee before the system became operational.

Although the sources of human factors problems in operational air traffic control systems cannot always be removed, much can often be done to reduce their effects on the operational system. The experienced human factors worker employs a mental checklist, based on his previous knowledge and on the literature, to identify the features of the operating system which are causing the difficulties encountered. He will usually be able to recognise any gross deficiency in the workspace or in the environment almost as soon as he sees it for the first time. It may be relatively straightforward and inexpensive to modify unsatisfactory aspects of the physical environment. Postural problems related to seating and console design, inadequate heating and ventilation, glare or reflections, pools of light or darkness, gross mismatches in the brightness levels of displays, inappropriate ambient lighting, shiny or wrongly coloured visual surfaces, excessive noise because of incorrect floor coverings or plastering in the operational environment - all these are examples of human factors problems which generally can be solved in operational systems, provided that some limited funding is available and administrative inertia can be overcome. It may also be relatively easy to modify aspects of displays, controls, or communications, depending on the system design and particularly on the extent of dependence on software. A balance has to be struck between the wants and the needs of controllers. A controller may express a strong preference for a facility which does not seem to be needed. On the other hand, he may make great efforts to compensate successfully for the absence of a needed facility which is not provided and cannot be introduced retrospectively.

The human factors specialist has to judge how serious the problems arising during operational use are. Some problems must be solved no matter what the cost, to ensure either the efficiency and safety of the system or the well-being of controllers. Others are minor and do not warrant any major expenditure of time, effort, or money, but should nevertheless be resolved when a suitable opportunity arises such as a system refit or major modification. A role of human factors in resolving problems is to try and ensure that the solution does not introduce further problems in exchange for quite minor benefits.

In giving human factors advice on operational systems, the human factors worker relies almost entirely on his knowledge and on standard data sources such as handbooks. If so little is known about a problem in an operational system that research on it would be necessary, a practical solution is unlikely to be found in time to be implemented unless the problem is very simple.

Nevertheless, operational systems have important links with human factors research. Problems which arise and can be identified in existing operational systems perhaps in unremarked and unremarkable form, may be spotted as serious human factors problems for the future, and thus lead to human factors research where the findings will be applied to future systems rather than current operational ones. Surprisingly frequently, an examination of current operational systems can give an inkling of future human factors problems, especially if they relate to known technological trends or known attitudes.

It is necessary to temper recommendations with practical considerations of their acceptability, practicality and cost in human factors resources. Certain problems, such as boredom[34], can be identified in air traffic control now but occur in more severe form in other contexts, in the case of boredom in air defence systems: therefore techniques for its investigation, hypotheses, and perhaps even findings about it may be derived from other relevant work initially, though they would require verification for air traffic control. Other problems, such as the controller's belief that increased computer assistance makes it more probable that he will "lose the picture"[35], may not arise in quite the same form anywhere else, and for that reason must have priority in the allocation of human factors resources to air traffic control problems. These problems, boredom and losing the picture, are both examples where trends in existing systems point the way to problems which may become more serious in future systems unless there is practical human factors research on them in the meantime.

Either inadvertently or as a matter of policy, the human factors specialist may become a channel for complaints by users of operational systems, partly because he has to obtain users' opinions in order to do his own job. In identifying future problems in a system, he should pay attention to those which users envisage as well as those which he himself detects. He also needs to be aware of problems which management or system planners may envisage while others do not. Some of the most pressing problems may not concern the physical environment, the workspace, the man-machine interface, or even the conditions of employment, but concern rather the influence which the controller himself has on future plans, on design changes in the system, and on the equipment and facilities which he is expected to use. A probable role of human factors in future, and an expanding role in some existing operational systems, is the communication to management and planners of the controllers' needs, the explanation to controllers of inevitable technical, managerial and financial constraints, and the reconciliation of different points of view to arrive at a system acceptable to all, though perhaps ideal to none. Occasionally human factors assumes this role piecemeal at the moment.

If the human factors specialist performs his functions properly, his recommendations should be seen to be independent of both management and controllers. His role should be based firmly on his impartial interpretation of existing scientific and psychological evidence and if it is it should be acceptable to all sides. His recommendations may not always be palatable or welcome to all, but must be even-handed and unbiased. He does not take sides, whether those of management, controllers, financiers, trade unions, governments, pilots, or passengers. Sometimes the judgement of the human factors specialist on the importance or otherwise of an identified problem does not agree with that of anyone else. If he is sure he is right and there is good evidence from other sources or from his knowledge of man's capabilities to support him, he must persist in drawing attention to the problem he believes to be important: if he does not, no-one else will.

A further role of human factors is to consider existing operational systems as similar to or different from proposed future ones. If there are differences, their human factors implications in terms of selection and training requirements for controllers need to be identified at an early stage. Perhaps some current problems can be traced to inadequacies in procedures or instructions which set unnecessary limits on human capabilities in the system, or to the failure of training to instil and demonstrate the optimum employment of equipment and facilities.

Examination of existing air traffic control systems can also reveal how far the controllers actually understand them. The extent to which users need to know the technical details of how a system is designed to function is a matter for debate, but if misunderstandings lead to misuse of equipment or to the total neglect of installed and serviceable facilities, then the reasons need to be found. Lessons may be learned for the future from such misunderstandings in current operational systems.

In relation to operational use, the main functions of the human factors specialist are the following:

(1) The maintenance of an adequate knowledge of current air traffic control systems.

(2) The development and maintenance of some form of checklist of all the human factors of potential relevance to operational problems in air traffic control systems.

(3) The application of general knowledge about the effects of physical environmental factors on performance to the physical environments of particular systems.

(4) The identification of human factors problems in future air traffic control systems by the detection of incipient forms of those problems in current systems.

(5) The successful classification of human factors problems in current systems as specific to air traffic control or general throughout large man-machine systems.

(6) The assessment of the scale and implications of proposed changes in air traffic control systems in human factors terms.

(7) The maintenance of knowledge of current and, where possible, future attitudes of controllers towards their jobs and working conditions.

(8) The establishment and maintenance of an independent role for human factors so that its recommendations are never interpreted as partisan or lacking impartiality.

(9) The study of the extent to which controllers understand the systems they are using and the assessment of the optimum knowledge of the system which they need to have for effective and safe controlling.

(10) The persistent statement of important but unrecognised human factors problems until their significance is acknowledged.

## 3f SYSTEM EVOLUTION

On the whole air traffic control systems have evolved, and probably will continue to evolve, in the same general way as other large man-machine systems. The human factors problems that they pose are not the same in all respects as those of other systems: in an era of rapidly expanding traffic demands, major advances are required simply to maintain existing air traffic control standards. Problems in air traffic control will not disappear if no action is taken, and the penalties for a major failure or error can be particularly severe. There are also uncertainties in deriving agreed criteria for judging the efficiency of what is being achieved, but such uncertainties are common in large man-machine systems which provide a service rather than make a product.

Many proposals during the planning and design phases of air traffic control systems have counterparts in other systems, because technology is able to turn these proposals into reality if they are acceptable. Similarly many of the aspirations of controllers have counterparts among workers in other large man-machine systems who have been affected in similar ways by advancing technology and automation[36]. Some of these changes in expectations about work are a reflection of changes in attitudes in society as a whole. Others come from experience or hearsay about technical innovations and their probable impact.

In relation to system evolution it is possible for the human factorsrole to be either passive or active. In its passive form, the human factors specialist looks at new trends and requirements for air traffic control and the proposals being made to meet them, and deduces the consequences for the operator in terms of the nature of his work, his well-being, selection and training procedures, the social context of the work, attainable levels of efficiency, workload, and the kinds of human error which are possible. In this passive role he tends to take problems as given and use his skills to solve them as best he can, or, where appropriate, to alert others to trends in system evolution which may ultimately cause human factors problems which on existing evidence cannot be solved.

As an alternative the human factors worker has a more active role. Instead of stating the consequences of system equipment changes proposed by others, he can advance statements about system changes and forms of evolution that are desirable in human factors terms. These consider the work roles which would make best use of human attributes and capabilities, the levels of skill which are appropriate for efficiency and job satisfaction, social and humanitarian needs of man in the work environment, and the acceptability as well as the efficiency of what others propose. Some of the consequent problems may not be ones directly concerned with system efficiency. For example, evidence to associate boredom with poor system efficiency is tenuous: the main reasons for trying to relieve boredom are, in system terms, to prevent disenchantment, high labour turnover, and high recruitment costs, and perhaps some misuse of equipment, or, in humanitarian terms, to design and plan systems with jobs suitable for human beings in terms of interest, challenge and satisfaction associated with the work.

In the past, the main role of human factors has tended to be passive rather than active. Nowadays, this traditional approach, while conceded to be important, is not necessarily sufficient. There need to be studies of acceptability, of attitudes, of pride and skill, and of other human attributes often at variance with the technological advances associated with the evolution of modern systems. Some of these problems have become crystallised in relation to proposals such as the introduction of colour coding displays, where the evidence in their favour is almost all in terms of increased morale, satisfaction, interest and acceptability, rather than in terms of system efficiency, safety or reduced errors[37].

It is part of the job of the human factors specialist to point out the human factors problems which proposed system changes may entail. Reasons for changes centre on greater capacity, or efficiency or on technological advancements, and their human factors consequences may not be appreciated. A key theme is the extent to which the man should adapt to technology, so that changes in technology imply new roles for him in the system[38], or the technology should adapt to him so that he retains the functions he is best at, and aids are intended to extend human, as distinct from system, capabilities.

In air traffic control there is not universal agreement on the direction in which future systems should evolve. Some believe that air traffic control systems of the future will become wholly automatic; others do not envisage such systems at all, either because they foresee a permanent need for possible human intervention, or because they believe it would be contrary to future social policies. The decision on the general direction in which air traffic control systems should evolve will not be taken primarily for human factors reasons, or with a full knowledge of all its human factors consequences. Therefore whatever premise is adopted for long term planning, design and system evolution in air traffic control, some of the human factors consequences will come as a surprise unless the human factors specialist can identify them, describe them, and predict their effects. A knowledge of what has occurred in other systems, and of the trends discernible in existing air traffic control systems, may help him to fulfil this role.

As systems evolve with advancing technology and to meet new needs, the roles of many concerned with them tend to change. In air traffic control the primary concern of human factors has traditionally been with the controller and with some of the implications of proposed changes for teams of controllers and for co-ordination and liaison problems. The roles of supervisors and assistants may alter as various aids are supplied, to the extent that such roles are no longer feasible. Different divisions of tasks may be made, and more flexible procedures may be followed to allow for a very large range in traffic demands. Tasks may have to be separated or amalgamated, and more information given about current status, future intentions, actions completed and actions not yet taken. The communications problems therefore change a great deal as systems evolve, and so does the man-machine interface.

Apart from the controller, other roles change drastically as systems evolve, notably those in computer programming, data gathering and system maintenance. The amount and quality of information in the system far exceeds the capacity of human beings to comprehend. Maintenance is based on the routine replacement of standard components and on standardised methods of fault diagnosis rather than on the exercise of human skills of fault finding and repair which relied on a detailed insight into the system, often of a very specialised kind.

Human factors contributions to system evolution are concerned with the whole range of human factors. At their simplest, they deal with the consequences of system evolution at the man-machine interface in relation to displays, controls, facilities and their design and implementation, so that they meet the needs of the man at work and are compatible with human capabilities and limitations. More complex contributions concern the human factors problems of man management, of acceptability, of new roles and status, of expectations among employees, and of the relations between the controller and technology. Exciting new technical developments such as artificial intelligence, the provision of various prediction aids, and the feasibility of alerting and memory devices, present opportunities for the extension of skills or the acquisition of new ones, and for interesting jobs. What is not clear is how far human factors policy ought to support such further aims, presuming that they are not incompatible with efficiency and safety. Many years ago the claim was made that human factors ought to be concerned with the lot of the operator as well as with the efficiency of the system[39]. In the meantime systems have continued to evolve with an almost exclusive concern for their efficiency, reliability and safety rather than for those who work in them. As systems evolve in the future, a policy will be needed on where the emphasis should be. Advancing technology both provides in principle a means for ensuring that the changes made will be to foster the skills, interests and well-being of man, and also provides possible means for excluding the man altogether from systems or for casting him in a very subsidiary role. In viewing such alternatives, it is the function of the human factors specialist to give impartial advice based on firm evidence on the human factors consequences of each option.

# CHAPTER 4

## MAN AS A SYSTEM COMPONENT

### 4a LIMITATIONS OF THE CONCEPT

Because an air traffic control system is a large man-machine system in which each controller is a component or element, it is possible to consider the controller as a system component when the functioning of the system as a whole, or a part of it, is studied. His actions, and their effects on the system, can then be expressed in terms compatible with the functions of other system components. In studies of an air traffic control system or part of one, separate analysis of each component of the system, whether it be a man or machine component, is often not attempted, but the response of the whole system or of a man-machine sub-system within it is examined by varying the input to the system or sub-system - that is the air traffic in an air traffic control system - and by measuring the output from the system or sub-system. The effects of the system on the traffic can thus be measured. Judgements of the safety and efficiency of the system can be made on the basis of these measured effects. The contributions of man and machine within the sub-system are not usually disentangled, and therefore this method cannot reveal much directly about human task performance. Unjustified expectations tend however to persist about the insights into the controller and his behaviour which trials and evaluations of systems and sub-systems can provide. A recent review of simulation of air traffic control in the United Kingdom[40] classified the themes in system terms, and direct evidence from the controller was generally confined to subjective assessments.

In many respects, it is helpful to treat man as a system component. The approach has an honoured history. Its origins can be traced to Bartlett[41] and to Craik[42], although the definitive influence was undoubtedly the famous paper edited by Fitts in 1951[43], which included the list of principles for the allocation of functions to man or machine, subsequently dubbed Fitts' list. This paper was originally written for air traffic control; its principles have since been applied to many other kinds of man-machine systems. The paper sought to define long term research needs, and in following a systems approach it cast man and machine in somewhat competitive roles for the allocation of functions, with a rationale which was plausible then but seems less apposite now because of the ways in which automation has developed.

This approach included the description of human behavioural characteristics and actions in engineering or mathematical terms, the concepts which had to be used to describe the non-human components of the system. The common language for describing man and machine components influenced several developments, including mathematical modelling[22], control theory[44], and fast time simulation[45]. With these or other comparable techniques, the functioning of the system could be described, explained or predicted, and some account could be taken of human variability, should this be warranted by the particular problem. General textbooks[32] describe the systems approach. Its applications to air traffic control in the United States were reviewed by Parsons[46] in terms of their methods, productivity, findings, applications and general scientific interest.

The most satisfactory applications of techniques for describing the man in engineering or mathematical terms, judged by their success in accounting for the variance, have occurred when the man was performing continuous or discrete simple tasks such as tracking, where in many respects he functioned similarly to known machine components and could be described adequately in similar terms. Difficulties in obtaining adequate descriptions arose with tasks such as problem solving, decision making, and prediction, where a large residual variance tended to remain unaccounted for, but more recent work augurs well for the extension of mathematical modelling to higher mental functions[47]. Air traffic control is characterised by a hierarchy of control loops with different time scales[48], which modelling techniques may help to clarify. The systems approach may offer the best prospects for integrating a variety of methods such as real-time simulation, fast-time simulation, mathematical modelling, control theory, operational analysis, eye movement recording, and activity analyses which collectively may provide a better understanding of air traffic control than any single technique can furnish alone.

Almost every study described by Parsons[46] treated man as a system component in the sense that measures and variables were appropriate for systems or sub-systems rather than human beings. This is natural in air traffic control where questions are posed and answers expected in system terms. System studies can demonstrate the feasibility of any new concept, proposal or innovation. Ultimately the justification for introducing any changes to the air traffic control system depends on advantages expressed in this way since they can be costed in quantifiable dimensions such as delays, fuel penalties and traffic handling capacities.

The approach of treating man as a system component in air traffic control studies has led to some confusion over the kinds of information about the controller that such studies can yield. Using the systems approach, task demands are stated in terms of the traffic to be handled, and the success of the man-machine sub-system in satisfying those task demands is judged by applying air traffic control criteria of efficiency to the measured output. While this can furnish direct evidence about task demands, it cannot provide comparably direct evidence about such human attributes as workload, given that workload is mediated by characteristics of the individual[49], such as abilities, experience, knowledge and emotional state. If the performance of a sub-system is impaired as task demands increase, this is a product of the interactions between the individual and the equipment he is using. For example, if the controller seeks to maintain the professional standards which he believes his colleagues expect of him as a controller, quite substantial equipment changes may be introduced without changing the output from the sub-system in relation to the input because the man's additional efforts mean that the product of the interactions between him and his equipment remains almost constant as he compensates for equipment changes. For this kind of reason in evaluations of air traffic control sub-systems, equipment changes often apparently produce fewer tangible benefits or disadvantages than expected. The fundamental reason is that man and machine as a sub-system entity were measured, and the respective contributions of each not disentangled.

Similar problems have arisen in attempts to measure stress[50], whether the concept is equated with cause, that is the pressure which the system puts on the man, or effect, that is the man's response to that pressure. The problem is made more complex because measures of stress or workload in theoretical terms assess it as high or low, but this avoids the practical air traffic control problem which is to assess whether it is too high or too low so that action must be taken to change it[51]. This consideration of stress and workload, concepts which are mediated through the characteristics of each individual, suggests a further limitation on the usefulness of treating man solely as a system component, namely the difficulty of dealing with human concepts thought to be relevant to the performance of the controller, but with no machine equivalent. The number of such concepts tends to diminish as automation advances and more higher mental functions can be described in machine terms. Concepts which seem resistant to machine descriptions include those concerned with social factors, with teams, with peer pressure, with needs of man at work, with subjective beliefs and attitudes, and with certain aspects of attention. For many concepts, such as pride, boredom, status, effort, challenge, job interest, job satisfaction, morale, professionalism, and self esteem, expressions of them in system terms are as yet non-existent or inadequate. A deceptively simple but in fact quite complex problem is that a machine can lie idle all the time but that a man must have some work to do that he considers sensible or as a component he rebels against the system.

Air traffic control has the characteristics of an organisation, and many of the tenets of organisational psychology apply to it. Controllers develop their own accepted professional norms and standards, which are relatively independent of management, equipment or other circumstances[52]. If most forms of automation are more suitable for individuals than for teams, the role of the team may decline, and with it the establishment of professional norms and standards which are a team function.

Beliefs and their formation are a mainspring of action. It is not unusual in air traffic control studies for the systems evidence to be contradicted by subjective opinions. Because controllers act on their beliefs a main reason for taking subjective assessments, despite their known fallibility, is to reveal these discrepancies between them and the systems findings. There are several possible explanations for the common finding that the introduction of colour coding onto air traffic control displays does not bring about improvements according to system measures but does according to controllers' beliefs. Perhaps colour coding is of no help; perhaps it helps some functions and hinders others and the two balance; perhaps it helps the controller who can achieve the same absolute standards of performance with less effort; perhaps it is not performance itself that is helped by colour but something else such as memory. Further explanations can be offered. The point is that because sub-system measures cannot differentiate between them they cannot provide an adequate explanation of what is happening.

Ultimately if the man is treated solely as a system component he is liable to rebel against the system. Therefore to treat him in this way is to treat him incompletely in some respects and to neglect some of his fundamental attributes.

It is essential, however to emphasise one point. It is not being argued that man should never be treated as a system component. For many air traffic control purposes, system measures and sub-system measures are absolutely essential, and constitute the optimum method for answering various questions. But past experience suggests a failure to realise that the questions which system measures can answer about controllers are limited because of the inherent nature of the measures themselves and of the systems approach which they exemplify. Their practical use is essentially confined to answering system questions. For questions about the controller other kinds of measure are normally necessary. This is not a new notion but a restatement of the point made by Taylor[39] twenty-five years ago. The earliest applications of aids in man-machine systems extended the abilities of the man but left him fundamentally in control. Controllers still prefer to think of aids primarily in the form of computer assistance rather than to think of themselves as assisting the computer. This distinction is fundamental in deciding what the future development of air traffic control systems and of the controllers roles in them should be[7,53].

Two consequences of the great technological advances in automation need emphasis. One is that functions can be similar in system terms yet very different in human terms, both in their consequences for the man and in the ways in which they must be measured. The substitution of a computer decision which the man must accept or reject, for a decision which he had to reach manually by choosing and evaluating relevant information, may seem a small step in system terms where the function within the system remains almost the same, but in human terms it represents a very large difference indeed, to the extent that if the system functions did not happen to be the same it would not occur to a psychologist to try and compare them. The second point is that as automation advances it becomes less and less practical to measure human performance as distinct from sub-system performance in air traffic control systems. Many functions treated and measured as human functions in the past have now been automated to the extent that the man and machine can no longer be disentangled. The corresponding measures now therefore are of the man-machine sub-system and are expressed in system terms, with all that is entailed in a loss of understanding and insight into the man.

## 4b THE ALLOCATION OF FUNCTIONS

It is easy to give the spurious impression in air traffic control and other contexts, that the allocation of functions is a far more logical process than in fact it is. Ideally, all functions would be listed, those which could be done by machine only or by man only would be separated from those which could be done by either, and the allocation of functions in this last category to either the man or the machine would take account of human capabilities and limitations, of technological strengths and weaknesses, of costs, of safety, and of functions already allocated, so that the outcome would be the allocation of functions to form sensible jobs for each man, and the successful integration of human and machine functions in the system. This is not what usually happens. Instead, the tendency is for the machine to do what it can, and for the man to do the rest. The criterion for allocating functions to the man tends to be not his ability to perform them well but the inability of the machine to perform them at all. Human factors considerations often therefore have an insufficient influence on the allocation of functions. This is the background against which the following considerations should be examined.

The central question in the allocation of functions is which functions should be fulfilled by the man and which by the machine. Advances in technology have now reached a stage where it is possible to contemplate in the future a fully automated air traffic control system. Several questions arise. One is whether the fact that full automation is becoming technically possible is a sufficient reason for introducing it. A second concerns the sorts of role which would be left for the man to fulfil if full automation were introduced. A third is that if the decision is not to introduce full automation what kinds of reason could lead to such a decision and would they be sensible in human factors terms. A fourth is the problem of utilising human attributes and skills in systems at various stages of semi-automation.

In the past, it has been customary in human factors texts to draw up lists of functions suitable for man or for machine. These were often still being referred to long after technological advances had made them obsolete. Because of differences in task demands, in facilities, in system complexity, and in computer assistance in air traffic control systems in different parts of the world, compilations of lists of functions for man or machine have little general value in air traffic control. The problem is best examined in relation to each specific air traffic control system.

The list of functions suitable for allocation to man or machine is not a constant. The question can only be posed about a limited number of functions. With modern air traffic densities and the equipment fitted in many modern aircraft, a reversion to simple procedural air traffic control methods is no longer a practical option. Therefore, many functions to do with gathering data are not considered for allocation to man or machine: data gathering is done automatically. This trend will continue. In current systems, traffic outside radar coverage, for example in mid ocean, is handled in traditional procedural ways with large lateral and longitudinal separations between aircraft at the same height, and with relatively infrequent updating of positional information. The large margins of safety which have to be built into such a system greatly reduce its capacity, with the result that much air traffic across the Atlantic at peak periods is allocated non-preferred heights and routes. Concepts such as NAVSTAR envisage communications networks based on satellites, whereby accurate, frequently updated information will become available on air traffic[54]. When such innovations are introduced some human functions disappear. The automated system can produce data of a quality which the man cannot match.

This is a recent example of the trend whereby the sensing, storage, collation, compilation and presentation of data are now done by machines to the extent that such functions do not appear on lists for allocation to man or machine. Thus as technology advances some functions disappear from the list: man cannot fulfil them.

The list however does not get shorter. New items are added to it because technological advances make it possible to fulfil functions by the machine which originally could only be done by the man. Predictions, problem solving and decision making are functions which are now on the list but once were not. As machines become more adaptive in the future, functions requiring flexibility, innovation and adaptation may be added to the list.

A further trend is discernible. The functions suggested for the man tend to be more passive. Rather than fulfilling functions himself, he checks that the machine has done so, monitors what it does, manages machine resources, and assumes supervisory roles. The reasons for this are somewhat irrational in human factors terms. The man is certainly not given monitoring functions because he is superior to the machine at monitoring, for he is not. Man can be innovative and flexible in ways which the machine cannot be, but only to the extent permitted by the system design and by his current knowledge. As systems become ever more complex, it becomes more difficult to build in facilities which enable the man to be flexible.

The reasons for keeping the man in the loop, or allocating functions to him, seem eminently sensible when stated in system terms, but when expressed in human terms they seem suspect, predicated on assumptions which seem untenable, such as the ability of the man to maintain attention and to keep his information fully up to date although he is seldom given anything to do. Some modern air traffic control systems are reaching a stage of complexity where aspects of them rely totally on the machine and where the complexity of the information is beyond the man's ability to understand. Some traditional functions for man, such as manual reversion in the event of system failure, therefore become progressively less feasible. In some systems, the man can no longer take over the machine functions effectively in the event of a failure, although he might be able, perhaps with the aid of traffic displays carried in aircraft cockpits, to maintain safe separations between traffic. A failure would then lead to serious defects in the efficiency of the air traffic control system but would not jeopardise air safety. In considering the allocation of functions to man or machine, a further frame of reference should be considered. If a function is already being performed by the controller at a level which is near the theoretical optimum then any prospective further improvement if the function is automated must be small. However, if the man is inefficient and his performance of the function, though impressive, falls far short of the optimum, there are at least prospects of a substantial improvement of system function which may be attained either by automating the function or by recasting its manual form. In the past this perspective has not always been used, and aids have sometimes been developed for functions which the unaided controller was already performing very well. Surprise has been expressed when the aids have apparently not produced much benefit. This kind of criterion should have some influence over the re-allocation of manual functions to machines.

If man or machine are treated as competitive[43] or as complementary[31], the implication is that a correct decision is possible about how each function should be allocated. Yet some functions may be performed equally well by man or by machine whereas some may be suitable for neither. Technology develops in ways which are independent of human factors and there is no a priori reason why the products of technology should relate to human functions in any particular way. Logically they are independent. It does not even follow that a man can use a technological innovation, or that the functions of man and machine can be reconciled. In manual and automated forms equivalent functions may not be sufficiently similar to be comparable. If they are and man and machine are compared performing the same functions, the findings from such studies have to be treated with caution. If the man is found to be superior to the machine, great effort is devoted to improving the machine until it equals or surpasses him, but comparable effort is not made to improve the man's performance till it reaches that of the machine if the latter is superior.

The option of fulfilling a function by both man and machine working in parallel is not normally considered. However, given that the need in air traffic control is to maximise safety, and that on the whole man and machine do not make the same kinds of error, there seems a case to fulfil appropriate functions by both man and machine independently since each should redress some of the deficiencies of the other. This radical approach poses many practical difficulties but has the incidental benefits of keeping the man attentive and in the loop, permitting manual reversion more readily if required, maintaining the man in a state of current practice, and probably providing better job interest.

A stage has now been reached where a clear decision is necessary on future policy regarding the role of the controller in air traffic control systems, as a guide to the successful allocation of functions. Even the notion that new technology will be introduced and that the man will fulfil new roles in relation to it places the burden of adaptation on the man in an era when one of the striking aspects of many technological advances is their adaptability. A further factor which is clearly a matter of policy is the extent to which air traffic control should meet changes in human wishes and aspirations regarding careers and jobs. If the policy is that controllers will continue in air traffic control but only in supporting roles, this implies that they must have sensible roles to fulfil. On the other hand, if the policy is to keep the controller in a central role and to think of computers as aids, this too could fail unless decisions about the allocation of functions pay heed to the roles which man can fulfil adequately and to the conditions which must be met before he can do so. Man is a poor monitor, to the extent that nowadays it scarcely seems sensible to put monitoring functions on a list for consideration for allocation to man or machine. It may be impossible in the future to design a system which allows effective supervision to take place and some functions such as supervision require close scrutiny as automation progresses. If the man is to be an effective manager of resources, this may imply a much more thorough understanding of those resources, of how they can be marshalled, and of what they can and cannot do, than most controllers currently possess. If the intention is for man to be employed as an innovative and flexible intervener in the event of major system failure, but otherwise as a monitor and manager of resources, it is very difficult to provide the means for him to fulfil such functions effectively in automated systems.

In formulating air traffic control policy about the allocation of functions to man or machine, one obvious point needs emphasising. Those who do plan systems and formulate policy do not themselves take kindly to suggestions that their own functions could be fulfilled automatically, although often such planning functions could in fact be automated. Air traffic controllers react similarly to proposals which suggest to them that their jobs could be fully automated. Plans on that basis therefore meet resistance. This is not a judgement on the rights and wrongs of the situation, but a statement of what to expect. Human factors knowledge generally permits predictions of this kind, and can usually pick out the aspects of automation which will engender the fiercest resistance. Such attitudes among the human components of the system also have no machine equivalent.

## 4. EFFECTS OF AUTOMATION AND COMPUTER ASSISTANCE

The concepts of automation and of computer assistance are sometimes treated as synonymous in air traffic control, and where automated aids are introduced their effects may be similar. However, to the controller automation tends to imply the replacement of one of his functions by an automated function, whereas computer assistance leaves him in a central role but provides some automated facilities to help him to do his job. The concepts therefore have different emotional connotations for him.

The earliest forms of computer assistance tended to be extensions of man's own functions, assisting him with data gathering, storage, compilation or presentation. His functions which used specialised air traffic control skills were generally left intact. Measurements of the man with such aids could still be expressed in terms of his performance rather than in terms of system performance.

The next stages of computer assistance affected certain human functions directly, mainly by replacing routine tasks. For example, the introduction of secondary radar, coupled with the appearance on the radar display of a label for each aircraft giving its identity and height, reduced substantially the verbal communication between the controller and pilot but also changed what the controller knew, so that he had to take additional steps to top up his memory by calling down information for that purpose. His understanding of the traffic seemed changed in some ways, perhaps because of his less direct involvement and less detailed participation in its control. Such kinds of computer assistance were a long way from full automation of functions, and their effects on the man's role were incidental rather than planned. The aids were introduced because so much information had to be gathered and stored and because it was possible to have more accurate, more frequently updated and more reliable information by transponding it directly rather than by relying on speech. No matter how busy the controller became, his information gathering was not dependent on verbal channel occupancy time. It was argued that such forms of computer assistance reduced certain routine aspects of his tasks, like speech workload, and freed more time for other functions such as decision making. This sounded plausible but did not seem to work.

The assumption was that the man's mental capacity for air traffic control was in some way fixed or constant, so that the reduction of one kind of loading would permit a commensurate increase in another kind of loading[53]. In air traffic control the bulk of evidence refutes this notion, and a measured reduction in one kind of loading has not led to commensurate measurable improvements in others. Fo[illegible] reasons can be advanced. One is that the reduction in verbal workload does indeed free resources [illegible] these resources are used up by additional functions which are a direct result of the change intro[illegible] like additional keying tasks to top up the memory. A second reason could be that resources are f[illegible] but it is not possible to designate the way in which they will be used, so that they might be dep[illegible] in unmeasured ways. A third reason could be that the freed resources are used in the designated [illegible] but that performance of the tasks is not improved by devoting more resources to them. The fourth reason is that the notion that man's information processing capacity is fixed could be wrong, whether based on filter theories[55], on theories of fixed resources[56], on theories of the variable allocation of fixed resources, or on theories that other factors such as strategies remain constant.

This fourth reason has some support on several grounds. The controller may adapt his strategies to the traffic loading, and probably to other factors, so that while loading can be measured indirectly by tracing changes in these strategies it cannot be predicated on the assumption that information processing load is a fixed quantity[57]. Also, the theory that man has a fixed information channel capacity is itself suspect, either because he has a capacity which is variable and can be expanded[58], or because when it comes to air traffic control theoretical notions of working memory appear to be misleading[59], or because air traffic control lends itself to parallel as well as serial processing of information, and to the extent that man can function as a parallel processor his capacity may not appear to be constant. For a variety of reasons, including the inadequacy of current theoretical constructs to provide adequate psychological explanations for the performance of many air traffic control tasks, some forms of computer assistance can introduce unpredicted changes, the causes of which can be difficult to trace.

A further stage of computer assistance extends beyond the gathering, storage, presentation and retrieval of data, for the computer is used in ways which, though they are ostensibly still forms of computer assistance, in fact alter the balance of responsibility subtly in favour of the machine. Many prediction aids, aids to decision making and aids to problem solving come under this heading. They may indeed extend the man's ability and enable him to perform tasks more efficiently than he could without them, but in doing so they affect not simply the processing and presentation of information to him but the development of his skill and understanding. They may also alter the social climate in which the work is done, often replacing man to man relationships with man to machine relationships. Although the applications of computer assistance to data handling may be as effective for teams as for individuals, the current level of technology tends to provide much more effective assistance in problem solving, decision making and prediction for the individual controller than for teams, and may therefore tend to reduce the role of team functions in air traffic control. In system terms, it may seem very similar to ask the man to accept or reject the computed solution to a problem instead of asking him to work it out for himself. However when these functions are expressed in human rather than system terms, they appear very different, to the extent that it can be very difficult to find common measures or concepts in which to express them both adequately for purposes of comparison.

A further problem of trust arises particularly if aids do not reach the same conclusions or decisions as the unaided man. To some extent if they always do, there may be no point in having them unless they are very much quicker than he is. A justification of the aid is that the decisions should in some respect be better, and this implies that they will sometimes be different. There is therefore a problem in convincing the man that they are right. If he takes an air traffic control decision manually, he knows what factors he has considered and what new evidence would warrant a revision of his decision, and in general the factors which he considers are relatively few and their weighting relatively simple. The computed solution which the man is asked to accept or reject is likely to be based on far more complex information, with much more complex weighting of the evidence. The man however may not know this or understand it. He can then be asked to accept or reject a computed solution on far less evidence than has been used in formulating the solution in the first place. This is not the way to achieve system efficiency or satisfactory man-machine relationships. This is therefore the kind of application of computer assistance which may meet resistance on the part of the controller who begins to believe that some of his responsibilities and traditional functions are being eroded, and does not accept as a form of assistance an aid which renders his own role subservient or subsidiary.

Further forms of computer assistance can be envisaged. Currently, while the man learns from his experience, the computer generally does not, but there is no reason why it should not be adaptive in future. Many forms of computer assistance have traditionally been most useful under conditions of light or medium traffic loading when they are least needed: this is most noticeable in tabular displays of air traffic control information. The small amount of data on them in light traffic is readily scanned, but when heavy traffic is being handled the much larger amount of displayed data leads to a search task exactly when the controller has least time to perform an additional search task. The inherent flexibility of modern developments in software could enable the computer to adapt to the loading of the system in the form of assistance which it provides, just as the man adapts his procedures to the loading of the system.

Ultimately with full automation man could be removed from his present role as a system component, and recast in the role of system manager, programmer or maintainer. Already with more advanced types of assistance reversion to manual control is very difficult, and a likely corollary of full automation is that reversion to manual control in the event of a system failure would become virtually impossible. This problem is not unique to air traffic control: possible remedies lie in the duplication or even triplication of systems. The requirements for the workforce of controllers would change greatly. Current selection procedures do not primarily seek computer programmers or managers for systems but individuals who have the desirable attributes and abilities for essentially manual forms of air traffic control, where the man is kept fully in the loop.

In recent years there has been much more interest in the effects of automation and computer assistance on the man and on the man's roles, and a greater acknowledgement that factors such as job satisfaction and the retention of existing skills should be considered if man as a system component is to remain efficient. Relatively little evidence has been gathered as yet, although studies are in progress, to determine how air traffic control systems of the future in more automated forms can still remain satisfying and challenging for those who work in them, so that the man can continue to perform his functions as a system component efficiently for as long as he is within the system.

The introduction of various forms of computer assistance removes some existing sources of error and brings in new ones, many of which are predictable. The replacement of verbal communication between pilot and controller by data transponded from air to ground to appear on the controller's display means that his main mistakes are no longer those of phonetic confusions but rather of visual misreadings. Even the errors due to expectancies alter in predictable ways. Looking ahead to the possibility of using speech in the form of automated speech recognition, although the incidence of errors may be similar between voice recognition and keyboard[60], the kinds of error which will be made are not necessarily the same. Such new technological developments in the form of automated speech synthesis and automated speech recognition bring new kinds of error which are just in the process of being discovered, the initial emphasis being to prove the technology until it is sufficiently reliable to be taken seriously for practical applications, rather than to study in detail the exact kinds of error which might be associated with it.

When various forms of computer assistance or automation are introduced, more emphasis is needed on the system-induced errors that they may bring, and on the human errors associated with various systems procedures. The full potential of using man-machine relationships to remove as many error sources as possible has not hitherto been the prime emphasis in most systems, but as technology becomes so reliable in other respects this approach needs to be examined. One way to use computer assistance and automation is to remove certain kinds of human error from the system altogether, by preventing certain actions, by querying others, or by drawing the controller's attention to apparent anomalies ever more insistently until he responds.

There are some major differences in national policies on the extent to which man should remain as a system component in the loop in air traffic control in the future, and on the extent to which full or partial automation should alter his traditional functions. Clearly further automation will come, and is desirable in principle. However, experience of automated aids so far is that they have sometimes failed to fulfil the claims initially made for them, partly because their relationships to the man were not fully understood or some of their incidental consequences for him were not foreseen. To obtain the most efficient performance from man as a system component entails enlightened decisions on how his abilities are best used in conjunction with those of the machine. This line of thinking requires the striking of a balance to get the best both from technology and from the man. It means that in some circumstances the man's role must change in order to utilise to the full the advantages of technology. In other respects it means that in order to utilise to the full the man's unique abilities, technology itself must be modified to help the man to achieve what he does best.

## 4d THE MAN-MACHINE INTERFACE

This general concept is used to describe the relationships that are possible between machine and man at his individual workspace, and in particular the means by which information can be conveyed from machine to man (displays), and from man to machine (controls). The design of the man-machine interface, and the facilities provided within it, determine what the man as a system component can do. The man-machine interface must therefore meet the needs both of the man and of the system. When differences are introduced in the form of changes to displays or controls, the consequent change in the output from the sub-system of man and machine is normally measured, but not the separate contributions of the machine and of the man to that output.

The principles for specifying the attributes of the man-machine interface are normally fairly straightforward, but there are difficulties in their application. A statement of the functions to be fulfilled, coupled with techniques such as task analysis, can reveal the information which the man must have displayed to him in order to perform all his tasks efficiently. The same principles can reveal the actions which it is necessary for the man to perform from which the controls which he must have can be deduced. Many of the principles in human engineering handbooks can be implemented in the detailed design of environmental and workspace aspects of the man-machine interface. These can ensure for example that all visual information is well above the visual threshold, given relevant information such as ambient lighting, viewing distances, eyesight standards, and details of the tasks. They can also ensure that controls such as keyboards are correctly located with optimum spacing between them for human use, provided that there are not too many controls competing for too little shelf space. However, while methods of task analysis may show the information which has to be transmitted from man to machine and vice versa, it is still necessary to ensure that the information provided is in an intelligible form to the man and that the information conveyed by the use of controls can be accepted by the machine. It is trite but important to emphasise that if no provision has been made for presenting a particular kind of information then the machine cannot present it to the man, and if no control has been provided to permit a particular human function to be fulfilled, then the man cannot instruct the machine to take the appropriate action. Man as a system component is entirely limited in his functions in relation to the machine by what is provided at the man-machine interface.

The integrative nature of the man-machine relationship is represented by descriptions of the man-machine symbiosis, indicating their mutual dependence and interactions[61]. As functions for the controller proliferate, it becomes even more important to design his workspace so that the relations between controls and displays are self-evident. Complicated control sequences which are difficult to remember may prove to be more trouble than they are worth when the controller is busy. Displays may contain all the essential information for a task, but if the level of detail, the codings, or the methods of collation are wrong, the man may find the information incomprehensible. The general emphasis has been on the provision of information as an end in itself, with insufficient regard to the known limitations of human beings in their ability to understand and use it[33].

A crucial attribute of the man-machine interface is the extent to which the man is expected to show initiative or to act at the behest of the machine. The decision on this issue, if not formally taken, is nevertheless inherent in the design of the interface itself. The design has failed if a particular action is needed to ensure efficiency or safety and the controller recognises correctly what that action is, but is unable to implement it either because he cannot remember whether it is possible to do so or not, or because he cannot remember what to do in order to implement it.

The purpose of displays is generally considered to be the presentation of information to enable basic air traffic control tasks to be done, and the evaluation of displays may be restricted to that function. Air traffic control displays now and in the future may have to fulfil the following additional functions:

(1) A memory aid, to give promptings or reminders on appropriate actions particularly in unusual circumstances, and on the facilities available to the controller particularly for selective retrieval of information.

(2) A problem solver, to formulate solutions, perhaps for the man to accept or reject.

(3) A decision maker, to state that conflicts, deviations, infringements, etc are present, rather than rely on human judgements about them.

(4) An attention getter, to alert the man to particular events, states, or data, or to direct his searching.

(5) A predictor, to enable the man to see future states consequent on current actions before he actually takes those actions.

(6) A feedback of the effects of actions, to give the man knowledge of the consequences of what he does and hence to permit learning, improve effectiveness, and foster the acquisition of skills.

(7) A teaching aid, to utilise the potential for automated teaching and training methods which is inherent in the man-machine interface design, given suitable software.

(8) An indicator of requirements, to remind the man of what his current tasks are and of the functions that need to be performed.

(9) An indicator of delays, to tell the man that he may have to wait until certain machine functions have been completed, or that actions by him are overdue.

(10) An indicator of errors, to tell the man that what he is doing is outside the parameters which the system can accept or respond to.

(11) An indicator of omissions, to tell the man that some action or part of an action has not been done by him and that the machine needs it.

(12) An indicator of system status, to tell the man whether the system is in use, and the functions in it which he can bring into use if he wishes to.

(13) An indicator of task progress, to remind him of the stage he has reached in doing a task and of the next required stage in its performance.

(14) An indicator of serviceability, to show functions which are inoperable and other functions which remain unaffected or are partly affected.

(15) A summary, for the user of the display and for others, in which [illegible] the information needed for the tasks is shown in less detail or in more collate[illegible]

Although in human factors terms and in system terms the man-machine [illegible] a described as an entity, in fact changes are generally made not in the whole interface as [illegible] ly in specific components of it. Most development and testing work tends to treat these [illegible] hanges in isolation, whereas the benefits demonstrated in isolation may fail to materialise, o[illegible] n a different form in the full man-machine interface. Most specific aspects of it cannot va[illegible] valuated out of context.

The emphasis on digitisation has had its effects on the design of the ma[illegible] ne interface: it tends to be far more successful in conveying quantitative than qualitative info[illegible] on, both from man to machine and from machine to man. This inadequacy takes many forms. Digital information on a display may in fact be very accurate, but there is no means of telling from its appearance how accurate it is or how far it should be trusted. Controls which function in discrete steps may be designed to seem continuous, and may not convey to the users the size of the incremental steps being used. Quantitative alphanumeric information may be preferred to qualitative pictorial or graphic information. Just as the man cannot tell from the display how far he should trust the information on it, so he has no means of indicating to the computer what faith he has in the solutions he is proposing. A recurrent problem with predictions is that the further ahead the prediction the less confidence there can be in its validity: so far, attempts to portray this have been primitive, as have efforts to indicate the point at which predictions are no longer warranted by the quality of the data on which they are based.

New display technology and new control devices are seldom designed specifically from the outset for air traffic control purposes. More commonly a technologically exciting concept which has been developed far enough to be proposed for practical applications is considered for air traffic control as one of several contexts in which it might be applicable. In seeking air traffic control applications, its advocates extol its known advantages but are less aware of any disadvantages it may have, and may tend to underplay those they know in the interests of getting the innovation accepted for further development and ultimate application. Many man-machine interface problems originate in technological devices in search of an application. Ideally the air traffic control need would be defined first in terms of operational requirements, and the desirable technology at the man-machine interface would be developed to meet that need. In a few instances, such as the touch display[52], a device has been developed for air traffic control from the outset, but this is rare. A whole range of display principles, light emitting diodes, rear-port displays, plasma panels, deformagraphic displays, various principles for colour coding, etc, have been tried in air traffic control and in other contexts as alternatives to conventional cathode ray tubes. It would be a considerable coincidence if a new operational need happens to coincide with a new technological development which met it exactly. More probable is that there is no need for the development, or at least that the need and the development are out of phase. A perennial problem at the man-machine interface is to try and adapt and optimise for air traffic control and for human use, technological innovations developed for general application.

## 4. HUMAN RELIABILITY

Air traffic control shares with other complex installations, such as nuclear power stations and chemical processing plants, the need for very high reliability of the whole system, and of every component in it, including man. Figures such as $10^{-7}$ and $10^{-8}$ are quoted as reliabilities to be attained or aimed for. Yet reliabilities of $10^{-3}$ or $10^{-4}$ are more probable for most human tasks. Many of the earliest attempts to treat man as a system component and to improve his efficiency centred on his unsatisfactory reliability as a system component. Relatively little effort has been devoted to assessing human reliability, compared to the effort expended on the reliability of mechanical and electronic components.

The reliability of man as a system component is largely determined by the system design. If that is inappropriate, no amount of exhortation can make him reliable. For certain tasks, such as those requiring the continuous maintenance of attention over long periods without much overt action, or the detection of rare and unobtrusive changes or events man is notoriously unreliable. For other tasks, such as keying, there are large individual differences, and the prospects of major improvements in reliability through good keyboard design and practice. Sources of unreliability in the use of keys and other controls are not random, but can be predicted, and hence minimised, by a knowledgeable appraisal or assessment of the design, spacing, layout, labelling, positioning and physical attributes of the keys in relation to the tasks for which they are intended. Some of the attributes of the man which are generally construed as advantages in system design, such as his capacity to innovate and to be flexible, may be construed as sources of unreliability if they lead to behaviour which is unpredictable in terms of the system as a whole.

A neglected aspect of human reliability concerns the man as a monitor of his own mistakes. In using control devices he makes mistakes, and he notices and corrects some of them but others remain undetected. However if the machine is programmed to make a mistake of the same kind as the man makes, he usually notices this mistake at once, confidently attributes it to the machine, and cannot be convinced that the error could be his own. The reasons why the man responds in this way are not understood, but the implication is that somewhat different mechanisms must be involved in detecting or failing to detect errors by a machine or by others and in detecting or failing to detect the same errors made by himself. This aspect of performance might repay study as a means of enhancing the reliability of the man as a system component.

Various techniques can be employed to assess the man's reliability. The most obvious is to measure his performance carefully in terms of his errors, omissions, inconsistencies, delays, and any other sources of unreliability to which he contributes. This entails not just counting his errors, but classifying them and examining their detailed nature. The criterion of reliability may depend on a theoretical optimum corresponding to perfect or ideal performance, or on a practical achievable optimum, perhaps the best performance that has ever in fact been recorded. There may be a considerable gap between these criteria, and in assessing reliability it is essential to specify the criterion employed.

Man's reliability as a component can be difficult to measure because, except for simple tasks which can be scored as successes or failures, his performance may be partly successful, or adequate but not optimum. Therefore simple measures such as failure rates are often inadequate to express human reliability in system terms. Performance measures may permit deductions on the effects of attention on reliability, but reliability in this context depends on what is being assessed, and misleading measures may be obtained if, for example, the man is performing a demanding task reliably at the cost of being unreceptive to other tasks or to other sources of information. A dull and undemanding task may be performed very reliably or unreliably, depending on its nature, and it is not possible to generalise. It does not follow that attending to a task increases its reliability: for many overlearned skills in particular the contrary is often the case. Many human factors problems are associated with conditions of high rather than low reliability of task performance by the man. This is true of boring tasks. A task may be boring if it no longer represents any kind of challenge to the man who is doing it, because he has learned to do it effortlessly, consistently and highly reliably without paying much attention to it. His performance of a boring task may thus be highly reliable: more to the point, well intentioned efforts to alleviate boredom may inadvertently impair reliability.

Physiological and biochemical evidence can indicate the effort which the man makes, which may in turn affect the reliability of his performance. Commonly, maximum reliability is equated with reasonable effort, and extremely low or high effort would be associated with poorer reliability of performance by the man. However, this traditional relationship between reliability and arousal mechanisms has to be treated with caution, since the evidence supporting it in air traffic control contexts is at best tenuous. If reports of accidents or incidents associated with air traffic control are conceded to be one index relevant to human reliability, the probability of their occurrence does not seem to have much relationship to the controller's level of arousal.

The man can make subjective assessments of aspects of reliability. These may take the form of confidence assessments in what he is doing, or may explain puzzling lapses in performance by reporting inattention, distraction or other subjective states. It is important to remember that subjective assessments of reliability and assessments of confidence are subjective: that is they represent beliefs, opinions and impressions, which do not necessarily agree with objective measures of performance, and may flatly contradict them. A controller, given a new aid, may confidently believe that his performance is improved by it, whereas objective measures show that it is not, or vice versa. Nevertheless, subjective measures may have their greatest practical importance in relation to reliability when they fail to support performance measures but reveal a discrepancy between what the man thinks he is doing and what he is actually doing[63].

More formal methods can be used to assess man's reliability in the system. One is to employ flow diagrams[64] which show the various options and critical decision points, and allow sources of error and unreliability to be identified and classified in a notation which is generally intelligible. The reliability at each decision point can be independently assessed and a general index of reliability of the man in the whole system can be derived from these assessments, though not by a simple combination of them, since human reliabilities at sequential decision points are partly interdependent, because of common factors in each individual such as knowledge, experience, intelligence, habitual working pace, and preferred style. The man who does one part of a task well tends to do other parts well. Certain critical incident techniques can isolate the events which should have most influence on the combined reliabilities assigned to each particular incident, and these combined reliabilities collectively may represent quite adequately the reliability of the system as a whole, provided that the reliability coefficients for each incident are not combined randomly, but take account of individual consistency. This has the paradoxical effect of increasing the range of system reliability insofar as it takes account of the differences between the best and the worst operators.

Reliability of the man as a system component is most easily measured with simple tasks, but the relevant techniques can be applied to much more complex ones including decision making and problem solving. The reliability of such functions can be improved by imposing a logical framework of the stages involved as a means of isolated the main sources of unreliability[65].

An alternative approach is to examine the innate limitations in various human capabilities and their consequences for reliability. Sources of mis-perception can be treated in this way, as can lapses of attention, conditions which foster wrong expectancies, excessive loading, and effects of stress and emotional factors. Although the exact consequences for reliability may be difficult to deduce in specific instances, the general effect of these factors on reducing the reliability of man as a system component can normally be deduced.

The introduction of automated aids can influence the man's tasks and his reliability in unexpected ways: yet often these could have been anticipated. They usually have one of two origins: automation has replaced the man wholly or in part in quantitative but not in qualitative roles, or a human function has not been automated in its entirety. Various examples have occurred. Certain kinds of information may be lost altogether when automated aids replace manual functions; in speech, tones, pace, inflections and hesitations may not simply convey extra information about confidence but also affect the man's ability to remember what was said, and this information is lost if the message is no longer spoken. If the man forgets an automated solution which he has accepted, because he has not had to work it out for himself, this is a source of unreliability. If he does not understand the computed solution, or deems it to be unsafe, he may substitute his own solution which, in fact, is less reliable. A further source of unreliability is the persistence of old habits and ways of information handling in newer systems where they are no longer relevant. There is an anomaly in relation to man and his reliability. Sometimes he can be impressively reliable with poor equipment if he accepts the equipment, likes the job, finds it challenging and believes that someone takes an interest in his work and in his conditions of employment: on the other hand, superb equipment which is unacceptable to the user can be made to appear deficient and unreliable. A man under stress may be less reliable, perhaps because he cannot help becoming careless and treats the equipment less delicately[66]. The point is that attitudes affect the reliability of man as a system component.

A further influence on reliability, likely to become more important in the future, concerns the changes in maintenance procedures in air traffic control systems. In the past when a failure has occurred a man with a detailed knowledge and understanding of the equipment in use, but not necessarily a broad technical knowledge, has often, by an exercise of his capacity to be flexible and innovative, succeeded in repairing the equipment and keeping it serviceable. In theory, modern maintenance procedures, based on the replacement of modules rather than on an understanding of the system, simplify fault diagnosis, and principles of module replacement rather than repair should enhance the reliability of the system as a whole. Unfortunately as far as maintenance personnel are concerned, this substitutes an unskilled routine job requiring little insight or understanding for a job which enabled the man to develop skills and take pride in his work. Although the potential for greater reliability is present, it may not be achieved if the job has lost its interest. Such specifically human aspects of reliability have to be taken into consideration as long as the man functions as a system component, whether as a controller or as a maintainer of the air traffic control system.

While it does not follow that a happy man is a reliable one, a man with negative attitudes towards his job is likely to be less reliable as a system component. Factors such as going on strike, having high rates of absenteeism, working to rule, and introducing various restrictive practices, should be considered as forms of unreliability in the air traffic control system, and treated as such in the context of assessments of the reliability of the whole system.

# CHAPTER 5

## HUMAN CAPABILITIES AND LIMITATIONS IN SYSTEMS

### 5a SENSORY FACTORS

Many of man's senses are of little practical use in air traffic control. Taste, smell, touch, kinaesthesis, heat, cold, pain and balance have little relevance, and are more likely to be sources of distraction than of useful information. Much of the information needed for air traffic control purposes cannot be sensed directly by man at all. With the exception of spoken messages from pilots, information about the aircraft under control is sensed automatically, for example by radar, and has to be converted into the main channels of human sensing, vision and hearing, and presented at a pace, in a form, and at a level of detail matched to human limitations. As further aids and sensors are introduced, as new sources of information are added, and as the quantity of information in the system increases, the problems of distilling the essence of the information, converting it to visual or auditory form, and presenting all that is essential for air traffic control tasks become more difficult to resolve.

Limitations in human sensory capabilities restrict the modalities within which information can be presented to the man. A further consequence of limited sensory capacities is that man is bothered by what he believes to be present but cannot sense directly, and needs reassurance that it cannot harm him. Such considerations apply to emissions from various displays used in air traffic control and elsewhere. Air traffic control equipment must meet legally defined, medically derived standards of safety and occupational health and this applies to radiations from cathode ray tube displays. The main practical problem is that in air traffic control the radiation emission levels are so far below the levels acknowledged as safe that it can be difficult to find equipment sufficiently sensitive to detect that emissions are present at all[67]. Because the controller relies on hearsay, and issues such as radiation emissions are very emotive, misgivings arising from human sensory limitations can become highly irrational, and may not be placated by the publication of the levels obtained by objective scientific measurement. An unfortunate consequence is that controllers may be troubled by and emphasise the wrong issues. Radiation emissions, on which a great deal of evidence has been painstakingly gathered, are clearly not a serious problem: subliminal luminous oscillations, about which far less is known and which cannot be sensed by the man if they are present, may perhaps be implicated in subjective impressions of visual fatigue[68], yet there is not enough hearsay about them for the controller to become concerned.

Although many human sensory capabilities are never fully used, they set tolerance limits which have to be met in air traffic control environments, particularly for senses such as heat. The limits of what constitutes comfort are a matter of the sensitivity of the relevant sensors. The aim is to achieve a working environment in which comfort is equated with unobtrusiveness, where nothing untoward is sensed which could constitute a distraction from air traffic control tasks. If air traffic is so light that the controller's main sensory channels of vision and hearing are not occupied much by his tasks, he may direct these sensory capacities towards whatever features of the work environment obtrude and he may then become more aware of information conveyed through his other senses. This awareness may alter his levels of tolerance. Put simply, if he is placed in a context of enforced idleness he may become aware of aspects of heating, ventilation, seating, lighting and workspace design which represent very minor departures from the optimum, or which are optimum conditions of comfort when he is busy.

All information presented to the man must meet his sensory limitations or he cannot receive it. Auditory information has fewer coding dimensions than visual. The main auditory information reaches the controller in the form of speech. Characteristics of communication channels such as the telephone and R/T must be checked to ensure that information intended for the man is actually present in a form which can be heard, and that the processes of transmission have not themselves degraded or distorted speech so drastically that the information it conveys can no longer be extracted from it as quickly and accurately as possible. In assessing the effectiveness of an auditory information channel to ensure that the man can sense its contents, it is essential to employ defined standards in terms of discriminable differences in frequencies and amplitudes. Thus in determining man's sensory limits and specifying information to fit those limits, it is important to ensure that no individual man will fail to meet the limits for which the system has been designed. A sensory impairment in an individual controller in the form of deafness therefore debars him from employment as a controller if its severity means that his hearing cannot meet the minimum standards specified.

Man's sensory limitations may be viewed as relative or absolute. For example, information on an alphanumeric display may be depicted at different levels of brightness. If all possible levels of brightness are present at the same time on the display, then the differences between the levels need not be very large to be reliably discriminable without error. These require relative judgements. If only one of the levels of brightness is actually present on the display, and the man has to know and discriminate correctly which level of brightness it is without being able to refer to the other levels of brightness, this involves an absolute discrimination, and much larger differences in brightness are required between levels before an absolute judgement can be achieved consistently without error. For any given visual dimension, very few conditions, perhaps three at most, can normally be used if absolute judgements are required.

Common psychophysical visual coding dimensions basically refer to size, shape, colour, contrast, brightness, and flashing, but the variations and combinations of these are very numerous. Even a simple line can vary in length, width, contrast, brightness, colour, stability, continuity, and many other forms of discriminable embellishment. Alphanumerics, with all their complexity, are a sub-division of the shape dimension.

Visual stimuli can become highly complex, but every aspect of each stimulus, if it is to be used, must be discernible. Studies to establish whether it is can be treated as sensory; for example, the question of whether alphanumeric or graphical information is understood does not arise unless it is known that the information itself is far enough above the visual thresholds under prevailing conditions to be sensed correctly.

With vision as with hearing the air traffic control system is designed on the assumption that those who will use it do not have serious impairments of their sensory capacities. For this reason serious visual deficiencies debar a man from air traffic control.

Technological changes such as the introduction of colour coding have to be examined lest they set more stringent requirements for human sensory capabilities of colour vision than have hitherto been needed. In particular, the combination of colour and brightness codings has to be designed with great care since these two dimensions are usually confounded and those with a minor colour vision deficiency may once have been able to rely on brightness discriminations which may no longer be present. Selection procedures must discard any individual with substandard sensory capabilities, no matter what his other attributes are.

Linked to man's sensory limitations are the respective uses of auditory and visual information. General guidelines including the following:

(1) Auditory stimuli are essentially temporal; the presentation of auditory information takes time. Visual stimuli are characteristically spatial; the presentation of visual information needs space.

(2) Auditory stimuli must generally arrive sequentially, whereas visual stimuli may be presented sequentially or simultaneously.

(3) Because auditory stimuli are sequential they cannot be kept continuously before the observer, though they can be repeated periodically. Visual stimuli offer good referability, because the information can usually be stored on the display and presented continuously.

(4) Auditory stimuli offer fewer dimensions for coding most information than visual stimuli do; richness of coding is a major advantage of vision.

(5) Speech, a form of auditory coding, offers great flexibility, and variation without pre-planning. Visual stimuli have to be coded in advance.

(6) The selectivity of speech messages offers a time advantage in that pertinent information is already selected for the receiver. With visual stimuli, searching for information may be necessary and the receiver does much of the selecting.

(7) The rate of transmission of speech is limited to the speaking rate, whereas visual presentation of information can be faster.

(8) Auditory information is more attention demanding, more potentially disruptive, and its reception depends less on what the man is already doing. Visual stimuli however, do not necessarily demand attention; the operator has to be looking in the right direction to perceive the stimulus.

(9) Hearing is somewhat more resistant to subjective impressions of fatigue than is vision.

(10) Reaction times to simple stimuli tend to be slightly faster to auditory than to visual ones.

It is important, before elaborate reasons are sought for a failure to utilise information, to establish that the information is in fact present in a form which can be sensed. Sometimes it is assumed if task performance has failed to meet operational requirements, that the explanation lies with human deficiencies and limitations in processing information. The fault may lie in an insufficient provision of adequate sensory data. As systems become more automated there is often a notable diminution of data which could be used for qualitative judgements.

5b PERCEPTION

Whereas sensory processes deal with the detection, discrimination and assimilation of sensed physical stimuli, perception as a concept includes the processes for selecting or discarding stimuli, structuring stimuli, attributing meaning to stimuli, and interpreting stimuli in relation to such factors as experience, expectancies and needs. Normally there is no direct awareness of the processes which constitute perception, but only of the product of those processes. The concept of perception, related primarily to vision and hearing, can be applied to any of the senses.

Perception is an immediate and continuing process, which to the perceiver does not seem analytic. He is therefore not normally aware of misperceptions, of stimuli which have been sensed but not perceived, or of perceptual omissions. Man as a monitor of his own performance cannot be independent of his own perceptual processes and cannot recognise as such errors and omissions which the perceptual processes themselves have produced.

Many studies and theories describe principles which govern the imposition of visual pattern and meaning upon stimuli. Though many facts are known which can form the basis of applications to air traffic control, much of the underlying theory is still controversial or inadequate. It is a matter of practical importance to be able to separate attributes of visual structuring that have developed as the result of inheritance or maturation, and therefore cannot readily be changed much, from attributes that are mainly a function of learning, and therefore offer the prospects of modification by training. Illusions, studied primarily for the insights they can give into competing theories of perception, reveal principles of perceptual structuring by means of specific instances where the structuring for most people is faulty, and thus illusions may enable the imposition of meaning and structure to be disentangled from sensory processes in certain circumstances. It is possible to learn to impose a particular meaning on a set of stimuli which subjectively is an instantaneous process, and once this has happened it may then become impossible to perceive that set of stimuli in any other way, even if the imposed meaning is wrong. Visually unstructured data may be difficult to understand or treat as coherent entities. It does not necessarily follow that because data can be sensed they can be perceived, or that because data can be perceived they can be comprehended.

The choice of codings for air traffic control information displays depends on the tasks, on coding dimensions that are technically possible, and on the knowledge of their technical and psychological advantages and disadvantages. The physical environment is also important: background noise levels may affect auditory codings, just as ambient room lighting affects visual ones. In applying the knowledge and principles of visual perception to information displays, the intentions are to minimise the sources of human error, to make displayed visual information legible and readable and remove phonetic confusions from auditory information, to reduce any ambiguities, to avoid undue delays attributable to human limitations, to utilise human capabilities fully, and to keep within known human limitations.

Knowledge about sensory limits, related for example to the discriminations of brightness and contrast, to minimum intensity levels, to the smallest detectable change in each visual dimension, to the uses and sensitivity of colour coding, and to the limits of visual acuity and accommodation, must be applied in the design of information displays, since the first step is to ensure that the information can all be sensed. Such factors cannot be treated as constants or absolutes, but must be set in their operational and physical environment. Visual acuity, for example, varies with the illumination of what is seen, its retinal location, contrast, the state of adaptation of the eye, etc. Precautions to overcome sensory limitations influence perceptual ones.

Because of perceptual structuring, the visual whole may not appear to be the sum of its parts. This simple fact is often neglected in the choice of visual coding dimensions and symbols. It is common to use one visual coding dimension to show one attribute and another dimension to show another, and then to combine both coding dimensions with the intention of showing both attributes in combination. This principle can be elaborated to generate complex perceptual forms incorporating several visual coding dimensions. These forms are intended to be an amalgam of numerous individual symbols to convey collectively in a single symbol all the information which each individual symbol contains[69]. For example, a single symbol intended to depict an aircraft as westbound, climbing, and in the process of being handed over to another controller may be an amalgam of three simpler, separate, symbols for each of these dimensions, but it may not look like an amalgam of them. Often this principle of amalgamating codings simply does not work. The principles of perceptual grouping and structuring ensure that the amalgamated symbol is seen as an entity and not necessarily as the sum of its parts: indeed several of the individual parts may no longer be recognisable as such. To take an oversimplified psychophysical instance, a short dash (-) superimposed centrally on an inverted "V" is perceived as an "A", and does not even look like two superimposed independent codings. This is one of the simplest practical limits imposed by the processes of perception and visual structuring. It determines the usefulness of symbology, both at a perceptual level and in the assignment of meaning. If unwanted perceptual structuring of the component elements of a complex symbol occurs, the meanings of the components may be lost. The kinds of meaning which can be imposed by various forms of structuring of perceptual material can have a decisive influence on task performance. When a decision is taken to have graphical or tabular, pictorial or symbolic information, all the consequent implications for perceptual structuring are not thought through, so that expected improvements often fail to materialise.

Much basic psychological evidence about perception and the rules governing it has been gathered in experiments with simple forms, since these were thought to be best for providing controlled conditions to explore aspects of visual structuring. Even with simple forms, numerous factors can have a perceptual influence, including familiarity, previous experience with forms, their size and viewing distance, their slant and constancy, the visual context and setting of them, the verbal labelling used for them, the set and expectancies associated with them, and whether they are static or moving[70]. There are difficulties in describing forms in concepts which allow findings to be generalised. Mathematical descriptions of forms include concepts such as complexity and redundancy. Perhaps the most remarkable aspect of the prolific theoretical work on form perception is its apparently complete divorce from practical studies using alphanumeric forms under laboratory conditions to measure their discriminability, legibility or readability. These latter studies have more potential relevance to air traffic control with its increasing use of alphanumeric information, but the problem arises that many studies of alphanumeric forms have not been in applied practical contexts but in the laboratory with carefully controlled featureless backgrounds. The findings therefore may not hold true for real life air traffic control contexts[71]. The generation of visual forms using matrices has led to numerous studies to find the most legible means of portraying each letter and numeral[72], and perhaps to a preference for alphanumeric information when symbolic, graphical or pictorial information might have been equally suitable. On the whole the principles of perceptual structuring are not used to the best effect in air traffic control information because they have little influence on specifications.

Visual perception is dependent on eye movements, to the extent that eye movement recording has been used as a technique in air traffic control and elsewhere[73] to study the information being sampled. Evidence about fixation and dwell times can be treated as a further human limitation in the perception and assimilation of information[74].

Two perceptual theories have exerted most influence on psychology recently. One concerns the cue theory of space perception, which treats the three dimensional world as a flat retinal picture[75]. This theory has led to many studies of forms and patterns using two dimensional forms, because the theory implies that the third dimension is not important, being a matter of inference. This contrasts with the psychophysical theory of Gibson[76], which treats a succession of retinal images as a pattern of optical information in which movement and three dimensional perception are inherent. Although the cue theory has had the dominant influence on display design, the balance of support now probably favours the psychophysical theory, although the latter does not rest primarily on empirical evidence that perceivers actually use or can use the information in the retinal image but depends rather on the more theoretical notion that in principle the use of such information is possible because in fact it is present. It may be profitable to treat air traffic control information more as an optical array than as cues.

## 5. LEARNING

Air traffic control has to be learned. People who can learn it have to be selected. Their potential for learning has to be realised by appropriate training. Their learning has to be applied, extended and entrenched though the practice of air traffic control and through the progressive refinement and development of skills. It is because of what he has learned that the controller can perform tasks which others without that learning cannot do. To a very considerable extent, the amount of knowledge that an individual air traffic controller possesses determines how good a controller he is or can become.

While man has a very large storage capacity for what he has learned, his rate of learning is relatively slow. The process of learning to become an air traffic controller takes years, and in some respects the controller goes on learning all his working life. Most laboratory studies of learning have considered simple material in order to develop theories, models and explanations of learning, and of allied processes such as the acquisition of skill. Simple studies can produce useful practical guidelines, such as the following:

(1) The efficiency of learning processes varies with the level of complexity of the material.

(2) Most learning initially improves greatly with frequent practice, but the rate of improvement tails off.

(3) Learning is gradually lost with no practice.

(4) Efficient learning requires some form of direct knowledge of results as a condition of progress.

(5) Even a little entrenchment and continued further learning of material which has apparently just been successfully learned is handsomely repaid by greatly prolonged durability of the learning.

(6) Complex tasks which have been learned efficiently do not normally require attention to their minutiae, and further learning of them is at the level of strategies and advanced skills.

In the earliest stages of learning, it is these fine details which have to be mastered, grouped, and incorporated into larger entities as successive stages of learning are reached.

Learning can be fostered by the traditional teaching aids: instruction, demonstration, the elucidation of principles, the working of examples, and the exposition of underlying logical guiding principles to be followed. The application of computer assistance to learning can help to reveal its logical aspects, and facilitate learning by showing its practical relevance and interconnections between learned items. Automated teaching methods provide immediate and regular knowledge of results, and can adjust the pace of learning continuously according to the state of knowledge reached by the learner. Air traffic control procedures lend themselves in principle to the application of automated instruction methods. The best combination is probably the use of computers and of traditional teaching methods.

One problem in teaching air traffic control is to try and ensure that its principles are learned, rather than a series of particular worked examples. The role of demonstrations has sometimes been underplayed; these may often show ways in which the correct solutions to apparently similar problems differ. Demonstrations can aid the development of a mental check list of the factors which have to be examined to ensure that the proposed solution of an air traffic control problem is efficient and safe. There can be a large number of these factors, and it is necessary to learn them thoroughly and to organise them in an orderly fashion so that their importance and relevance can be correctly judged in each circumstance. An example may clarify this point. Let us suppose that the controller detects a potential conflict between two aircraft on his radar display. The number of factors relevant to the action he should take is very large. Each one may, in certain circumstance, be the most crucial. They include:

(1) The physical distance between the tracks on the radar display.

(2) The scale of the radar display, and hence the actual separation between the conflicting aircraft in miles or kilometres.

(3) Their relative and absolute speeds.

(4) Their headings, and angles of approach.

(5) The time to conflict.

(6) The aircraft heights.

(7) Aircraft types and manoeuvrability.

(8) The ease of contacting the aircraft.

(9) The probability that instructions to the aircraft will be understood.

(10) The known intentions and destinations of the aircraft.

(11) The known quality or reliability of the data on the radar display.

(12) Separation standards, and other instructions in force.

(13) The amount and behaviour of other traffic under the control of the same controller.

(14) The positions of any other traffic which may interact with the conflicting traffic, etc.

By now, perhaps, the problem does not seem so simple, and the amount of relevant learning can be glimpsed.

Air traffic controllers rely heavily on learning to convey information. At the simplest levels of communication, standard tools such as the ICAO alphabet* have to be learned. At more complex levels, the kinds of air traffic control information, the standard message formats, the normal sequence in which different items of information appear in a message, the standard phraseology used to help to ensure that the message is intelligible and not misunderstood, all have to be learned. At higher levels of learning, there is the need in communications to be able to interpret the needs of the speaker from what he says, and to judge his competence, his confidence, and his comprehension from his spoken messages. This kind of learning uses quite subtle cues, and the more straightforward procedures have to be mastered before the controller can progress to acquire these more subtle skills.

In systems which evolve and introduce new methods and facilities, there is sometimes the need for refresher courses in which the controller relearns items which are out of practice, or for retraining in which he must replace the familiar learned items with others. A knowledge of basic learning principles in relation to human capabilities can help to ensure that these processes of refresher training and retraining are efficient, and that they do not lead to confusion between the new and the old.

The errors, omissions and inconsistencies of individuals can be partly a product of their learning. When a controller makes a mistake, this usually means that something has not been learned adequately. Mistakes can be classified as those which he notices and can correct, those which he notices but has not learned how to correct, and those which he does not notice and which therefore persist, but which he might have been able to correct had he noticed them. Learning may be assessed by the fluency, efficiency, consistency and especially safety of the learned performance, but it should also be judged by the nature and frequency of residual errors and the ways in which the man has learned to correct them. Similar considerations apply to omissions which again can be traced to deficiencies in learning.

One kind of learning is usually called trial and error. It applies to an action where the outcome is not known in advance and where, if the outcome is favourable, the action will be repeated and if it is not, a different action is likely to be substituted. Air traffic control is not the place for trial and error learning but the fact remains that if other learning has not taken place, trial and error learning is the last resort of the man forced to take actions when his knowledge is inadequate. The more experience of the consequences of actions that can be engendered, the safer air traffic control is likely to be.

Psychological theories of learning, now and in the past, have had little to say directly about such practicalities. At one time, learning was by far the predominant concept in the whole of psychology, and most psychological theories formulated were learning theories. Most of these are now forgotten or discredited. It is against this background that the modern psychologist's scepticism, and recently criticised denigration of some learning theories, should be viewed[77]. Nowadays, learning is more commonly considered as the first temporal stage of memory, the second and third phases being storage and retrieval. This kind of framework seems more suited to the learning of a single item or a single association, if it is thought that all learning is ultimately a matter of associations, than it is to learning as additions to knowledge, which receives a broad mention in some texts[78], but none in others. Yet most air traffic control learning is the acquisition of knowledge.

One aspect of learning of particular importance in air traffic control has received little psychological study. This concerns learning what not to do. An essential part of the controller's training is the breaking of inappropriate habits, and the recognition of his own limitations. For example, he must never become so involved in resolving a problem that he ignores everything else that is happening. He has to learn that no matter how important or urgent a problem is, he must while solving it continue to pay some attention to other events that concern him and to other aircraft which are his control responsibility even though they may not be directly concerned with the particular problem. Similarly, he must learn that his ability to detect potential conflicts is fallible, and his ability to resolve them limited. He has to learn that if an aircraft is flying round the arc of a circle, he is liable to misjudge how long it will take to do so and the distance it will cover in doing so. These are common human limitations and sources of error. The controller has to learn to recognise and compensate for his own fallibility.

## 5d REMEMBERING

Many early studies in psychology, primarily concerned with rote learning, examined the effects of the method of learning or of the scheduling of learning on the ability to recall what had been learned. In these studies, remembering had nothing to do with understanding: indeed the experimental material often took the form of nonsense syllables, deliberately chosen because they were incomprehensible. Studies of memory used simple, recently learned material which was self-sufficient and did not have to be related to, or incorporated in, existing knowledge. The findings had no direct relevance to memory for complex material learned long ago and integrated into a corpus of knowledge, or to the long-term maintenance of such knowledge. Such studies of memory are so remote from the acquisition of knowledge used in real-life tasks that they do not, and for methodological reasons cannot, contribute towards our understanding of the acquisition of that knowledge[79].

An example of the practical relevance of memory to air traffic control safety occurs when a controller clears an aircraft at a low level to climb to cruising level, with the intention of remembering from time to time that he must verify that the aircraft remains safely separated from other aircraft and can

* ICAO ALPHABET

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A | ALFA | B | BRAVO | C | CHARLIE | D | DELTA | E | ECHO | F | FOXTROT |
| G | GOLF | H | HOTEL | I | INDIA | J | JULIET | K | KILO | L | LIMA |
| M | MIKE | N | NOVEMBER | O | OSCAR | P | PAPA | Q | QUEBEC | R | ROMEO |
| S | SIERRA | T | TANGO | U | UNIFORM | V | VICTOR | W | WHISKEY | X | X-RAY |
| Y | YANKEE | Z | ZULU | | | | | | | | |

continue to climb safely. If another problem or an emergency then arises, this reliance on memory becomes parlous and vulnerable. Because human memory is fallible, tasks and procedures are devised so that as far as possible safety does not depend solely on the memory of one man. If it must, then every effort should be made to understand the processes of memory, and to make memory more sure. Memory has long been and still is the subject of prolific research in psychology[80]. Perhaps this research, by illuminating the mechanisms of memory, can provide practical guidance on how it could be strengthened and its limitations circumvented.

Occasional attempts have been made to bridge the gap between theory and application to air traffic control by conducting traditional psychological experiments on memory using air traffic control material such as radio frequencies and transponder codes[81]. Such material may however be little better than nonsense syllables to the naive subjects often employed. It is not related to a body of knowledge covering air traffic control procedures, communications between air and ground, and tasks which the pilot or controller have to perform in response to the message. It does not have, in the laboratory, the same practical significance as in real life. To mishear or forget is not potentially dangerous. Such studies however can, by generating numerous failures of memory, suggest that there ought to be a better way to code information to make it more memorable, and they can exemplify the proposition "that if a person encodes a short sequence of items for the purpose of maintaining the sequence in memory for a short period, and he is then distracted, memory for the sequence will be rapidly lost"[82] – in less than two seconds in fact.

On the basis of laboratory studies, three separate kinds of memory are normally distinguished. The first refers to what is happening at the moment. A sensory information store can apparently hold comprehensive and relatively unstructured information on what is being sensed for up to about half a second without conscious effort on the subject's part. This constitutes the present, to be distinguished from true memory, although it is sometimes called primary or direct memory. Far more can be seen or held in this sensory store for a fraction of a second than can be remembered. The second kind of memory is normally called short term memory. This covers periods generally of a few seconds, and up to a few minutes at most, and refers to information which only has to be remembered for a short time or is in the process of being organised for long term storage. The third kind of memory, referred to as long term memory, concerns all memory longer than a few minutes, and refers to our knowledge of the world from our experience, understanding, and acquisition of information.

These divisions do not fit practical considerations neatly. Clearly in air traffic control the controller relies heavily on long term memory for his general knowledge of the principles, methods and techniques of air traffic control and for his specific knowledge about the way those principles are translated into practice in a particular air space under his own control. The traffic at any given instant is changing within a timescale which refers to short term rather than long term memory. However, the theory of memory implies a separateness between long term and short term memory which does not appear in practice. The controller sometimes worries about what he calls losing the picture. It is difficult to fit this into theories of memory. Sometimes it is the meaning of the perceived information rather than the information itself which is apparently lost. Rebuilding a picture lost in this way can be a painstaking process involving the transfer of information in short term memory to long term memory. In theoretical terms, forgetting can either relate to material once remembered but now no longer accessible, or to material which has never been learned in the sense that it has never been in a short term or long term memory store.

The complexity of real life tasks tends to defeat the application of psychological theory, and theories of memory exemplify this. Perhaps the main practical limitations of memory are that the committal to memory of information is a relatively slow process, that the recall of information is in some respects unreliable and fallible in non-random ways, that the process of rehearsal may itself change somewhat what is being rehearsed, and that some forgetting is inevitable but not necessarily the kind of forgetting which the operator would choose.

Memory is seen as positive and forgetting as negative, but in practical terms this may not always apply. It would seem that in air traffic control one criterion to establish the best ways of presenting information could be to choose codings, formats and display methods which make the information easy to remember at the time and facilitate its subsequent recall. Alternative coding conventions have generally been compared in terms of their effects on task performance rather than on their relations to memory. While information should be usable when it is present, the desirability of making it memorable, even if that were possible, is questionable. For many purposes, it would seem more advantageous to be able to forget it once its usefulness and relevance have gone. Information which is continuously recalled hours or days after it had any value may be unwanted lumber. In solving today's problems the man may have no need or wish to recall the fine detail of the problems which he solved yesterday. In some circumstances in air traffic control it would therefore seem beneficial to choose codings and formats to promote forgetting, or at least to know how to do so. Unfortunately on this point theories of forgetting offer no practical help. While different visual coding dimensions are probably not equally memorable, although the information on this point is far from complete, there seem no practical guidelines to select coding dimensions to aid forgetting.

An objective of training is to establish a body of long term knowledge which can act as a frame of reference for adding subsequent knowledge, and can be organised to facilitate the selective recall of what is relevant to any given problem, and to discourage the unproductive recall of what is irrelevant. Practical evidence derived from theoretical studies of memory may enhance training [83]:

(1) When information has been learned so that it can be recalled, its long term retention in memory and recall can be greatly enhanced by continuing to learn, or overlearn, it for a little longer.

(2) The extent to which new information is similar to familiar information influences the ability to recall it without recalling the old information in addition to it or instead of it. Systems which evolve gradually may engender problems of memory of this kind.

(3) Memory of information is apparently greater if the memoriser is already knowledgeable about the subject matter, not because memory capacity is improved but because material to be memorised can be ordered into larger chunks or meaningful units. The ability of the air traffic controller to remember a great deal about the traffic he has been controlling is not because he has a particularly good memory but because his knowledge of air traffic control enables him to treat the information in larger chunks or units. Although memory may have something like a fixed capacity in terms of the number of chunks which can be put into memory or retrieved from memory in a given time, this is not of practical significance since it has the effect that the greater the existing knowledge is the greater the capacity for learning related material can become.

Much academic work on memory dwells on the distinction between recognition, which requires little searching, and recall, which is primarily a search and retrieval process. Recognition is usually both more reliable and subjectively easier than recall. In air traffic control, the distinction between recognition and recall does not usually have the practical significance that it has in the psychological laboratory. Often both mechanisms are involved sequentially; information is retrieved by following the set procedures which have to be recalled; once it has been retrieved and displayed it can then be recognised. The correction of errors involves their recognition as such, and then the recall of the means of correction.

## 5e ATTENTION

The importance of attention in designing air traffic control workspaces, tasks, displays and facilities is now more widely acknowledged than it once was. Attention sets the main practical limits on the pace at which information can be assimilated, particularly from large tabular displays which have to be searched to select information from them, as distinct from radar displays where the pattern of information has to be perceived and attended to. In most circumstances in air traffic control, much more information than can be attended to at once is presented on displays, since this information is needed to do the whole task. Ergonomic principles seek to ensure that the information is presented so that every item can be perceived clearly and with a minimum of ambiguity. The information will only be used if the man attends to it at some point, and when he does attend, his interpretation of it, the meaning he assigns to it, and the use that he can make of it, all depend on what he already knows about air traffic control and his tasks. At one time much emphasis went on ensuring that the information needed for the task was provided; then the concern was to ensure its discriminability; but the successful achievement of these stages is insufficient. The information remains largely unintelligible and useless to someone without a knowledge of air traffic control and its procedures.

From their own experience, people are aware that they can attend to only a limited amount of information at any one time. They are also aware that to some extent they can choose what they will attend to, but in certain circumstances may lose this facility to direct their attention so that, willingly or not, they find themselves distracted by information which they do not want to be concerned with, or drift into a daydream in which none of the information around them is receiving their attention. In air traffic control tasks, neither distractions nor daydreams are ever desirable. Efforts are therefore made in the design of tasks and facilities to ensure as far as possible that attention is maintained on the air traffic control task at all times. While such efforts can be partly successful, it may ultimately be unwise to predicate the safety of the system on the assumption that they can always succeed. Uncontrollable lapses of attention, particularly in highly familiar environments with overlearned tasks, appear to be an inherent characteristic of human behaviour, and it would be prudent to try and design air traffic control systems to remain safe when the man is not attending as well as when he is.

Attention can seem like a beam which can be pivoted or switched but only directed exclusively to one place at one time. This is a potentially misleading analogy. Although the man may have the propensity to attend to, and become exclusively absorbed in, a single problem until he has resolved it, such singlemindedness can be potentially dangerous in air traffic control and an important part of the training of the air traffic controller is to ensure that, no matter how important a problem becomes, he still attends from time to time to incipient problems elsewhere and to other aspects of his task. He cannot afford to become totally oblivious to everything else that is happening. This is related to the feasibility of task sharing, to the ways in which tasks can be shared, and to individual differences in the ability to share tasks, an ability which seems independent of the nature of the tasks themselves[84]. This raises the issue of the extent to which effective task sharing can be promoted in air traffic control by suitable training, facilities and task designs.

Attempts to control and direct attention are likely to be only partly successful. On primary radar displays, the rotating light beam exercised a strong influence on the direction of attention which the observer found difficult to counter, whether it fostered efficient use of the display or not. Codings such as flashing, which are primarily designed to direct attention rather than to convey information, may be counter-productive if they go on attracting the man's attention after they have served their initial purpose. The design and layout of equipment, particularly of displays and visual coding dimensions, can influence the distribution of attention. There is thus the possibility when workspaces are designed, of influencing attention towards its optimised division in terms of efficient task performance.

Notions of task sharing, and of primary and secondary tasks between which there is attention switching, may be predicated on the assumptions that the man processes information serially and that information processing capacity is fixed, both of which can be questioned[85]. Studies on these topics reveal a further characteristic of attention which has unwanted practical implications, namely that a person instructed to divide his attention between tasks in a particular way cannot always follow such an instruction, try as he may. Attention cannot always be directed. This has benefits and disadvantages. It means that in a dire emergency it should be possible in principle to attract the man's attention using a stimulus of appropriate coding and high intensity. It is also possible to steer and control attention to some extent. On the other hand, it may never be possible to exclude all distractions.

Various principles can be used to draw attention and alert the controller. New information may appear very boldly to draw the man's attention to it. Once he has perceived and acknowledged it, however, the need for its obtrusiveness has gone. A flashing coding, or higher brightnesses or larger characters, all of which can revert on acknowledgement to usual methods of depiction, may be suitable for new information. Emergency information may be depicted in a way which attracts and holds the attention. Again, this depiction should last only for as long as the emergency, which is likely to be much longer than for new information. Flashing may therefore be less suitable but colour can be effective in this role; enhanced size or brightness might also succeed. Information which is continually changing may be depicted obstrusively or unobtrusively, depending on the importance of the changes which are taking place. An important consequence of replacing manual by automated functions is that whereas in manual systems the man had to make each change himself and so knew that it had occurred, in automated systems he may not even notice one and his attention may have to be drawn to it. If a single item in a tabulated list changes he may be aware from detecting a movement that something has changed, but not know what. It can be very irritating to search a tabular information display to try to deduce which item has changed, relying on memory of what was there before. An indication is necessary of items of information that have recently changed, perhaps by increased size, brightness, or a mark such as an asterisk which remains present for a short time after a change and then reverts automatically to its normal state. How long "a short time" is would depend on context, but perhaps 10 seconds would be typical. Gross changes in displays may be introduced in order to draw the controller's attention to a particular problem, such as auto alert facilities to show that an aircraft is straying from its track, or conflict detection facilities to show that there may be an impending conflict between traffic which the controller must attend to. Where more than one item is concerned, as in conflict alert, it is important to depict both conflict items in a code which differs from other displayed information, and to use the same coding for the conflicting pair, so that they can be seen as related, and preferably perceived as an entity or distinct sub-category.

The needs of the task will dictate the quantity of information to which the controller's attention should be drawn. At one extreme it may be desirable to draw his attention away from one display to another. At another extreme it may be one small piece of information, such as two aircraft at the same height, which it is important that the controller should know. Suitable methods of coding can not only guide the attention but determine the level of detail at which the controller should attend. This should enable him to see the problem as a whole and not focus on one small part of it or on the problem in the context of a much larger and irrelevant context.

The information in a large tabular display cannot all be attended to at once. Display design can help to impose an orderly sequence on the pattern of search and attention, by indicating relationships among the displayed data and by structuring the information so that none is inadvertently missed out. If the information on an air traffic control display were used only for a single task, then there would be a single criterion for determining the relative importance of different categories of information, and this criterion could be adopted to determine the relative visual prominence and attention demanding properties of various information categories. However, in air traffic control the same information can be used for many tasks, and it may not have the same relative importance for each; furthermore, information which is most important for some tasks may be superfluous for others. The more boldly it is coded for the tasks for which it is vital, the more distracting it becomes for the tasks for which it is not needed. In general therefore, on most air traffic control displays, a balance has to the struck between the coding needs of various tasks. This problem becomes particularly acute when different controllers perform different functions, sharing the same display.

There is much concern in air traffic control with lapses in attention and their potential consequences, not only because these imply a temporary absence of control of air traffic but also because if the man fails to maintain his attention it can be potentially dangerous. There is an unresolved dilemma here. It is contended that the controller must pay attention to his traffic all the time and the safety of the system presumes that he does so. Systems, functions, facilities and tasks are designed to ensure that he does maintain his attention. Yet it is not possible for anyone to maintain attention indefinitely on anything. Lapses in attention are bound to occur, and the most commendable and effective efforts to ensure continuously maintained attention can only reduce these lapses and never eliminate them completely. By all means let us do our best to ensure the controller's continuous attention, but let us not make the safety of the system depend on our success when we know that our success cannot be complete. Passive monitoring roles in air traffic control do seem to make lapses in attention more probable: this needs quantitative verification under experimental conditions. It does seem that it may never be possible to prevent all lapses in attention entirely but only to adjust tasks so that they need attention to do them, to keep the man continuously in the loop, to require the exercise of skills and knowledge, and to prevent his role from becoming too passive.

One aspect of attention which has received theoretical rather than practical study concerns its relationship to expectancies. People who are attending may perceive what they expect to see rather than what is actually there. Some codings, such as movement and flashing, may draw the controller's attention to information but may not help him to understand it once he has attended to it. The methods of drawing attention to information can affect what the man expects to see.

When the man is overloaded, this may become most apparent to him in the form of excessive demands on his attention, where he knows that he should be attending to several things at once but cannot do so, and has to decide how his attention should be allocated. In such circumstances he can appreciate that his performance is being limited by his ability to attend to and understand the information present. He may fail to perceive something important because there were too many other things to attend to. This can be potentially dangerous and is considered in relation to the possible causes of incidents or accidents. However, incidents or accidents may also occur when the man is underloaded, and has too little to attend to. Lapses of attention may be associated with underload rather than overload. It may be with serious underloading that the probability of daydreaming and the problem of the maintenance of attention to the task become most acute.

## 5f INFORMATION PROCESSING

From time to time, a particular psychological theory or set of constructs becomes so dominant that claims are made to treat the whole of psychology in its terms. In the past this has occurred with certain learning theories. At present, information processing is sometimes treated so broadly as to become nearly synonymous with psychology[78]. The frame of reference commonly used in psychology in relation to information processing has not generally been applied in air traffic control, where in the past the man has often become overloaded with information because his limitations of information processing have been insufficiently understood.

According to a simplified description, the air traffic controller assimilates information from his displays, his surroundings and his communications, and processes and interprets that information in the light of his capabilities, knowledge, training, experience, procedures, instructions, preferences and attitudes. He gains an understanding of what has occurred, is occurring and will soon occur, chooses and implements appropriate actions, and continues to ensure that these actions are safe, efficient and appropriate for as long as necessary. According to conventional wisdom, the controller attends to far less than he could sense, and mostly processes what he attends to rather than what could be sensed. The processes of attention limit the information he can assimilate and use, but he also has severe limits in the rate at which he can process information. Because he can deal only with a few items or units of information at a time, it is desirable:

(1) To parcel that information for him into units which are as big as possible but which can be assimilated as entities.

(2) To make the information in separate units as compatible as possible with that in other units.

(3) To guide the man so that he does not waste time trying to assimilate information which is of no relevance.

(4) To ensure that the information presented is at a level of detail which allows him to tackle the tasks which he must perform.

(5) To make maximum use of the man's existing knowledge and frames of reference rather than of new knowledge which has to be gathered and processed before he can use it.

A current way of looking at information processing in theoretical terms is to consider whether the limits on the man are ultimately data limited, in the sense that he has in some respect insufficient information to carry out his task properly in the time available, or resource limited, in the sense that although the information is present, limits of attention, of effort, and similar concepts ultimately determine how well it can be used[56]. Clearly it is not efficient if he has inadequate information on the one hand or excessive data on the other. Therefore in practical terms the aim may be to match the separate limits set by data limiting factors and by resource limiting factors so that they are not grossly different. This would imply that the information has been well tailored to the needs of the task and to the man's abilities and limitations.

A recurring finding in air traffic control is that the typical controller possesses more information about the traffic he is controlling than would be predicted on theoretical grounds. This is because the combination of selection, training, knowledge and experience in the controller leads to an efficient frame of reference which also fosters the incorporation of further data efficiently. The information structure and units which he has learned are also broad and integrated as part of their initial perception, before information processing takes place. The controller who takes over an operating position from a colleague requires quite a long time to build up his picture of the traffic. He has to process a lot of information in order to do so, and the prolonged time reflects the limits of his ability to process information and construct a very elaborate framework even with his knowledge and experience. Once he has constructed it, he relies heavily on it for controlling traffic and feels vulnerable if circumstances suggest that this carefully constructed picture may vanish, disappear or become meaningless. He may therefore worry about what he calls "losing the picture", believing that, if he does lose it, its reconstruction is a long process, and that during the reconstruction the system is more vulnerable and perhaps less safe. The evidence to support this belief is not strong, but nevertheless the belief is strongly held[35].

Because the controller brings a great deal of existing knowledge to his task, and because he needs to know a lot of information to do his task efficiently, the choice of information for him, the level of detail at which it is depicted, and the coding conventions employed, can all be expected to affect considerably his efficiency as a processor of air traffic control information. This is reflected in the pre-occupation of much air traffic control research and evaluation with displays, with layouts, and with information coding. However, much of the emphasis has been on the choice of information deduced from task descriptions. It has seemed to be implied that the human factors work is substantially finished when it can be shown that the information needed to do the task is present, but it is not. In practice it is easy to present data which contains the information needed for a task, but which the user cannot fathom. Some computer manuals inadvertently illustrate this point very well. An essential stage of human factors is to ensure that information is not merely present but can be used and can be understood.

Compared with a computer, man cannot process a great deal of information in a short time. It is partly because of this, that computer aids are needed in air traffic control. It also follows that in many respects it is impossible for the man to check what the computer is doing, simply because it can handle and process the information at a pace with which he cannot compete. To check the computer therefore he needs to know what sort of mistakes it can make, and what sort of errors may seem plausible to it but not plausible to him. It is not possible for the man to make the same calculations as the computer in order to check their correctness. This is an a priori principle and it should have a major influence on the respective roles of man and machine in the system. A computer can be programmed to process and weigh data from many independent sources but if there are too many independent sources of data for a man to process in the time available he will simply miss out some of them and they might as well not be present for all the influence they have on his understanding and decision making.

The choice of types of coding, such as alphanumeric, graphical, pictorial or symbolic, can have considerable influence on the ways in which information is processed by the controller and on the rate at which the information can be processed, although this does not always have as much influence as it should have on choice of appropriate coding. Data in the form of flight strips differ from data derived from radar displays in terms of the priorities and level of detail, of the information contained, and of the processing which the man can readily achieve. The controller selects the information which he finds easiest and quickest to process, and which is most compatible with his existing thought processes. Information which has to be recoded before it can be used is inefficient and may be neglected or ignored, and it introduces extra errors, combining those normally associated with the interpretation of information with the further ones introduced by mistakes in recoding. When information on aircraft identity first appeared on radar displays, controllers strongly preferred it in the form of the aircraft callsign because in any other form it had to be recoded[86].

In the design of air traffic control tasks, procedures and workspaces, much effort has to be devoted to circumventing human limitations of information processing, and to maximise efficiency by means of preknowledge, experience and training, by the choice of appropriate codings, by presenting the information at the correct level of detail, by making information compatible with existing frames of reference, and by ensuring that as much of the man's time as possible is taken up by productive information processing. A limit on information processing also occurs if there are long periods with no information to process, interspersed with periods when there is too much. If the information processing load can be spread evenly, this makes the most efficient use of limited time and helps to ensure that the information is as up to date as possible.

## 5g UNDERSTANDING

In general man acts only on information which he understands or thinks he understands. Ultimately it is pointless to present him with information which is incomprehensible to him, or to draw his attention to information which he cannot make sense of. It is also wasteful to present him with information which he tries to understand for a long time but ultimately discards because he is not sure what it means. The product of information processing is understanding. Understanding is the basis for solving problems and taking decisions. It is therefore somewhat strange that less attention is paid to the process of understanding than to those of presenting information or of taking actions. This is partly because, if the man and machine are viewed as a sub-system, human understanding is perhaps the aspect of that system which is most difficult to disentangle from other influences and most difficult to measure. Nevertheless understanding is of crucial significance: it is the culmination of the other processes of sensation, perception, learning, memory, attention, and information processing; it is the precursor of the processes of problem solving and decision making. Most of the understanding which the controller brings to bear to the air traffic control situation before him at any given time depends not on characteristics of that particular traffic situation, although they are relevant, but on the vast body of knowledge and experience about air traffic control and its methods and problems which he has accumulated. This is ultimately what characterises his behaviour and separates the controller from the non-controller.

The controller uses his understanding when he postpones certain actions but not others, when he gradually changes task strategies under high workload, when he plans in advance, when he builds and maintains his picture of the air traffic under his control, and when he directs his attention. It is taken for granted that the controller must understand the principles of air traffic control and must have a considerable knowledge of the characteristics of the region within which he controls traffic, its geographical airspace, its divisions, its main vertical structuring, the location of reporting points, of airways, of danger areas, and so on. It is not taken for granted that the man needs a detailed understanding of the hardware and software of the system in order to use it. It would be too impractical and costly for every controller to have the detailed knowledge of software in the system which a programmer of that system needs to have, even if it were shown to be desirable, which it has not been.

Understanding is aided if it can be referred to logical and general principles of air traffic control and of system design. It should not be necessary, in order to understand the traffic situation or the procedures to be followed, to remember a large number of specific rules. A small number of general rules should suffice. Ideally, the logic of a keyboard layout, for example, should be so clear that it should be possible to perform a new keying sequence with it which has never been performed before, the meaning of which is self-evident from the logic of the layout and the sequences of keys. The use of such logics is a great boon to understanding. It is less important which particular logic is adopted, as long as it is followed rigorously and consistently everywhere that it applies, and as long as the boundaries within which it applies are clear.

A problem which has become severe in other man machine systems and is showing signs of appearing in air traffic control is the following: when aids are provided in the form of computations and recommendations for the man to act on, they rely on information at a level of detail and an order of complexity beyond his ability to understand. If he is asked to accept or reject that computer recommendation, the information which he in his turn uses to accept or reject it is much less adequate and comprehensive than the information used to make the computations and to arrive initially at the recommendation. This seems illogical. It also follows that the man is unable to recalculate and verify the computed solutions. This raises the problem that there may be no point is having elaborate computed solutions which are better than the man alone can calculate and which are intended to compensate for his own limitations, unless their implementation is in some sense mandatory, since if the man is able to override them his own solution, given that the automated aid is safe and efficient, is likely to be poorer than the automated solution which it replaces. There is a serious problem of man machine relationships here, and it arises because of the man's limited understanding of what is happening. His limitations may be circumvented partly if he understands more about the system and how it functions, but in any specific instance the machine will always be able to out-calculate him and his understanding therefore is bound to be incomplete. All the consequences of this, and the optimum man-machine relationships in this contexts, have still to be worked out, but in the interests of efficiency and safety the problem has to be faced.

Much of the relevant theoretical work on understanding has been confined to language and speech[87] or to social understanding of the behaviour of other people by the study of gestures and expressions[88]. Less work has been devoted to the problem of how well people understand the complex jobs which they actually do. In air traffic control there is not only the practical problem of how much controllers do understand, but the further problem of specifying how much they need to understand. Here a widening gulf is appearing: although various attempts have been made to bridge it, none has really succeeded. The gulf is between the understanding of the designer of the system and the understanding of the user. Neither comprehends fully the problems which the other faces. The designer may be concerned with problems such as technical feasibility and costs. The user is concerned with controlling air traffic, with using his resources to the best advantage, and with the attitudes of management towards him as he sees them. This is a topic ripe for misunderstanding, since neither has sufficient knowledge of the other to see the other's point of view. The less manual air traffic control becomes, the more this problem seems to arise, and the greater the gulf between the needs of the designer and the needs of the user seems to become. This is not a problem confined to, or typical of, air traffic control, but is characteristic of modern man-machine systems in general. It does mean that no-one has a clear sight of all the information needed to resolve it. Some possible solutions such as the participation of controllers in design teams or in the writing of software, or practical experience for designers in controlling air traffic, have been tried but not with sufficient success for them to become common practice. Although in theory anyone can share his allegiances between disciplines, in practice it seldom seems to occur. Many an air traffic controller has become a programmer, or been appointed to a responsible managerial position, to the plaudits of his fellow controllers who feel that at last someone in authority will understand them and their problems, and be able to express their point of view; but the same controllers have subsequently been disappointed because that person in his new position sees all the other problems which the controllers themselves do not see, is influenced and perhaps over-influenced by them, and from the controllers' point of view is lost to them as a favourable influence and advocate. There is also a further problem of interdisciplinary misunderstanding in air traffic control. It arises between controllers and maintenance staffs. It may be necessary in the future for each to have a greater understanding and acknowledgement of the needs of the other, and for both to have a greater understanding of how technical and financial decisions are reached which influence their day-to-day work.

## 5h PROBLEM SOLVING

In some respects, air traffic control can be viewed as a sequence of problem solving, particularly in heavy traffic. In the past, with manual systems and relatively low traffic levels, much effort has been devoted to the early detection and solution of impending problems before they become serious and hazard safety or lead to inefficient manoeuvres. Much air traffic control has been conducted at a tactical ad hoc level. The trend is away from this kind of air traffic control towards strategic solutions to any problems which arise and towards preplanning so that problems are prevented. The concept of flow control, by the careful timing of initial departures followed by long term, relatively small adjustments to an aircraft's route, height or speed, is in many respects intended not only to improve efficiency but also to forestall problems, particularly potential conflicts between aircraft and infringements of separation standards which, when they arise in congested air space, may be quite difficult to solve safely. Problems are therefore gradually changing from tactical to strategic and from the solution of difficulties to their prevention.

Air traffic control can be considered as a hierarchy of problems, the solutions to many of which are constrained by decisions reached during the design stages of the system. The kinds of problem which each man in the system has to solve are therefore determined not mainly by himself but by the position he occupies in the system, by the information which is available to him, and by the facilities which he knows how to use.

It is often held among controllers that there is not necessarily one best solution to every air traffic control problem. Individual controllers tend to have their own preferred solutions which depend on different selections and weightings of evidence and different appraisals of the relative importance of various consequences. Automated aids to problem solving are often based on the assumption that a single optimum solution to a problem can be specified, and this is one reason why such solutions do not always seem the best solutions to the controller. If there is an optimum solution it may sometimes be specified in mathematical terms, but though the mathematics may be faultless the premises on which the calculations are based can sometimes be challenged. In particular, the relative importance of the various factors may be disputed[89], and from time to time new factors may be added which invalidate the previously optimum solutions, call for their revision, and engender further debate on what relative weighting the new factors should be accorded. For example, the need for noise abatement and for a greater awareness of ecological factors means that the relative importance of environmental noise as a factor has increased, and the optimum solutions to air traffic control problems may have to be modified to take account of this. More recently, the greatly increased cost of aviation fuel has added to the relative importance of fuel conservation as a factor, so that fuel efficiency carries a greater weighting now than it used to have, and the optimum solutions to problems have to be modified again accordingly. It is only possible to specify an optimum solution to a problem if it is agreed which factors are relevant and what their relative importance is.

It is not yet possible to approach with automated aids the flexibility of the human being in solving problems. A central difficulty is the matching of man and machine in problem solving: automated aids to problem solving may go so far as to propose solutions, but the decision is ultimately left to the man to accept or reject the automated solution. The difficulty has been to provide the man with an adequate rationale to fulfil this role satisfactorily, so that his contribution does add to safety and efficiency rather than replaces an automated solution with a manual one which may be further from the optimum. A further difficulty, not yet resolved, is that in manual air traffic control systems problem solving is often a team activity, with much consultation between controllers and sometimes negotiation between pilots and controllers. Automated aids tend to be more suitable for individuals than for teams, and team functions become fragmented into individual functions as more automated aids are provided for the individual controller, particularly under high workload when each team member tends to go his own way and to have no time to follow closely his colleagues' activities. This affects many aspects of the control task, but may be particularly important for problem solving where the processes of consultation and supervision are no longer possible[90].

Problems in air traffic control vary greatly in their time scale. Those in oceanic control are very different in this respect from those which arise from an unexpected overshoot in a busy terminal area. The value and desirable forms of problem solving aids depend on the complexity of the information in relation to the time available. The time scale also affects the knowledge which the controller can have about the correctness of the solution to a problem which he has implemented and about the full extent of its implications for the rest of the air traffic control system. It can be difficult to predict more than a few minutes ahead, particularly in congested airspace, but nevertheless the preferred solutions even to problems which have arisen very suddenly and which must be solved at once are those which take account of the traffic situation which will result from implementing the preferred solution, so that as far as possible one solution does not trigger a succession of problems.

Training in problem solving can be rather difficult. It must include the ability to appreciate all the consequences of a proposed solution, including indirect and longer term ones, and the ability to maintain some attention to other aspects of the air traffic control task while the solution of a problem is being worked out. It is difficult to obtain descriptions of how controllers solve problems. One method which could be attempted is to ask the controller to verbalise the problem concurrently or retrospectively, but there are aspects of air traffic control which are essentially spatial and visual and which do not lend themselves to complete description in words. There are also limits to the extent to which the controller can verbalise what he is doing, since he is not particularly trained to do so. There may be relatively little activity while a controller is solving problems. If he has to consult information which he needs, then that can be recorded, but if a great deal of information is present, the problem is to determine which he uses and which he ignores. How is it possible to tell the difference between a controller who detects a problem, examines all its aspects with care, and decides correctly that the optimum solution is to take no action, and a controller who also takes no action because he has failed to detect the problem at all?

Various techniques have been employed to try and trace what the controller does, and to deduce how he solves problems, including work derived from theories of attention and studies relying on eye movement recording. None of these can cope satisfactorily with this example of the controller who mulls over a situation and then decides to keep attending to it but to do nothing yet. One important aspect of training in problem solving is to fine tune the controller's judgements of whether there is a problem or not, and of how long he should wait to find out whether one develops. The earlier a solution to a problem can be found, particularly in terms of avoiding action, then the less urgent the avoiding action need be, and the smaller the necessary manoeuvres and consequent delays become. However, avoiding actions instituted too early will include a proportion which were in fact unnecessary. A balance has to be found which represents the optimum timescale for taking action to solve problems.

Various theoretical approaches on the selection of information and on the utility of information selected can be studied, but this can only be done productively if the criteria are clear on what constitutes maximum efficiency and ideal solutions. At present, such criteria are not clear. There is also some tendency to teach problem solving by a series of examples, between which the connections are vague, rather than by a demonstration of underlying principles, to which every specific problem can be referred. Perhaps the aim should be to try to derive a kind of mental checklist of all the factors which can be relevant in solving an air traffic control problem, and to train the controller to make the optimum selection of factors from this list which apply in each individual case.

## 51 DECISION MAKING

Much recent psychological work on decision making has been concerned either with the processes of managerial decision making and with their optimisation in accordance with known human capabilities and limitations[91], or with laboratory studies of quantifiable decisions, usually involving mathematically defined optima and stochastic processes[92]. It might be hypothesised from studies of the latter type that controllers would over-emphasise accessible information and under-emphasise information which is obscure or difficult to obtain, but this has not been confirmed in air traffic control contexts. It might likewise be hypothesised that in taking decisions controllers would attend to what is familiar rather than to the unfamiliar, perhaps to the extent of tending to discard the latter altogether, but again confirming evidence from air traffic control itself does not exist. Controllers have a long training which is bound to influence the means by which they reach decisions, and indeed is intended to do so. This may be advantageous for their decision making if training is correctly tailored to their needs but it carries the danger of imposing inflexible thought processes which can lead to stereotyped decision making. While appropriate training may encourage the controller to look at each problem afresh, and not to assume that the solutions which have succeeded in the past need necessarily still be most apposite, training does not seem to have been particularly successful in ensuring that the controller not only looks carefully at the evidence which bolsters a decision he has already taken but looks equally carefully at evidence which undermines it or suggests that it should be revised. In air traffic control as elsewhere, people needs a lot of evidence before they can admit that they might be wrong.

Although some of the basic findings about the way human beings reach decisions must be applicable to controllers who work within typical human constraints, not much of the experimental work on decision making has been very helpful to air traffic control, with two main exceptions. One concerns the examination of decision aids in command and control systems[93], and the other concerns the series of French studies on the relevance of cognitive theories, such as signal detection theory, to the kind of decisions which the air traffic controller makes[94].

Man is slow and inefficient if he has to weigh optimally numerous independent sources of information in order to reach a decision, particularly when he must gradually accumulate information and derive probabilities from it. A practical consequence may be a preference for cherished tactics or solutions which the individual becomes well known for adopting. Such rigidness is unlikely to produce optimum decisions consistently. Subjective and mathematical randomness differ. The man tends to impute causal connections where none exist, to equate randomness with lack of repetition or pattern, and to presume that an event must be due to occur soon because it has not occurred for a long time.

More knowledge about the controller's decision making can perhaps be gleaned from studying the formation of his picture of the traffic, his frame of reference, the role of his memory, and in particular the time scale within which decisions are reached. This last point should be a main determinant of the information depicted on displays, its layout, its coding and its level of detail. Display contents have a profound influence on the decisions which can be taken using the information on them.

A further pertinent human characteristic which affects decision making is the formation of habits. The standardisation of instructions, training in air traffic control procedures, the uniformity of equipment, and the implementation of standard ergonomic recommendations in workspace design, all foster the formation and reinforcement of habits, although their objectives are seldom expressed in such terms. Because of habits, the operator can occupy another position similar to his normal one if the latter becomes unserviceable, and perform his tasks efficiently there. His training transfers at the broad level because the facilities and communications are similar, and at the specific level because each specific control is so similar to its counterpart that habits of usage acquired at one position transfer completely to the other. A reason for the general reluctance among controllers to accept any change which is apparently made solely for the sake of change is that, if the change is major, habits may not transfer and new habits may have to be painstakingly acquired.

Real life air traffic control decisions are about the control of particular aircraft, the maintenance of smooth flows of traffic, the avoidance of conflict situations, the economic and efficient solution of problems, and so on. The controller also makes decisions about the allocation of his own resources. He decides what problems to deal with, how to allocate his attention, when to act, and when to take the initiative. He decides how far to trust the information presented to him and its probable quality. The manner in which he reaches decisions may determine the extent to which he is fully in control, planning ahead and avoiding problems, or is responding exclusively to the demands of the system, so that his task becomes the solution of a sequence of problems some of which may originate from his own incorrect decisions about the allocation of his resources.

A further influence on the controller's decisions is his knowledge of the alternatives available. In the simplest case, if there only seems to be one solution to a problem decision making becomes easy. If there are two solutions, decision making may still not be complicated. The more solutions that can be seen, the more complex the decision making process becomes. This suggests that decision making may become more complex as experience and skill are developed and a greater insight is gained into tasks and system functioning. A further product of his experience and skill is his appreciation that there are more factors to take into consideration in decision making than were initially apparent. A further relevant relationship is that between decision making and expectancies. Air traffic control decisions are influenced by expectancies based on the past behaviour of air traffic and on assumptions that traffic will obey the controller's instructions and not behave unexpectedly. The importance of expectancies is sometimes revealed inadvertently in simulation studies in which apparently minor differences between simulated and real life conditions receive great emphasis because the expectancies from real life are not quite in accord with the simulated conditions.

Generally in air traffic control the controller has knowledge of results in that he knows the consequences of his decisions within a short time. Unforeseen consequences of his decisions may also become apparent soon enough for him to see the relationship between them and the decision which produced them. The basic conditions for learning and improvement are then present. Knowledge taken into account in reaching decisions, and knowledge of the consequences of decisions, combine to provide a basis for reviewing subsequent additional evidence, for determining whether it is new and relevant, and hence for judging whether the decision should be re-examined. A problem which arises when automated aids are introduced into decision making is that it becomes less clear what constitutes new evidence.

Decision making is a function often considered as ripe for automated assistance. From the point of view of the controller, decision making aids may be a misnomer as the functions they introduce can be unlike the decisions which he used to take. Even in a manual system, the controller has an incomplete understanding of all the implications and consequences of his decisions, and of the penalties that could be incurred by wrong decisions, since their ramifications extend to system functions that he has no knowledge of. He has less understanding however when automated aids to decision making are employed, to the extent that his capacity for effective intervention may be seriously undermined. In system efficiency terms, it may be better either to remove decision making functions from the man altogether or to accept that the aids needed for such functions may be of a very different kind from those provided now.

There is a tendency, not warranted by current knowledge, to presume that man's decisions are rational and that his subjective notions about optimum decisions are therefore realistic. There is the further tendency to presume that there must an optimum decision. In air traffic control, this may not be so. Several solutions to a problem may be possible, all with approximately equal consequences in terms of efficiency, safety and economy, and all giving different weightings to various factors. As long as there are arguments about the optimum weighting of these various factors and insufficient objective evidence to support a firm conclusion, there can be no adequate rationale for making an arbitrary decision or imposing a particular problem solution which the evidence cannot support.

As he acquires experience, the controller gradually learns from his mistakes and wrong decisions: these processes of gradual learning and the correction of mistakes have not been thoroughly studied in air traffic control contexts in any way which can lead to further optimisation of decision making. Where mistakes can be identified, as in accounts of incidents where separations have been infringed or air misses have been reported, the outstanding impression is that such incidents have very little in common and that there is no single kind of decision which can be identified as intrinsically unsafe and therefore as a profitable subject for further training and learning. Rather it seems that the errors which precipitate incidents are representative of all errors, the vast majority of which do not lead to incidents. The causes of each incident seem to lie in the particular environmental conditions prevailing at the time rather than in the nature of any errors that were made.

5j MOTIVATION

There is a curious dichotomy in psychological work on motivation. Much applied work has paid progressively more attention to it as a factor relevant to real life jobs, and this interest has spawned many theories based on evidence from operational contexts, although the proliferation of theories suggests that none is likely to prove adequate for all evidence and all jobs[95].

By contrast, interest in motivation as a factor in cognitive functions studied in the laboratory seems to have waned. Some cognitive theories pay no heed to it; others borrow concepts such as needs or satisfiers from the applied work, or subsume motivation under a broader heading such as knowledge of results or feedback. To the man performing tasks, motivation seems important. Evidence on how important it is in terms of efficiency, errors and safety is much more equivocal. It is difficult to manipulate motivation as an independent variable untrammelled by other influences. Help in understanding motivation in air traffic control from basic laboratory studies therefore seems limited. This seems a pity: as a concept it is complex[96], and it seems of practical importance to know more than we know now about its effects on the efficiency of air traffic control in general and on safety in particular.

People who can control their own workload often make themselves busy deliberately. Congenial work can have intrinsically satisfying properties, so that some continue to work voluntarily at their job during nominally leisure hours if there are no external constraints on doing so. Even within the laboratory it is apparent that tasks vary greatly in the quality which they possess to motivate the subject to do them well and to try hard. Some demand and receive his full commitment and he may be reluctant to stop doing them. Others seem so inherently unappealing that his full collaboration can never be enlisted. Insufficient is known at present about the properties of tasks which provide strong motivation to perform them well. Confident predictions cannot therefore be made about how motivating a particular task will prove to be. It is generally assumed that motivation has a cause, in the sense that a rational explanation of it is possible if only it could be found. It is also assumed that motivation is central to performance. However, the driving force behind many tasks may come largely from the satisfaction of performing the task itself. It is surmised that it is a good idea to try and ensure that people at work are highly motivated. Here, humanitarian and moral notions may become enmeshed with ideas of productivity and cost effectiveness. In many contexts the man who is happy in his work apparently performs his tasks no better than one who is not. It may not be true that the man who is highly motivated in his work performs his task better than one who is not. Supporting evidence for such a contention is surprisingly sparse.

The study of motivation must therefore start with the question of why it is being sought. It can then progress to establishing what is affected by changes in motivation. From such knowledge, a realistic appraisal can be made of what attempts to improve motivation are likely to achieve. Perhaps the main effects of good motivation are in terms of low staff turnover, high morale, willing collaboration with new ideas, tolerance of administrative or managerial setbacks, and factors of that kind, rather than direct improvements in efficiency or safety. On the other hand, motivation may be the key to efficiency and safety. The fact remains that we do not yet know.

5k COMMON MISMATCHES OF SYSTEM REQUIREMENTS WITH HUMAN CAPABILITIES

Designers of air traffic control systems, facilities and workspaces do not normally have a comprehensive knowledge about human capabilities and limitations, which are outside their terms of reference. The simplest mismatches, and those which can be the most readily resolved, refer to workspaces. Examples are working positions at which the controller cannot sit comfortably, controls such as keyboards which are wrongly placed, displays at an incorrect angle or distance for viewing, with information which is inadequate in brightness or contrast, and with excessive glares or reflections. Most human engineering handbooks contain sufficient information for these problems to be detected and prevented at the design stage, and to be cured in operational settings, given adequate financial, technical and human factors resources. It is relatively easy to ensure for a given specified physical environment with known minimum standards of eyesight and hearing for operators that information is presented far enough above the visual and auditory thresholds to be easily read or heard. Most common sources of visual or auditory errors are now known, and mismatches resulting from them can therefore be avoided. Nevertheless there is a general failure to recognise human limitations in higher mental functions, and this is the source of many intractable mismatches between man and machine.

It is common to present information at the wrong level of detail. Either it is too simple, and the man has to resort to cumbersome procedures to call down other information which he must have, or it is too complex, and involves him in time wasting search activity and in errors and misunderstandings when collating information from different sources. A urther source of mismatches is a failure to impose a coherent logical order, both on the information displayed or available for display, and on the control facilities and their layout and sequence of use. Control display relationships also need to be matched. The displays themselves can be used, although often they are not, to give reminders and to aid teaching. It is common to misjudge the rate at which man can process information or collate information from disparate sources. Information may not be presented in a form which is readily understood or compatible with the man's thought processes and mental images. Commonsense would suggest that it should be so presented, although proof of this is lacking. Hitherto displays have been evaluated primarily as means of conveying information needed for the performance of tasks. In the future, displays must continue to fulfil this function but must also satisfy other needs, such as memory aids, predictors and indicators of human error. Mismatches now occur because displays do not meet these further needs very well; sometimes the needs have scarcely been recognised.

Displays also lack qualitative information. Sometimes accuracy is equated with clear portrayal, and it is presumed that information which appears on a display of good technical quality must itself be of good technical quality. This need not be so. Many current and projected air traffic control displays give no indication of the accuracy of the information on them, of the extent to which it should be trusted, or of what a display failure would look like. A current mismatch is the absence of information about how the system can fail and how a failure can be circumvented.

Displays which present a full representation of the task which the man is doing may lead him to attempt to do the task according to the representation alone rather than according to what it actually represents: for example, he may keep blips or labels on a display apart rather than aircraft in the sky separated. His mental picture may not be of aircraft at all. This kind of consequence for the man of changes in information portrayal undertaken for other reasons is not always appreciated: its effects remain largely unknown in terms of safety and the provision of a good air traffic control service. The controller himself can become somewhat uneasy as more and more equipment seems to intervene between him and the aircraft for which he is responsible.

There is some current concern with the effects of the system on the man and with the kinds of mismatch which can take that form. Symptoms of stress in the man can be construed in this way and often have been. It is contended that the responsibilities which the controller carries, and the circumstances under which he has to work can, particularly if associated with overloading, lead to occupational health problems and long-term impairment of well-being. Evidence on this point varies from country to country, but is never strong[97]. Concentration on the problem of stress has perhaps unfortunately overshadowed greater long-term problems. The trends of giving the man less to do and of using automation more in air traffic control will gradually remove overloading, or may do so as a form of stress, at the cost of aggravating the problem of boredom[98]. In many practical contexts, underloading is as serious a problem as overloading, but does not attract as much attention. Many air traffic control facilities have to be manned for long hours when there is little or no work to do. Aircraft accidents and incidents are not associated exclusively with overloading, and underloading is no guarantee of safety. There may be an optimum loading in terms of efficiency and safety, or there may not be a single optimum in the sense that the desirable state is to require the man to continue gradually to learn and to adapt without ever seriously overloading him. The optimum is then dynamic and changing. This kind of matching between man and machine, and particularly the need to help the machine to be more adaptive to the man, has not yet been seriously studied but offers promise for the future.

A further source of mismatches in the past has been the natural tendency to automate what could be automated and to leave manual what had to be left. As a result manual functions were not allocated to the man because he was good at doing them but because a machine could not do them at all or could not do them well. Nevertheless he was expected to do them. A further extension of mismatching concerns the fact that functions like decision making and problem solving change a great deal when automated though nominally they may remain unchanged. Aids to flow sequencing, to conflict resolution, and to other functions may take the form of a computed solution which the man has to accept or reject, with an incomplete understanding of the basis of the computation. This is not like the human decision making which it has replaced. A mismatch occurs if the machine solves the problem, and the man does not understand the solution but retains the responsibility for its safety.

Man is a poor monitor compared with most machines. He is not particularly good at marshalling and manipulating resources, although this sort of managerial and supervisory role is seen as his in future air traffic control systems. Certainly it seems to require a fuller understanding of the detailed capabilities of the resources at his command than current proposals envisage he will possess. Efforts are persistently made to ensure continuous attention even when there is nothing to attend to. The maintenance of continuous attention seems to have become an end in itself and there is a reluctance to concede that it is unattainable. The safety and efficiency of the system may presume that attention can be maintained when the practical point is that the system must remain safe even when attention is not maintained. This is a very serious mismatching between system and human capabilities. Traditionally the strengths of man include his ability to innovate and be flexible. The wherewithal to enable him to be flexible in a progressively more automated system is difficult to provide. If he cannot in fact be flexible, either there is no sensible role left for him or means to be innovative must be restored.

A further source of mismatches concerns the fact that air traffic control is a team activity. Forms of computer assistance suitable for teams rather than individual controllers are slow to appear. The tendency is for each man to become more autonomous. This has numerous implications for job interest, satisfaction, the development of professional norms and standards, and collaborative effort. It is noticeable already that in evaluations of designs for future systems team work sometimes breaks down as the system becomes progressively more loaded, so that tasks which are done collaboratively by a team under light or medium traffic loading tend to become fragmented into individual tasks under heavy loading, and each individual team member becomes too busy with his own tasks to keep his knowledge of his colleagues' activities up-to-date[99]. The team no longer functions satisfactorily as such: automated aids tend to promote this effect whether it is planned for or not.

There is a tendency sometimes to make human functions too easy. This takes insufficient account of the needs for man to develop and use skills. A further problem is the importance of the controller's attitudes, preferences and prejudices in his willingness to use the equipment with which he is provided and to gain an understanding of how to use it to best advantage. Comparatively little is known about the attributes of equipment and workspaces which engender favourable attitudes towards them. Considering the amount of effort which goes into marketing commercial products, astonishingly little effort has gone into marketing innovations in air traffic control.

In principle, automation helps the controller to perform his tasks and can reduce routine, although in practice it may increase routine. It can provide assistance to make predictions, to solve problems, and to reach decisions but this assistance may actually take the form of predictions made, problems solved and decisions taken. It can increase the data handling capacity of the system but is much less successful at improving the information processing capacity of the man. It can extend the available time scale so that air traffic control becomes strategic rather than tactical but this advantage may be negated if there is no clear indication of the reduction in the reliability of information as its time scale increases.

In theory at least automation can allow greater control over workload so that the man could resort to manual methods when lightly loaded and have genuine computer assistance when heavily loaded. His ability to make use of such a tool is not known and it does lend itslef to misuse. He might have to learn how to use it to best advantage and not to reserve for himself all the problems which he found interesting. In principle automation can probably reduce stress as a source of mismatches, but this benefit might not materialise in practice. The complexity of potential mismatches between man and machine in air traffic control is often underestimated. A full understanding of the needs of air traffic control, of the desirable operational standards, of human limitations and abilities, and of the full implications for the man of equipment provided and equipment changes proposed, needs to be gained before automated aids can be provided without mismatches. The sources of mismatches between man and machine have often inadvertently been chosen when the equipment and facilities have been selected. In relating to a machine, man can find it hard to accept that a machine does not forget, a machine does not understand but abides by the rules, and a machine knows absolutely nothing at all about what it does not know.

# CHAPTER 6

# JOBS AND TASKS IN AIR TRAFFIC CONTROL

## 6a THE DESCRIPTION AND ALLOCATION OF JOBS

Although the distinctions drawn between jobs and tasks are not always consistent in the literature, in general a job is a much broader and comprehensive concept. The typical job consists of many tasks. It is necessary, in describing jobs in air traffic control and relating them to selection and training requirements, to examine both the common characteristics of various jobs and the ways in which they differ. The description of each job therefore has to be sufficiently detailed to enable this to be done. Job descriptions show how jobs change as systems evolve. Some changes are progressive; an example is the information presented on air traffic control radar displays and its method of depiction, which have evolved with technological progress. Other changes are sudden; an example concerns the contemplated removal of the traditional jobs of the supervisor and the assistant in air traffic control with drastic recasting of the divisions of responsibility among the remaining controllers.

The compilation of a job description is a skilled activity which requires a comprehensive knowledge of human factors and an understanding of the job. It is essentially therefore a collaborative venture. Although the human factors specialist can draft the job description, he must verify it, or aspects of it, with controllers, with those concerned with selection and training, and in the case of future rather than current jobs with system designers and planners. A job description should not be compiled by controllers alone for it requires human factors knowledge they are unlikely to possess. A hallmark of a good air traffic control job description is that it is couched in a broadly similar framework to descriptions of jobs outside air traffic control, with comparable terms and concepts and an equivalent level of detail. This allows characteristics of air traffic control jobs which are unique to air traffic control to be distinguished from those which recur in comparable jobs in other large man-machine systems. Such information can provide a useful perspective for air traffic control selection, training and job design, but this would be lost if job descriptions were too parochial.

A job description covers every task which forms part of the job, but does not analyse any task in fine detail. It indicates the relative importance and prevalence of various tasks. It includes the responsibilities of the man, the initiatives he has to take, the extent to which he is autonomous, his relationships to others if he is a member of a team, and required facilities, skills and attributes. A job description should be expressed in relatively non-technical language, since it must eschew jargon which would be incomprehensible to others. Although in air traffic control it is possible to describe each job exclusively in air traffic control terms, this limits the usefulness of the job description and it has greater significance and value if it is expressed in other concepts, usually man-machine system terms, or psychological terms, or both. The specification of every action by the man is a matter for task analysis rather than job description.

The notion of a job carries different implications in different contexts and there are therefore ambiguities associated with it. In some contexts, such as job satisfaction, the meaning of the concept approximates to the total work that one man does, treated as a whole and personal to him, so that his attitudes towards it can be measured. In other contexts, a job may refer to a group of work positions within one organisation, so that many people may be employed in the same job but not people in different organisations[100]. In still other contexts, a job does not have the continuity implied by the above notions of it, but is a coherent structured set of activities with a definable product or objective, with a definite beginning and end, so that an individual, singly or as a team member, can complete one job and start another.

A thorough job description should detect some differences among jobs which are normally treated as equivalent. A successful job description should ensure that each job which has a distinct name or title can be differentiated clearly from every other job not so named. This sounds straightforward but is not: it implies that the job description can reveal exactly what jobs performed in different locations but with the same title have in common. The selection, training and allocation of controllers to jobs may depend primarily on the location of the jobs if this is the source of greatest commonality in the job descriptions, or on the title of the job if the job is thought to be substantially the same wherever it is done. The difference is between job descriptions of terminal area controllers at, for example, Kennedy, Heathrow or Frankfurt, where the job is described primarily by location, and the job descriptions of controllers as sector supervisors, oceanic controllers, or area radar instructors, for example, where jobs are classified by the nature of their responsibilities rather than by where they are done.

Job descriptions provide a logic for categorising air traffic control jobs by showing what they have in common and how they differ. Job categorisation is complex - a terminal area controller in a remote tower with few aids and little traffic has a very different job from his colleague, who uses many facilities to deal with dense and varied traffic near a busy international airport, but is also called a terminal area controller. Job descriptions bring out these differences and similarities which are used both to categorise jobs and to select, train and allocate controllers to jobs.

Job descriptions must be objective and impartial. The process of obtaining them must be as passive as possible and in no way interfere with or influence the conduct of the jobs themselves. This becomes particularly important if job descriptions are used as a basis to define the desirable skills and responsibilities of each job in order to negotiate appropriate gradings, pay and conditions of employment. Job descriptions are also employed in the design of air traffic control systems, in research and evaluation, in choosing appropriate equipment and facilities, in the definition of skills and selection procedures, to provide a framework for training, in the allocation of controllers to jobs, in the examination of proposed system changes and their consequences, and in task analysis.

## 6b TASK ANALYSIS AND TASK SYNTHESIS

These two concepts are not always separated, but a distinction between them can be useful. The products of a task analysis and a task synthesis are similar, but the means of achieving each are different. The distinction is as follows: a task analysis refers to a task which exists, and the methods of task analysis therefore involve descriptions and classifications based, at least in part, on observations and measurements of how those who are skilled and experienced in the task actually perform it; a task synthesis refers to a task which does not yet exist but is being proposed or planned, and the methods of task synthesis therefore involve descriptions and classifications based primarily on deductions about what the task will be like, and what skills and experience will be needed to perform it. In this sense, a task analysis is factual, and a task synthesis hypothetical or speculative. Much of the literature on task analysis fails to draw this important distinction.

One purpose of task analysis is to provide a basis for stating what task changes would result from a proposed system change, and for tracing the consequences of these task changes. Evaluations, which often rely on simulation, are concerned mainly with the practicality, efficiency and safety of the proposed system. Some form of task synthesis is a necessary part of the detailed planning of the evaluations, particularly with reference to the facilities which must be installed at each simulated operating position. Proposed changes may also alter controllers' attitudes. A detailed task analysis of the comparable roles in existing systems is a necessary precursor of the successful definition of the attitude changes which proposed system changes may bring, particularly if the concern is not with the attitudes to the whole job but selectively with attitudes to particular functions[101]. Some tasks or actions may be changed or removed with impunity as far as the controllers' attitudes are concerned, whereas other tasks or actions may lead to marked changes in attitude, favourable or unfavourable, if they are tampered with at all.

There is no single optimum level of detail for a task analysis or task synthesis; the best level of detail depends entirely on the objectives. Successful task analysis or synthesis represents a great deal of work; because each additional level of detail adds a lot more work, it is desirable not to examine tasks at a more detailed level than will suffice for the purpose. Two further factors in addition to level of detail have a major influence on the task analysis or synthesis. One is the flexibility of the task. Is there one agreed best way of performing it? Is the whole task always the same? Can parts of the task be omitted, be added, be repeated, be done out of sequence, or be done in different ways? Many air traffic control tasks are complex in this respect. No single solution to an air traffic control problem may gain universal acceptance as the best possible. The second factor is the language used to describe the task. This also varies with the objectives. The task and its sub-tasks may be described in behavioural terms (detect aircraft on potential collision courses, decide if action is necessary, assess consequences of proposed action, etc); or in system performance terms (the successful maintenance of safe separation between two converging aircraft, the measured minimum separation between them, etc); or in equipment terms (the appearance of a flashing symbol on a display, the acknowledgement of this symbol by the depression of the appropriate key, etc).

A recent task analysis handbook prepared primarily for training purposes[102] provides guidelines for partitioning tasks into sub-tasks, and for defining the required supporting skills and knowledge. Normally both these stages form part of the task analysis or synthesis. Tasks and sub-tasks deal with actions, which include some overt behaviour which can be defined, measured and timed, and activities, which may also include cognitive functions essential to the task but with no discernible behavioural counterpart. In task analysis or synthesis, every action and activity which the task requires is [illegible] usually in their standard chronological order if there is one. Task analysis, based as it is on [illegible]vation and measurement, also involves some deductions on the information which must have been co[illegible] judgements which must have been made, solutions to problems which must have been evolved and deci[illegible] which must have been taken before the observed actions could occur. These deduced items are included in the listing; in analysis, but not in synthesis, they can be confirmed subjectively by those who perform the task. Measures of behaviour and actions provide the frame of reference for the task analysis and a sequence for the listing, into which the more deductive activities can be fitted. The task analysis may also include a broad categorisation of the relative frequency and importance of various tasks and sub-tasks, but this is not essential and depends on the objective. If the purpose is to verify that all necessary equipment is provided then the relative importance of various items of equipment may only be significant in relation to its layout rather than to its presence. However, if the purpose is concerned with the incidence of errors and the achievable levels of performance of the task, then information on the relative frequency and importance of various sub-tasks is essential. A task analysis may allow all the possible sources of error during task performance to be defined, but may not include any evidence at all about the performance achieved, the errors which actually occur, or their relative prevalence.

Although the frame of reference for the task analysis consists of overt actions and events, there is never sufficient evidence of this kind for a task analysis except for the simplest of manual tasks. Descriptions of the operator's actions must be obtained passively without interfering with the actions themselves. Methods include time and event recording, photographs, films, videotapes and other visual records which can be categorised, sequential timed descriptions by one or more trained observers, flow diagrams, and critical incident techniques. With varying degrees of success, these methods in principle can be followed without direct interference with the task. Other techniques such as eye movement recording, which may involve some instrumentation of the controller, may yield data which contributes usefully to the task analysis, but they are less obviously passive as techniques.

The descriptions of actions in a task analysis or synthesis may have little explanatory value. There may be a record of where the man looked and of what he did, but no precise indication of exactly what he looked at and why, of his reasons for his actions, or of what he believed he was doing. Therefore, for complex tasks such as those in air traffic control, the bald description of events has to be complemented by an informed explanatory account of the associated cognitive processes. This relies heavily on the skill and judgement of the task analyst.

A task synthesis may be compiled to reveal what information a man must have to fulfil a particular role. Practical considerations of cost and technical resources may then be used to evaluate the task synthesis, which would not normally contain such factors directly. The synthesis may challenge the feasibility of a proposed operational task by revealing that certain information which cannot be provided is nevertheless indispensable, or by showing that sub-tasks beyond human capabilities are inherent in the proposal.

In task synthesis there may be far more options to consider than in task analysis, regarding the performance of the task by man or machine and the required level of task performance. Task analysis may dwell much more on the tasks which would be required to meet system objectives, with the implied sub-tasks, facilities, knowledge and skills, and with the assessment of the feasibility of attaining the objectives. Task synthesis may also be concerned with alternative tasks consequent upon various possible degrees of automated assistance. As with task analysis, the framework is of actions, albeit hypothetical ones, complemented by the deduced cognitive processes required. In synthesis even more than in analysis, the judgement of the task analyst is critical.

Task analysis and synthesis, though of great value for many purposes, have their limitations. A whole task is never the same as the sum of its parts. The product of analysis or synthesis is essentially the sum of the parts of a task.

The final phase of task analysis or synthesis is the derivation from the task descriptions of the skills and knowledge on which successful task performance will depend or which would appear relevant enough to enhance performance if they were present. Descriptions of air traffic control skills have generally been rudimentary[103]. They can be couched in general psychological terms or in specific air traffic control terms. A better taxonomy of skills is needed, but a general one for all air traffic control in all contexts is not feasible - the differences between jobs are too great - and therefore it must be specific to the task analysis or synthesis. The rudimentary listing of skills mentioned above[103] has nevertheless been sufficient to demonstrate that the main differences between air traffic control and other skills lie in the central processing of information rather than its input to or output from the system, and that the diversity of these central processing skills in air traffic control tends to vitiate any taxonomy of them[104].

There are opportunities for error in task analysis which do not arise in task synthesis. Task analysis involves the description of the actions of fully proficient and experienced controllers in current practice. Although the process of measurement should be as passive as possible, the mere knowledge that measures are being taken for a task analysis is enough to introduce certain changes. Controllers want to be seen at their best and to appear efficient. They will not be idle even when there is nothing for them to do. They will follow procedures punctiliously and avoid unorthodox ones. Normal social chatter will be curtailed, irrelevant remarks reduced, language moderated, and uncomplimentary and derogatory asides self-censored. Equipment serviceability will be minimised, with faults reported when they might otherwise be tolerated, and remedied as a matter of urgency when urgency is not needed. A task analysis can thus be biased to portray an unrealistically slick and smoothly functioning system.

Task synthesis is in principle more comprehensive and objective than task analysis, since it is not limited by the constraints of actual tasks and can contemplate extensions to tasks beyond any which have previously been adopted. Traditional practices and constraints have a less strong and less restrictive influence on task synthesis but are an inherent part of task analysis. A recent trend towards the evolution of future tasks by feasibility studies, in which the participating controllers suggest changes which are then implemented and commented on in their turn, provides a different and more flexible approach to task synthesis and integrates it more closely with the partitioning, allocation and grouping of tasks, sub-tasks and responsibilities.

## 6c GROUPING OF TASKS

The task analysis or synthesis produces a list of tasks and sub-tasks at a level of detail suited to its objective. One objective, associated in particular with major system changes or with the introduction of a new air traffic control system, is to verify that every envisaged function for the man would be within the capabilities of a trained operator, and then to group tasks. Numerous criteria may facilitate the successful grouping of tasks:

(1) Tasks which share common requirements for skills and knowledge should be considered as potentially suitable for performance by the same individual.

(2) Tasks which have requirements so disparate that they are unlikely to be found in a single individual should be assigned to different people.

(3) Tasks which form a coherent progressive sequence, and sub-tasks which follow a single sequence, can be assigned to the same person, and may minimise duplication of effort and unnecessary communications if they are.

(4) Tasks which must be fulfilled concurrently must be integrated so that they can be done together, separated and allocated to different individuals or teams, or done sequentially where delays in their performance can be tolerated.

(5) Tasks suitable for individuals must be clearly distinguished from those to be performed by teams.

(6) Tasks which use common facilities in different ways for different purposes at the same time must be clearly separated if the performance of any one of the tasks would be liable to interfere with the effective performance of any of the others.

(7) Tasks which vary greatly in complexity, required knowledge and experience, status, and responsibilities may not be suitable for allocation to the same individual since they would pose problems of the definition of grading, status and responsibilities, and of selection and training.

(8) Tasks should be grouped to facilitate the definition of responsibilities, jobs, and selection and training requirements.

(9) Task groupings should take account of traditional practices, divisions of responsibility, and skills, which should not be discarded without good reason.

(10) Tasks should be grouped so that each individual or team is sufficiently autonomous to make progress in performance of their own tasks without having to wait for others to perform theirs.

(11) Tasks should be grouped to minimise gross differences in workload between individuals and between different times for the same individual. The capacity of the whole system must not be seriously reduced because the distribution of tasks and sub-tasks incurs overloading of one or a few controllers long before any others are becoming overloaded.

(12) Tasks should be grouped to avoid wasteful duplication of facilities and functions: for example, two controllers should not both be trying to contact the same pilot for different purposes at the same time.

(13) Tasks should be grouped to take some account of envisaged future developments and system changes so that they can be reconciled with each grouping. This probably entails that proposed changes should have clearly defined implications for a limited number of tasks rather than scattered and apparently arbitrary ramifications for many.

(14) Tasks should be grouped so that the tasks and functions of each grouping can be reconciled with revised groupings wherever this is required. In particular task groupings must be compatible with envisaged responsibilities. This applies in particular to the continued feasibility of teamwork, to the future roles of supervisors and assistants, and to the amalgamation and splitting of tasks to accommodate gross changes in workload and task demands.

Ideally, in task grouping, much emphasis is placed on the commonality of the desirable human attributes for the successful performance of the various tasks assigned to the same individual. In principle this commonality is a laudible aim if it can be achieved. In practice, however, it can become a counsel of perfection, far removed from the realities of task and sub-task groupings. In air traffic control tasks, two other considerations are often of greater importance: one is the allocation of tasks to equate workload across individuals as much as possible and to achieve flexibility of workload, in order to maximise the traffic handling capacity of the whole system; the other is the apparently negative requirement to avoid the allocation to the same person of tasks and sub-tasks which seem to demand conflicting human capabilities, instructions or attributes.

The charge that some of these requirements for task grouping seem too obvious to be worth stating is countered by the fact that in the past even these obvious requirements have often not been met. The roles of supervision, assistance, teamwork and safe controlling in progressively automated systems depend greatly on the way that tasks and sub-tasks are grouped. The smooth functioning of the system implies that controllers do not normally get in each others' way. The divisions of responsibilities must be clear so that vital functions are not omitted because everyone thought they were being fulfilled by someone else. A task which consists substantially of routine data entry and another task which requires complex decision making and prompt and decisive action require attributes and qualities of temperament so different that to seek them in the same individual seems over-optimistic. Yet in air traffic control they are regularly sought in the same individual.

## 6d INTERACTIONS BETWEEN TASKS

Interactions between tasks are of three main types:

(1) Interactions between tasks which are the responsibility of a single controller, and which must be done at about the same time, consecutively or by sharing his effort between them.

(2) Interactions between tasks allocated to or shared by different controllers in the same workspace, for which different selectively retrieved information or different facilities may be appropriate.

(3) Interactions between tasks done at different times or different positions in the system, where the concurrent independent performance of a task by one controller influences the tasks of others through the system design and facilities, or where a current task is influenced by, and dependent on, the performance of a previous one by the same or another controller.

Interactions of the first type have to be resolved by a combination of job descriptions, task allocation and grouping, and system design. An examination of the interacting tasks in the light of basic knowledge of human cognitive capabilities and limitations will reveal which tasks can be reconciled and done concurrently (for example, because an experienced controller can do one without attending to it), which must be separated altogether because they would interfere with each other too much (for example, because they both demand full attention or require different selections of information which cannot all be present at once), and which might be shared (for example, because each is a part-time task and both need similar data). The level of attainable performance will depend in part on whether the controller's time-sharing ability[84] has had any influence on his selection and training. It is important in considering interacting tasks of this type to identify the kinds of error which might occur because of mutual interference between them, and to ensure that such errors could not become dangerous.

Interactions of the second type are primarily a matter of workspace and system design, and of decisions on whether tasks should be autonomous or dependent on each other. Tasks to be performed by a team must be designed from the outset to foster this aim. The allocation and positioning of facilities at the workspace determines which functions can be shared or done collaboratively, which must be the prerogative of a particular team member, and which could be allocated to another team member. The extent to which facilities are replicated and duplicated also influences this second type of interaction between tasks. The guiding principle must be that each controller should be able to perform all his tasks without seriously disrupting any other controller in the performance of his tasks. It must not be possible, while one controller is using a display to perform one of his own tasks, for another controller, without previous warning, consultation or agreement, deliberately or inadvertently to change the content of that display as a legitimate part of one of his tasks, in any way which interferes with the performance of the task already being done. If, to perform his own task, a controller needs to know what a colleague is doing, he must be able to determine this readily without disrupting his colleague's actions. Either he can watch his colleague and the information he is using or he can call down at his own work position the relevant information about his colleague's actions. A common fault, as task loading increases, is for the tasks of each controller to interact less with those of his fellow team members, because he has insufficient time to note their actions, with the result that the team tends to break down under high workload, and the interactions between tasks, envisaged in the system design, no longer take place.

Interactions of the third type are primarily a matter of system design, and the provision of appropriate facilities at each operating position. In the case of tasks at the same position, the system must provide appropriate information on the relevant tasks already done and on what they have achieved, in a form which is intelligible, appears at the appropriate time, and can be remembered. For tasks done at other positions, the system must display to the controller that they have been accomplished, and their import for him. One of the commonest interactions between tasks in air traffic control concerns the sequential control of an aircraft by different controllers as it taxies, departs, climbs, cruises en route, descends, approaches, lands and taxies again. For each control task, information about the actions of previous controllers is relevant. Much planning of the control of air traffic is done using information about pending traffic, which is actually under the control of someone else. Interactions between these tasks are therefore an intrinsic aspect of air traffic control. Interactions must be studied with particular concern for the kinds of error which can arise with inadequate foreknowledge of other tasks and for any ambiguities which can occur during the handover of aircraft between controllers.

## 6e WORKLOAD

The concept of workload is very broad [105]; in air traffic control, it almost invariably refers to mental rather than physical workload. Almost the whole of the recent extensive literature on workload has dealt with mental workload. Confusion arises because system planners and designers often interpret workload as the load which the system imposes on the man in the form of task demands. They therefore expect workload to be described in terms of the functions assigned to each man which he must perform to a required standard in a given time to meet the system objectives. If workload is equated with task demands, it may be described in system rather than human terms, and, being imposed by the system, it would not differ according to the operator who happened to be present. This notion of workload is straightforward, quantifiable, and relatively easy to describe. Unfortunately it does not correspond with the human factors concept of mental workload in real life tasks.

Mental workload, being a priori mental, is an attribute of the individual man and his responses to task demands. It therefore varies not only with the task demands themselves, but with individual attributes of the person performing the task. The same task demands impose very different mental workload on the novice and on the experienced controller. An air traffic control task presented to someone with no knowledge of air traffic control would be impossible for him to perform. The same task presented to a trainee controller during the early stages of his training might elicit an inadequate performance with very high workload and maximum effort. Nevertheless the self-same task presented to a fully proficient controller in current practice might impose little workload, and seem simple, undemanding and even boring.

These gross differences depend little on the particular nature of the task demands; they are primarily a matter of knowledge, experience, skill, and training. Therefore the adequate measurement of the workload of the individual controller entails some means of allowing for these individual factors, either by the direct assessment of them, or by indirect means of assessment whereby system characteristics, task demands, individual responses and actions, and individual effort can be quantified. Small wonder that efforts to quantify the workload of the controller have hitherto been largely unsuccessful except within very limited objectives. The individual controller's judgement on whether his mental workload is tolerable and acceptable also depends on professional traditions, pride, norms and standards, which influence the effort that the controller himself is prepared to make, and expects his colleagues to make, in order to cope with high task demands.

The study of mental workload is a live issue at the present time. It was chosen as the theme for the first attempt to develop an electronic journal using an electronic network, although the actual contributions of this venture to the furtherance of the understanding of mental workload were relatively few [106]. The prospects for the successful quantification and measurement of mental workload in real life contexts seem to be receding rather than advancing, for several reasons. The idea that the concept of mental workload corresponds with any coherent measurable entity can no longer be taken for granted. The notion that in some sense the mental capacity of an individual is a fixed quantity which can be partitioned and manipulated seems dubious. Man may be a serial or a parallel processor of information, depending on tasks and circumstances: therefore the idea of a fixed mental loading capacity cannot be sustained. When tasks are partitioned, the whole is not equal to the sum of the parts, because the processes of partitioning, manipulation and summation themselves influence workload. Although psychological theories do not seem very helpful for solving practical workload problems, at least the reasons for this are now becoming clearer.

Since mental workload depends so much on the frame of reference which the individual brings to the task, in the form of what he already knows and can do, it is not surprising if laboratory tasks, the frame of reference for which depends on instructions and training which can be mastered in a few minutes, do not produce findings on workload which can be extrapolated to real life tasks in air traffic control, the frame of reference for which depends on instructions and training which may last for months or years and not even be mastered then. Serious attempts have been made to bridge this gulf between laboratory and real life in the study of mental workload[49], but in some respects from the applied side the gulf still looks unbridgeable. In the meantime, any single measure which purports to be an adequate representation of mental workload should be shunned as highly suspect. There is fairly general agreement that a multiplicity of measures is needed for progress in the measurement of mental workload, and that even these cannot guarantee success[49,107].

The members of a group of experienced air traffic controllers doing the same air traffic control job are not likely to differ greatly in the mental workload which the same task demands would impose on them. The practical concern with individual differences in mental workload in air traffic control therefore relates more to selection and training and to differences between tasks than to differences between fully proficient people. Hence it is feasible to consider that one controller might be able to make some assessments of the workload of another provided that the validity of this procedure was verified. The problem in specifying mental workload refers less to controller differences than to the very large effects on mental workload of professional expertise. Without expertise, a task may be impossible; with it the same task may be easy. This expertise takes many forms, few of which are observable or measurable directly in mental workload terms while the task performance is in progress. Deductions may be made from the controller's actions that he must have known the correct procedures and implemented them efficiently at about the optimum time. The extent to which he understood and allowed for all the possible consequences of each decision is much more difficult to ascertain but is the kind of factor that any successful study of the controller's mental workload has got to take into account. Relatively small differences in what he knows or in what he can recall successfully may have major consequences for the controller's mental workload.

Measures of workload have become complex enough to justify an AGARDograph devoted to them[5], in which much of the relevant American work on the assessment of air traffic control workload was surveyed in three papers[108,109,110]. The proliferation of techniques for mental workload assessment is exemplified by a recent classification using thirty-five separate techniques[111], under the headings of subjective opinion, spare mental capacity, primary task, and physiological measures. Misgivings have been expressed on the validity of air traffic control workload measurement under simulated air traffic control conditions[112]. Most general studies of workload have sought to assess high workload but have failed to address the practical problems of workload which is too high or too low, in the sense that steps must be taken to adjust it. If workload is too high or too low, task performance may not be optimum and measures may show this; but of much greater practical significance than the general level of task performance as a consequence of inappropriate workload may be occasional instances of actions which are dangerous. Measures of the nature of errors in high or low workload, as distinct from the incidence of errors, are quite uncommon. Analysis of reports of aircraft accidents and incidents suggests that their prevalence does not depend much on workload, but this is an impression: its scientific proof would require the derivation of very sophisticated and subtle criteria to establish what would be expected by chance and how this would compare with what is observed to occur. At the present time the concept of workload seems liable to become debased by excessive and uncritical usage, a fate shared by the concepts of fatigue and stress[5].

Nevertheless, somehow mental workload should influence task analysis and task synthesis, the grouping of tasks and the study of the interactions between them. In practical terms, the performance of the air traffic controller must not be degraded unacceptably because he has too much to do; he must not continuously have to make great efforts to cope with his tasks; excessive task demands must not be allowed to impair human well-being; unavoidable haste and pressure from tasks must not lead to dangerous irrecoverable errors. Such considerations do influence the construction of tasks, the divisions of tasks and the traffic loading of tasks. Perhaps it is possible to continue to make practical progress without being able to define or measure mental workload in any precise way. Certainly it is not practicable to shelve the problem of mental workload assessment until definitive measures of workload have been derived, since there is no real sign that such measures are in the offing.

In Moray's text[49], workload is discussed in relation to experimental psychology, control engineering, mathematical models, physiological psychology, and applications. Gartner and Murphy[113] distinguish between workload as task demands, workload as effort, and workload as activity or accomplishment. The concepts of performance, workload and stress have not always been carefully distinguished and sometimes the same measures are apparently related to these different concepts without an adequate explanation of how this is possible[114]. Psychologists should persevere in their attempts to adduce more satisfatory measures of mental workload since success would bring real benefits. For example measures of mental workload could then be used to assess what the controller's experience, knowledge and skills ought to be, and hence to aid the specification of the form and content of selection and training. However, it now seems probable that any assessment of the controller's mental workload which is comprehensive enough to be of practical use must take account of what he knows as well as of what he does.

# CHAPTER 7

## THE WORK ENVIRONMENT

### 7a PRINCIPLES OF WORKSPACE DESIGN

In air traffic control, the workspace is purpose-built, that is designed exclusively for air traffic control tasks and conditions. The process of workspace design is a collaborative interdisciplinary effort between system planners and designers, technical experts in engineering, communications, system hardware and system software, and human factors and occupational health specialists. It should also involve controllers. Directly or indirectly, constraints on the design are introduced from numerous further sources, including finance, architecture, and heating and lighting engineering, and these too influence workspace design.

The role of human factors is to ensure that all the human factors implications for workspace design of the system objectives, the job descriptions, and the design and grouping of tasks, are recognised, and that the workspace design, evolved through interdisciplinary collaboration, takes sufficient account of human factors requirements to enable all the envisaged roles and functions of the man to be fulfilled at operationally acceptable levels of efficiency and safety, preferably under conditions which are as near optimum as can reasonably be achieved. The requirements of air traffic control in relation to workspace are generally so numerous, so complex and so diverse as to preclude any workspace specification which would be ideal in human factors terms. Generally, there are too many different tasks to be done, too much equipment and too many facilities to be fitted in, and too much envisaged flexibility of manning levels, to permit a workspace specification which is optimum for all circumstances, or even optimum in any circumstances. The emphasis is to strike the best compromise in workspace design so that no functions ever become very difficult or impossible, and most can be done very well. A fundamental practical question is whether to design the best workspace possible for standard operating conditions in the knowledge that it may be far from optimum in non-standard conditions, or to depart further from the ideal under standard conditions to accommodate unusual operational conditions more adequately.

Workspace design is influenced by, and may have some influence on:

(1) The tasks and the equipment needed to perform them.

(2) The physical environment within which the tasks are done.

(3) Manning levels, including requirements for task splitting or amalgamation, for supervision or assistance, and for on-the-job training.

(4) Conditions of service, especially rostering and off-watch facilities.

Workspace design presumes that much of the detailed planning and task analysis has already been completed. There are three distinct levels of detail in workspace design, progressing from the general to the particular, and these must be tackled in order, retaining some flexibility to allow for interactions between levels. The three levels of detail are:

(1) The general working environment.

(2) The workspace of the individual operator.

(3) The detailed specification, layout and location of each equipment item within each individual workspace.

Objectives of workspace design which have some influence on its processes include the following:

(1) To promote the achievement of the highest possible standards of operational efficiency by ensuring that the design of the workspace introduces no avoidable constraints on performance, accuracy or rate of work.

(2) To ensure that the workspace design is compatible with the design aims of the system, in relation to the division of tasks, the allocation of responsibilities, and the balance between teamwork and individual autonomy.

(3) To ensure that the workspace can accommodate all the envisaged manning levels satisfactorily, including the splitting or amalgamation (bandboxing) of positions, and can permit all further roles, associated with or ancillary to air traffic control itself, to be fulfilled, such as supervision, assistance, and on-the-job training and instruction if applicable.

(4) To permit the safe, smooth and efficient allocation and transfer of control responsibilities, and effective liaison, co-ordination and communications on the ground and between air and ground.

(5) To ensure that each individual has ready access to all the information he needs about the state of the system, and about the activities and progress of his colleagues.

(6) To ensure that all the items required for tasks are present, easily visible, and laid out logically to encourage efficient flowing physical movements and task progressions.

(7) To ensure that the layout of equipment, facilities and displays reflects their importance and frequency of use, and helps to show how the tasks are structured.

(8) To ensure that each item of equipment is placed in its optimum position, that the direction and magnitude of the forces required to activate it are within recommended limits, and that the type and sensitivity of controls are appropriate for the functions to be performed with them.

(9) To minimise potential errors, omissions and ambiguities by identifying those which could be engendered by aspects of workspace design, in conjunction with task designs.

(10) To prevent aspects of the physical environment and workspace from becoming obtrusive or a distraction to any of the people who are working there.

(11) To ensure that the workspace promotes effective training and learning of tasks, provides for each operator sufficient knowledge of the system for him to understand his role and functions correctly, and gives him sufficient information on the consequences of its actions for him to achieve optimum performance.

(12) To ensure that physical environmental factors, such as noise and acoustic properties, heating and ventilation, ambient lighting, glare and reflections, and surfaces, paints and colour schemes, etc, cannot degrade performance or efficiency or have adverse effects on well-being.

(13) To prevent any injury or physical strain on the operator, and to verify that the physical work environment cannot be the source of any occupational health problem or hazard.

(14) To foster the interest, job satisfaction, morale and self-esteem of operators.

(15) To provide a work position which is comfortable for each operator, if necessary after suitable and easily made physical adjustments; comfort is equated with unobtrusiveness rather than luxury.

(16) To provide a physical environment which looks pleasant and is acceptable to all who work in it.

(17) To ensure that the physical layout of equipment is compatible with all ancillary functions such as maintenance of equipment, cleaning, demonstrations to visitors, accessibility for watch handovers, etc.

After jobs and tasks have been designed, the equipment needed for them has been deduced, and the allocation of responsibilities has been tentatively agreed, then the workspace can be designed, firstly in broad outline, and then in detail. Manning levels and accessibility requirements should have some influence on the size of buildings and of rooms. Job and task designs, and the allocation of functions to individuals and to teams, influence the grouping of individual workspaces into suites and consoles, and the positioning of these in relation to each other. The definition of facilities, especially display facilities, and the extent to which they are for individuals or shared, influences the need for general wall-mounted displays, and the desirable contents of them. Such displays may also be influenced by the need for each individual to relate his roles and functions to those of the system as a whole and to its current state, which a wall-mounted display may summarise. General summary displays may also be of use for briefing and for visitors. The number and location of general wall-mounted displays, the amount of information on them, and the methods for generating or projecting the data which they contain, all have a profound influence on the positions which suites can occupy in relation to them, on the general lighting of the room, on the problems of glares, glints, reflections and light scatter, and on the size and layout of the contents of the control room.

A problem encountered in workspace design concerns decisions on deceptively simple issues which are expressed in potentially misleading ways. An example may clarify this point. Some years ago, there was great debate among air traffic control planners on the respective merits of horizontally or vertically mounted displays in a suite, especially radar displays. In some quarters this is still a contentious subject. As an issue it seems simple and straightforward; the main benefits and drawbacks of horizontal and vertical displays can be listed. Horizontal displays may more readily be shared by a team, particularly for consultation, but are awkward to sit at, difficult to light from overhead, and discourage individual team members from acting autonomously. Vertical displays are more suitable for individuals but team members may have to communicate indirectly, for example by inter-console marking. Vertical displays are more comfortable to sit at and easier to fit into a general lighting environment. There are numerous further differences, including the positioning of controls in relation to the displays and to those who operate them. The point is that the choice of horizontal or vertical display will determine many of the communications which take place and the kinds of teamwork which can succeed. Therefore perhaps the communication problem should be solved first and the appropriate displays deduced. This means that the problem is not primarily one of displays at all. To be fair, this issue of horizontal or vertical displays has to some extent been overtaken by other events, including advances in automated communications and information transfer and the ergonomic and occupational health problems associated with some horizontal displays, but if the problem is solved solely as a display problem it can lead to difficulties in other aspects of the system and workspace design. It is difficult to seat a group of controllers in physical comfort round a horizontal display; it is perhaps comparably difficult for several controllers to share a single vertical display satisfactorily.

In air traffic control a change of responsibilities must take place smoothly and the transition must not lead to any disruption of the air traffic control service. Therefore at watch handover the workspace must temporarily accommodate both incoming and outgoing controllers, without mutual interference. Occasionally with very heavy traffic an incoming controller needs some time to learn enough about the traffic situation to take over the control of it. In extremely heavy traffic, the outgoing controller may be so busy that he has no time to explain to the incoming controller what he needs to know but is not evident, and handover has to be postponed until the traffic loading has eased. This is rare, because both controllers know when the watch handover is due and try to plan to allow it to take place. The point is that unless the workspace is designed to take such rare but vital circumstances into account, then lack of physical space may make a safe handover more difficult or impossible.

Such general points have to be settled in the workspace design before the details of the layout of each operating position can be settled. It is always possible that when each position is being laid out, no safe or efficient layout can be devised, and a revision of the task designs is called for, which entails changes in equipment and responsibilities and a re-examination of decisions about workspace layout at a more general level. Such problems usually occur because of attempts to pack too many facilities into too little space, and therefore can be foreseen. When the stage of laying out each position has been reached, handbook data can be used as a guide and as a basis of a checklist of relevant human factors, but specific handbook recommendations must never be applied uncritically in any air traffic control context without interpretation by experienced human factors specialists. For a variety of reasons, the figures cited in human factors handbooks generally have to be modified for air traffic control applications.

In the past, workspace design has often included physical models and mock-ups, life-size or at reduced scales, so that those concerned can envisage what the workspace would look like, and can comment on it and modify it before they are committed to build it[115,116]. These techniques will continue to be useful but can now be supplemented by computer models as a tool of workspace design. These models may take various forms: the physical and environmental constraints can be specified by computer programmes and the computer instructed to formulate one or more layouts which will satisfy all requirements, varying the relative importance of various factors. Computer graphics and drawing modes can be used to generate a visual impression of layouts, and to view these synthesised visual impressions from a variety of perspectives. Proposed changes can be examined by this means without the need to build any consoles. This method, potentially a valuable aid to planning and to the verification of workspace layout, is critically dependent on the correctness and comprehensiveness of the data fed into the computer and on the instructions to it. A crucial condition of its success is that no important factor has been forgotten.

## 7b THE PHYSICAL ENVIRONMENT

The main characteristics of the physical environment relevant to air traffic control are its thermal attributes, noise levels, radiation, and visual appearance, this last being a product of room size, lighting and the colours and textures of surfaces. For many of these characteristics, there are recommended national standards and tolerances. These must be adhered to whenever possible. Sometimes however, they have to be compromised, perhaps grossly, to overcome technological limitations: the need to compromise is less common now than in the past.

### The Thermal Environment

In dealing with the thermal environment in air traffic control, it is best to treat controllers as sedentary and as not making much physical effort, as distinct from mental effort, in the course of their work, although a few air traffic control personnel, notably supervisors and assistants, may not be sedentary for much of the time.

The recommended air temperature for reasonable comfort in an air traffic control environment is about 21°C, or at least within 2°C of this level in most European environments. In the United States, a figure of 24°C may be more readily equated with optimum comfort. Clothing is usually light, and shirt sleeves are common among air traffic control workers. Much air traffic control equipment generates considerable heat which must be ducted away and not become a major source of radiant heat for the air traffic control operator. If an air traffic control centre contains large windows in the work environment, it is usually necessary to draw blinds over them to prevent high temperatures and excessive light levels in direct sunlight. In air traffic control towers, although heat can be a problem, the various means to keep sound levels down often also reduce the effects of outside temperature on the interior.

The correct temperature will not ensure comfort unless the humidity is reasonable. A humidity figure of around 50% is usually appropriate, humidity being measured by comparing the percentage of moisture present in the air with the amount of moisture needed to saturate it. Although some departure from 50% humidity is tolerable, levels above 70% are usually interpreted as humid and stuffy and clothing starts to become uncomfortable, and low humidity levels can lead to dryness in the throat and perhaps coughing.

The third main determinant of thermal comfort at work is air movement. As a general rule, the air should move sufficiently to be just detectable at the workspace. Under reasonable temperature and humidity conditions this movement is around 10 metres per minute. Faster air movement may be tolerated, and even welcomed if the air is hot or humid, but can be interpreted as a draught, particularly if the air is cold. Slower movement may be preferred if the air is cold, but the aim should be to maintain temperature, humidity and rate of air movement at near optimum levels. Careful planning of air intakes, fans, and forced air movements is needed to take account of the position of each operator in relation to the room and especially in relation to the furniture which disrupts the air flow. Fans must not be a source of noise in the environment. If smoking is permitted, smoke should be ducted away.

### Noise Levels

These are important for the efficiency and safety of air traffic control. The noise environment in air traffic control is unusual. In many towers and local control centres, though not in the most modern air traffic control centres, it is possible to hear the noise from aircraft. The work environment has to be provided with sound insulation to ensure that aircraft noise does not interfere with the control of aircraft traffic. In some environments, such as temporary control cabins sited near the end of runways, the noise of departing and arriving aircraft may provide confirmation to the controller that an aircraft under his control which he cannot actually see has taken off or landed, but this is not a desirable way of organising air traffic control. Extraneous noise should very largely be excluded, though not necessarily to the extent that take offs cannot be heard at all.

Air traffic control relies heavily on speech, and that speech is of three distinct kinds - between controllers and pilots via R/T channels, between controllers and other controllers in the same environment by direct speech, and between controllers and a variety of others using telephone links. The controller therefore not only has to wear a headset through which he can hear messages; he may have to use a telephone without taking off his headset, and may have to hear what his colleague next to him is saying to him directly while also hearing what is said through the headset or a telephone. Castellated earmuffs, with or without covers, may maintain user comfort, and enable R/T messages to be heard without attenuating extraneous sounds and conversations too much. The problem of striking the correct balance between these three kinds of spoken messages is difficult enough to solve by trying to specify appropriate headsets and hearing conditions without aggravation of the problem because the controller has to contend with extraneous background noises as well. It is desirable in air traffic control environments to keep the background noise level down to about 60 db at most, and preferably not above 55 db, and to quell noise as much as possible. Air conditioning should not require noisy fans or ducting, nor should any installations within consoles and other air traffic control furniture, intended to remove the heat generated whenever equipment is switched on.

Some environmental noise is inevitable but much of it can be reduced. Sound absorbent plasters and wall coverings can make a large contribution. Acoustic tiles on ceilings, and if necessary on walls as well, can absorb much unwanted noise. Well hinged and properly maintained doors should not squeak, and compressed air attachments to doors should ensure that they close quietly. Much of the noise of movement can be deadened by suitable floor coverings. Good quality carpeting, preferably with an appropriate underlay, can absorb much of the sound from even the noisiest footwear. The opportunity should be taken, particularly in large control centres, to choose floor coverings which also impose a pleasant visual texture on the environment. Tufted carpeting or carpet tiles are preferable to plain carpeting for this purpose and the latter may be the only means to deaden sound on floors effectively in environments with false floors and removable panels for maintenance.

If noise le els are high, all speech must be louder: this in turn makes messages more difficult to hear, and speech has to be amplified more to be heard. Speech which cannot be amplified very much, for example over the telephone, may become difficult to hear unless it is spoken very loudly; this in turn leads to louder competing messages in the work environment. High noise levels therefore tend to be self-perpetuating, and they force louder and louder speech to maintain intelligibility. Auditory warnings or signals become unreliable or unusable. Messages are misheard more often and have to be repeated. Errors occur and misunderstandings arise. A noisy environment has no advantages. Everyone can be much quieter in an environment which is quiet to begin with.

Radiation

Radiation is not a hazard in air traffic control environments. Safety standards are clear and generally enforced, and the equipment currently marketed does not have emissions which approach hazardous levels, even in full-time use. The emissions from modern visual display units are so low that they are difficult to measure. For the air traffic controller, the radiation emissions within his home environment are likely to be as high as those at work. The user of equipment is therefore not subject to radiation hazards. Nor should maintenance staff be, provided that they adhere to the laid down safety procedures.

Visual Appearance

The first determinant of visual appearance is the adequacy of the dimensions of the building, room and workspace for the work that is done there. A large room should be quite high to maintain pleasant visual proportions, and particularly to accommodate any general wall-mounted displays. A further benefit of height is to permit reasonably uniform lighting levels throughout and to convey an impression of spaciousness.

Adequate provision for accessibility, watch handover, on-site maintenance, on-the-job training, supervision, and cleaning and servicing in a continuously manned environment can be aided greatly by the optimum use of the space available, and can foster the impression of an ordered and uncluttered environment. It is difficult to convey an impression that good quality work is being done in a physical environment which looks like a shambles, even though the two factors may not in fact be closely related, and the disarray may be the inevitable outcome of inadequate space or of bad design, rather than the fault of those who work there. On the other hand, the occupants of the workspace can reduce the visual attractiveness of their work environment by leaving chairs and other movable items in disorder. When care has been lavished on providing a visually pleasant appearance, there is some obligation on the occupants to keep it so.

The lighting, and its interactions with the colours and textures of visual surfaces, determines the suitability of the visual environment for the tasks. Certain guiding principles are relevant in every air traffic control environment:

(1) The level and spectrum of ambient lighting must be compatible with the levels of luminous information on displays and with the characteristics of display phosphors.

(2) Glares and reflections should be minimised, and serious sources of either must be removed.

(3) Lighting levels throughout the workspace should be fairly, but not exactly, uniform: in particular, pools of light or darkness should be avoided.

(4) The colours of the environment should be chosen with a full knowledge of the lighting and of the appearance of surfaces in each colour when lit by the lighting to be installed.

(5) Lighting should generally be from diffused sources rather than localised spots, to minimise shadows and promote uniformity.

(6) Colours of surfaces should generally be matt, unsaturated, and light.

An appearance which gives the impression of care and thought in the design may be more important than the choice of particular colours. The visual environment should be designed as a whole, including the colour and texture of all furniture, floor coverings, walls, and ceiling. For flooring, carpet tiles in two neutral, pastel, fairly light colours which do not contrast sharply with each other can provide the best solution because they impose a visual texture on the environment so that its general size and dimensions can be clearly gauged, and because they have the advantage of being selectively replacable in the event of localised wear or damage.

Not so long ago, most air traffic control environments were dark, and ambient lighting levels had to be kept low in order to ensure that the information on displays, especially on radar displays, could be clearly seen. Also, displays sometimes flickered, a condition which can be annoying, obtrusive and distracting, and which led to many complaints. Flicker also produced horrific accounts of mainly mythological deleterious effects on well-being, for which objective supporting evidence was hard to find. Nevertheless, although evidence for its adverse effects is sparse, except in the range 8-14 hertz which is rarely encountered in real-life tasks, flicker should not be tolerated when it does not have to be. Modern display technology has largely removed both the dark air traffic control environments and the flickering displays.

There is normally no discernible flicker in displays which operate at 50 or 60 hertz, and no serious problems in air traffic control environments at renewal rates above about 35 herts. This latter figure depends on the size of the display, the amount of information on it, how the renewal of information is synchronised, the light output of the luminous characters or data on the display, the ambient lighting level, the decay rate of the phosphor, the nature of the task, the dwell times and eye movements patterns of the operator, and individual operator characteristics such as visual eyesight standards and age.

The aim should be to produce air traffic control visual environments at or a little below the visual lighting levels recommended for offices. It is reasonable to aim for an illumination level of around 500 lux[117]. There is nothing sacrosanct about this figure and efficient air traffic control can be conducted at other levels without any adverse effects on operators provided that the tasks and equipment are planned for those other levels. A level of 500 lux should certainly not be achieved at the cost of reducing the visual contrast of the information on any display so that it becomes difficult to read, or of making hard copy seem much brighter than the information on visual display units. Of overriding importance is adequate but not excessive contrast for all displayed information, and a good balance between all the surfaces which the man must look at regularly in the course of his normal tasks. Just as it is undesirable to have frequently used information at different visual distances so that the man must re-focus every time he looks from one to the other, so it is also undesirable to have information sources grossly different in brightness so that the pupil size of the man changes substantially whenever he looks from one to the other.

Sources for the recommendations in this Section tend to be scattered, but any handbooks of ergonomics data[118,119] form a useful starting point.

## 7o SUITES AND CONSOLES

The approximate positioning of suites within the control room, and their positions in relation to each other, should be known before the detailed specifications for particular suites and consoles are drawn up. This is necessary because of the interactions between the locations of consoles and their specifications: most notably, the height of a suite or console must be greatly reduced if the operator has to be able to look over it to see wall-mounted displays. Although wall-mounted displays which summarise the current state of the system can have a useful role, the operator's tasks should not require him to look at both wall-mounted displays and on suite displays, with frequent changes between them, in order to obtain essential information.

Recommended stages in the development of sector suites and consoles are job analysis; profile specification; determination of the relative location of displays, controls and communication facilities; verification of reach and viewing distances; considerations of the interactions with the physical environment; implications for the well-being and occupational health of the operators; and final evaluation[120].

In designing suites and consoles it is necessary to know all the facilities which have to be incorporated in them and the constraints which will govern their use. The main information used in their design can be summarised as follows:

(1) The number, size and relative importance of displays, and the envisaged relationships between them in terms of their contents, sequence of use, frequency of use, and expected patterns of eye movements.

(2) The controls and input devices, their sizes, sensitivity and actuation forces, their sequence and frequency of use, their relationships to each other, and their relationships to displays.

(3) Communications facilities, their type, location, bulk, pattern of usage, and positioning and stowage when not in use.

(4) The allocation of usage of displays, controls and communications among team members, in relation to constraints of viewing distances and angles, and reach distances; jointly used facilities which have to meet the viewing and reach distance constraints imposed by more than one operating position; duplications of usage where the sharing of facilities would lead to excessive interference or unwanted interactions between operators.

(5) Operational needs, relevant ergonomic evidence, and anticipated decrements or penalties for failing to comply with minimum ergonomic standards; the specification of more information displays to meet operational needs than can possibly be accommodated within a console, without violating ergonomic criteria of width, height, viewing distances or reach distances.

(6) Other incidental requirements including the accommodation of job aids, manuals, instructions and hard copy, the provision of writing surfaces, of adequate support for elbows, wrists and hands, for ashtrays if smoking is permitted, and for cups if these are allowed.

(7) Individual differences between operators, especially those related to well-being, such as minimum medical standards of eyesight and posture.

(8) Anthropometric data on the range and distribution of body sizes to be accommodated at the suite or console.

In some contexts, where the tasks are relatively simple and the number of displays and controls at each operating position is small, it is possible to introduce some flexibility in the design of suites and consoles. A single display, a word processor on a desk for example, may be moved about to suit the wishes of the individual operator, and associated keyboards may be treated in the same way. Such flexibility is precluded by the complexity of most air traffic control tasks with their need to accommodate numerous displays and controls within the consoles, and also by the requirement to match the console design with the specified physical environment, especially the lighting. The task of eliminating all major sources of glare and reflections in a large control room is daunting enough when all displays are fixed so that with care all the sources of glare and reflections can at least be predicted; it can become impossible if numerous single displays can be moved about at will.

Figures 1, 2 and 3 illustrate some recommended dimensions for console profiles, based on European and North American anthropometric data, and assuming that the controller may be either a man or a woman. The adjustments to be allowed for would be different if only men or only women had to be accommodated because of the substantial differences in their average body sizes. If the size of the whole population to be accommodated is substantially different from that of European and North American populations, as it would be in the case of Japanese controllers for example with significantly smaller body sizes and reach distances, then the whole console design should be different, including a lower shelf height, shorter shelf depth, and perhaps different display angles to take account of lower average eye positions.

Idealised profiles are given in Figure 1 for a console housing a large radar display on the axis BC, and in Figure 2 for a console housing smaller displays with a greater provision above eye level for control panels and displays which are used less often or rarely, such as those for setting up equipment or which function as ancillary memory aids. These two figures illustrate the application of the same principles to meet different requirements. The starting point is the anthropometric data from which ranges of adjustment, clearances, and reach and viewing distances can be derived[121].

The console profile is designed as a whole and each surface interacts with others. It may therefore be difficult to know where to begin when designing it. Probably the dimension which it is best to determine first is the height of the upper surface of the shelf at the front edge nearest to the operator. Normally this should not exceed 720 mm, the height shown in the figures. It can be lower, subject to constraints of thigh clearances and shelf thickness, but it should not be lower than 640 mm., and this is permissible only with a very thin shelf. The maximum thickness of the shelf at the front is about 80 mm. which is a tolerable but never a desirable figure. This must be associated with a height of 720 mm. and leaves no flexibility whatever to take account of other factors.

The shelf itself may be flat (Fig. 1), or sloping (Fig. 2). A sloping shelf is usually intended to accommodate input devices which themselves slope, to make them easier to use: examples are stepped rows of keys, or touch sensitive surfaces which function either as controls or as combined controls and displays. The shelf may also slope to help to reduce the excess space needed to house small displays (axis CD in Fig. 2); alternatively it may be flat to facilitate the incorporation of large displays without extending the top of such displays above the level of the eye (Fig. 1). Two further influences on shelf angle should be noted. Firstly, the extent to which room lighting can induce glare or sheen may depend partly upon shelf angle and therefore the interactions between shelf angle and room lighting must be considered. Secondly, the shelf can be used for a multitude of other functions, including writing, reading hard copy and job aids, and holding coffee cups without spillage - most of these functions favour a flat shelf.

A depth of about 300 mm. is normally recommended for the upper surface of the shelf. This depth can be increased slightly to accommodate equipment, but not by much if short operators must be able to reach and operate comfortably controls in section BC (Fig. 1) or CD (Fig. 2). As far as possible, the front part of the upper surface of the shelf, perhaps the 120 mm. or so nearest to the operator, should not contain any controls but should provide a smooth surface for hands, wrists or elbows to rest on. A deeper section of at least part of the upper surface of the shelf should be kept clear of controls if extensive reading or writing is required regularly as part of the tasks. The front vertical surface of the shelf, depicted as 20 mm. thick in the Figures, can accommodate sockets for plugs and a few setting up controls if necessary, but these should be recessed and not placed centrally in the console.

The position and dimensions of the shelf top having been determined, progress can be made with the other console dimensions. All displays above the shelf have to be related to eye position; although it is possible to postulate an ideal eye position and use it to fix the positions and angles of displays, it is better to establish first whether the ideal position is attainable, since major discrepancies from it would warrant revisions of display angles in particular, and these in turn can affect other factors such as the positioning of light fitments. The next desirable step is therefore to establish the eye height.

A reasonable eye height for a seated operator working at an air traffic control console is 1150 mm., or thereabouts. This recommended height presumes that in his normal working posture he leans forward so that his eye position in relation to the shelf is approximately as drawn in Figures 1 and 2, and that he does not normally sit back and upright while working, although he may occasionally sit back to view a large diameter display as a whole, and his viewing distance may then become about 750 mm. instead of the more customary 420-450 mm. Most if not all the controls would be out of reach of an operator sitting back and this cannot therefore be a normal working position and should not be used in determining display locations.

The eye height of 1150 mm includes a correction for slump, the normal slightly hunched and relaxed working posture which reduces eye height by 80-100 mm. and increases the downward viewing angle by a few degrees, compared with the more straight backed and rigid posture more often associated with self-conscious circumstances such as being measured anthropometrically, rather than with real-life.

Although ideally 1150 mm is the eye height for all operators, and is achieved by appropriate adjustments to the seat height, in fact considerable variations in eye height may occur because of individual differences in postural preferences or because individuals do not know, or fail to make, appropriate adjustments to the seat. The range of seat adjustment of 100 mm. is not generous, but the upper limit is set by the need to maintain adequate thigh clearance between the seat top and the underneath of the shelf (a minimum clearance of 200 mm is the usual recommendation), and the lower limit is set by comfort and by the need to reach controls. In air traffic control workspaces, tall people usually sit high, and short ones low, a borderline decision dictated by operators' wishes more than by ergonomic optimisation.

It should be noted that there are two separate and incompatible principles which may be followed in designing consoles and seating. Handbooks generally fail to draw the distinction between them. One principle, more commonly described in handbooks and adopted when the displays themselves and perhaps the shelving are adjustable, means that a short operator will sit low and a tall operator high to be comfortable: as a result there are considerable variations in eye position, viewing angle and viewing distance and these are compensated for by repositioning th. equipment; a footrest is less necessary. The other principle is preferred with displays that are in complex and constrained environments like aircraft cockpits, particularly when variable eye positions may pose insuperable problems in preventing glares and reflections for all operators: the aim is to achieve a single optimum eye position for all operators, and the tall operator tends to sit lower than the short one to attain the recommended eye height, and further back than the short one to have comfortable reach distances for the manually operated controls: a tall operator needs ample leg room and a short operator may need a footrest. The extent of fore and aft adjustments of the seat depends on whether there are any foot-actuated controls.

In air traffic control it can be difficult to position foot switches so that everyone can use them comfortably. If foot switches are employed, they should have a simple on-off function so that usage of them is not continuous or prolonged. It may sometimes be necessary to make their position adjustable. A footrest should not be fixed. Whereas a tall operator may want to dispense with it altogether, a short operator may want to set it high and bring it closer to him (or more probably her). These two dimensions of desirable easy adjustment for footrests are not independent.

The depth of the seat should be about 380 mm. The seat should be horizontal. If it is tipped, the front should be slightly higher than the back and the seat should not slope by more than 5 degrees from the horizontal. Armrests are a contentious issue; on the whole they are more trouble than they are worth in most air traffic control contexts. They must be set low to remain clear of the shelf when the seat is at its highest adjustment, and they can get in the way when members of a control team are sharing facilities, particularly where adjacent chairs both have armrests. By contrast, there is no doubt at all that the chair itself should incorporate adequate support for the back, in the form of adjustable lumbar support and preferably some support for the upper back also, which the operator can feel whenever he sits back.

To accommodate the longest thighs in comfort, the underneath of the shelf should extend back at least 460 mm. in the whole region that the operator may occupy. At ground level, space should extend back at least 750 mm. from the front of the shelf. This figure is a minimum; it is desirable to provide more room if possible, so that tall operators can straighten their legs if they wish without encountering the console.

When the eye position has been established, either an ideal one or a revised one to take account of particular restrictions, the layout of displays and their viewing angles and distances can be settled. The general principles are that the operator's line of sight should be approximately perpendicular to the centre of the display, and that the whole of frequently viewed displays should lie below the horizontal through the operator's eye level. If there is only one display, a downward viewing angle of about 15 degrees, with a consequent angle of mounting of the display at 75 degrees from the horizontal, is about the optimum, but in air traffic control there are likely to be several displays at each work position, and they all have to be fitted in. In Figure 1, representing a large display on axis BC, the requirements of the viewing angle leave little scope for varying the angle at which the display can be placed and therefore at which other smaller displays on the same axis must lie. Other displays which are viewed frequently should be accommodated on the same axis alongside the large one. Within reason, horizontal head and eye movements are preferable to vertical ones if they have to be performed frequently; there is therefore a preference to locate displays alongside each other rather than one above the other, if there is room. In Figure 2, the main displays would be on the axis CD, with those referred to less frequently on axis BC. In both Figs 1 and 2, the panel AB should contain only displays which are rarely used. Controls associated with a specific display and not used often, for example for setting up, may be beside the appropriate display. Frequently used controls should all be on the shelf. It is important to lay out the workspace so that the relationships between displays and controls are clear.

Figure 3 shows reach distances, and the relative positioning of operators sitting alongside each other and sharing a suite. Controls which both operators must use should be placed within the minimum reach distances for operators in both positions. Some controls are more suitable than others for effective use with the non-preferred hand (e.g. a rolling ball has this advantage, and a light pen has not), and this may be an important attribute when determining the preferred location for a control designed to be shared. A display which is intended to be viewed by more than one operator has to be sited to facilitate this, with due regard for the implications: alphanumeric characters are viewed at an angle; approach angles on a plan position display may be misjudged; unwanted parallax effects may occur; many more sources of glare and reflections may be encountered and have to be circumvented; etc.

The distance between the centres of the seats for adjacent operators should not be less than 650 mm. If there are normally several operators in a row in a suite, even this distance may seem cramped, and should be increased by about 100-150 mm. for permanent occupancy. However 650 mm. is a reasonable width to allow for temporary or intermittent occupations, as in on-the-job training or occasional supervision or increased manning levels. It is also suitable for suites with only two positions if there is a gap between the suites.

The layout of suites and consoles is intended to promote the objectives of the air traffic control system design. It is therefore undertaken as a response to specifications of tasks, equipment, and operator characteristics, and is not intended to be an innovative, disruptive or obtrusive aspect of system planning and evolution. The intention is to provide what is required as efficiently as possible, rather than to introduce new requirements, although occasionally constraints at the console may warrant the re-examination of the original requirements. It is obviously possible to draw up a specification which includes far more displays, controls and facilities than can be accommodated. There can be no satisfactory solution to such problems without incurring some penalties. A role of human factors is to specify what the penalties would be, and to advise on whether in human factors terms they would be acceptable in relation to the known objectives and standards to be attained.

Most problems which can arise from layouts, especially those related to the physical environment, can be deduced from drawings and principles. Console layouts such as those shown in the figures, allow the region to be defined within which certain visual problems can arise. For example, in Figure 1 lines drawn from the eye to B and to C, and continued as if reflected from BC can be used to establish the region of the ceiling of the room within which a light would be seen from the operator's eye position as reflected in a tube positioned on the axis BC. Furthermore the extent of any cowling of the light or of the tube necessary to eliminate such reflections could be established. The effects of changes in display size or angles on reflectance can also be predicted.

In some air traffic control environments, a large radar display is literally vertical. The operator's line of sight is not at right angles to the display but the problems of glares and reflections from the environment can be eased at the cost of introducing some errors in parallax and judgements of relative bearing. A vertical display may be most successful when there are few other displays to be incorporated or where the height of the console must be kept low because the operator has to be able to see over it.

In other air traffic control environments, large radar displays are mounted horizontally. Although this may promote task sharing, horizontal displays have certain fundamental disadvantages from the point of view of suite and console layout. It is impossible for several people to sit comfortably around a horizontal display, because each man has to sit at an angle to it, and the display is where his legs would normally be. Controls have to be housed round the edge of the display and the operator has to stretch over the controls to see the display and minimise parallax from it, whereas to use the controls he needs to sit back. Light reflectance can be almost impossible to eliminate if several people can sit round a horizontal display and view it from many angles.

It is difficult to use a horizontal display in conjunction with other displays and especially with a flight strip board. The latter contains several columns of flight strips in holders, normally at an angle of not much more than 40 degrees from the horizontal, because it is essential to be able to remove, replace and manipulate individual flight strips without disturbing the others, and particularly without them falling off the flight strip board. The traditional flight strip board was a very flexible tool, and it is proving difficult to retain all its advantages in electronically generated tabular information displays intended to replace it, although electronically generated displays can reduce the operator's work substantially. Ergonomically, the flight strip board was very difficult to reconcile with other air traffic control furniture, because of its bulk and the need to treat it as both a display, the whole of which must meet display viewing distance requirements, and as a control surface, the whole of which must meet reach distance requirements. Attempts to provide a flight strip board, other displays, and a horizontal radar display can lead to insuperable ergonomic difficulties in devising satisfactory suite and console designs and layouts (Figs. 4 and 5).

The gradual replacement of the flight strip board by electronic information displays does not signal the end of displays which must double as control surfaces; far from it. Touch wires, touch sensitive surfaces with or without a matrix of light beams, light pens, and plasma panels may all employ a display surface which is intended to be touched directly by the operator's finger or by a device held by the operator. The display surface must not only meet the visual viewing distance requirements but be wholly within reach. There is no point in building a console, installing a display intended for viewing at 750 mm., replacing it with a touch sensitive surface, and then discovering that it is out of reach.

There is no ideal ergonomic solution to the problems posed by displays which are also touch sensitive surfaces. Either the man must look down at them far further than would normally be recommended for regularly viewed displays, or he must reach up to them far further than would be recommended for regularly used controls. Compromises, such as mounting the device at an angle of about 30 degrees or 40 degrees to the horizontal, seem as likely to retain both problems as to solve both. The most favoured solution is for control requirements to predominate so that the device is treated primarily as a control and housed in or near the shelf. This solution is most likely to be satisfactory where the display is intended primarily to aid learning and ultimately the operator can learn to use it largely by touch. If the man always has to look at the device while he is using it, the pace of usage may remain slow.

Consoles need to accommodate ancillary equipment. Below and to one side of the shelf there should be provision to stow manuals and job aids, and this stowage should be designed to facilitate their selection. It should be possible to see the title of each by looking at them when stowed, and to retrieve the one required, and replace it correctly afterwards, without taking other items out. This is a matter of layout and labelling of the manuals and aids themselves and of providing stowage which fits them. A v ... index may be useful.

Contro... rs use headsets. At each work position, there should be somewhere convenient to house a headset temporarily while it is not being used, without damaging it. Headsets often have cabling attached, which is wrapped tightly round the headset itself for stowage, a practice which can cause wear and damage. Perhaps the cabling should be housed on a gently spring-loaded coil within the console itself, to be pulled out and attached to the headset with an automatic release of the spring-loading whenever required.

## 7d AIR TRAFFIC CONTROL CENTRES AND CONTROL ROOMS

In relation to the work environment, the human factors problems posed by centres and control rooms are mainly orthodox, and solutions to many of them can be achieved by following the guidelines outlined in the earlier parts of this chapter. If an air traffic control workspace is continuously manned, allowance has to be made for extra requirements for space, for example to accommodate watch handovers. The appearance of an air traffic control centre or control room does not usually vary according to exterior daylight or darkness, so that in designing the work environment it is reasonable to try to make specific recommendations to achieve an optimum solution within the known constraints of tasks and loadings, since these recommendations do not have to take account of uncontrollable variables associated with physical environmental conditions. Designs and simulations of centres and control rooms can therefore specify and replicate their appearance faithfully, and equipment configurations can be tried and tested under environmental conditions similar to those in real life. When all the data used by the controller are either presented on visual displays with specified contents or heard through headsets or telephones or from colleagues around him, as they are in control centres and in control rooms, the variables which will affect familiarisation and training can all be specified and studied.

As a consequence, a simulation of a control centre or control room can in principle be so realistic that a casual, or even an informed, observer may not be able to tell whether he is watching simulated or real air traffic control. He may glean hardly any clues from the physical environment, the workspace, the information sources present, or the activities of the controllers. Do Figures 4 and 5 show real or simulated air traffic control? Contrast this with the most elaborate simulation of an air traffic control tower or an aircraft cockpit. There the problem is to ensure that the simulation contains sufficient representation of the information for the man to do his tasks or learn to do them, so that the aspects of them of particular interest can be studied. To the informed bystander, a flight simulator, or an airport control tower simulator, is instantly recognisable for what it is, a simulation, in a way which a simulated air traffic control centre or control room may not be. An ironic consequence is that more attention has been paid to the difficulties of simulating air traffic control towers or flight decks than to the problems of simulating air traffic control centres or control rooms. Much of this attention has been devoted to the replication of the visible real world and of the cues from it which are utilised in tasks, a problem which does not arise when the workspaces simulated contain no view of the real world.

One outcome has been a split between centres and control rooms on the one hand, and air traffic control towers on the other, in the kinds of human factors studies of them which are generally undertaken. Practical real-time evaluations, which employ elaborate measures of the task demands and of the controllers' responses to them, tend to be of centres and control rooms, for which purpose-built simulation facilities exist to study them in general terms or to replicate any specific one in detail. Task performance has therefore been extensively studied, in relation to changes in equipment, in demands, in procedures, in instructions, in training or experience, in the influence of physical environmental and workspace variables, and in controllers. The work environment is studied as such, because its critical aspects can all be specified, controlled and replicated.

The workspace of an air traffic control centre or control room, particularly a modern one, is usually sufficiently spacious to allow choices in the positioning of suites and consoles, in the location of general displays, and in the fulfilment of ancillary functions such as maintenance and accessibility. There is also flexibility in designing the physical environment, in its colours, textures, and lighting. Such comparative freedom in design may make the attainment of an acceptable solution more probable, but gives scope also for more critical mistakes in the specification of the workspace. On the whole however, as a workspace, the air traffic control centre or control room is easier to replicate than an air traffic control tower in human factors terms.

In most respects a simulation facility can be adapted to simulate a particular control centre or room by building and installing appropriate suites and consoles. Depending on the objectives, various equipment configurations and layouts can be tried, and displays can be left blank, can show a typical static picture, or can present dynamic information to allow the feasibility of envisaged air traffic control tasks to be established, or even to obtain performance measures of specified tasks. Some of the possible stages are illustrated in a mock-up study of a TRACON[115], the facilities for which can become quite elaborate (Fig. 6). Every feature of the environment, the furniture, the hardware and the software is stated, and provision is usually made for ready adjustments to them so that alternative configurations can be tried and their practicality and appearance gauged. Findings about the physical environment and layout of workspaces and of the equipment items within them can be expected to have high validity if the study has been conducted competently, because the physical environment is constant and its main attributes can be replicated. Furthermore, there is a good prospect that many of the findings will be applicable to comparable environments and workspaces wherever the lighting, the suites and the console configurations are similar.

## 7e AIR TRAFFIC CONTROL TOWERS

In many respects air traffic control towers pose different human factors problems from centres or control rooms, for five separate but interacting reasons:

(1) The physical environment, especially the lighting, is not constant, but can vary grossly from bright sunlight to exterior darkness, and the direction of the main light source also varies with time of day.

(2) The controller has a view of the visual world outside the tower, and uses information gleaned from looking out while performing his tasks.

(3) The controller's view from the tower is panoramic, and he may need to look all round him, or at least through a large arc. As a result his postural and viewing positions are not standardised, and he has to be able to see over any equipment installed in the tower in most if not all directions.

(4) The controller can see, and perhaps hear, aircraft moving, and detect them against backgrounds of sky, cloud, darkness, poor visibility, and ground with its seasonal variations in appearance.

(5) In principle, towers are likely to differ from each other more than centres or control rooms, and therefore the prospects of findings obtained about one generalising to others are poorer for towers than for centres or control rooms.

The information which the controller needs for his tasks is therefore not contained solely within the tower, and no replication of the tower alone can be adequate to study every aspect of his tasks and roles. However, certain aspects of his workspace, its furniture and the equipment installed in the tower can be studied by mock-ups to obtain findings within these strict limitations[116]. Much of the tower controller's knowledge of the current state of the aircraft under his control and of the consequences of his own actions is obtained by looking at the aircraft on the ground or in the airport approaches, aspects not covered in mock-up studies (Fig. 7).

It is possible to provide sound human factors advice about any air traffic control tower by visiting it, taking appropriate measures of the workspace, furniture and physical environment in relation to the tasks and anthropometric data, and applying human factors principles to evolve a workspace design which meets human factors requirements. In any real life environment, it is always feasible to apply human factors principles in this way, and to identify the constraints which may make an acceptable solution impossible. Although the application of data on such factors as console profiles can be straightforward, it can be much more time consuming and difficult to compile job descriptions, or to work from job descriptions and a task analysis or task synthesis to determine the required display contents and to derive acceptable methods of depiction and portrayal of information. This information must be reconciled under all circumstances, if necessary by automated or manual adjustments, with the gross variability of the ambient lighting. In towers, space tends to be at a premium, all consoles must be low, and the layout of operating positions must ensure that no controller can block his colleagues' view of essential information inside or outside the tower.

Many human factors problems are posed by the need to simulate the outside visual world and the aircraft flying in it as seen from the tower, in order to study validly tasks and procedures, to explore the effects of changes, to evaluate performance, or to determine and provide all the requirements of both students and instructors during training. For most purposes, it is simplest to simulate the view from the tower at night, since all the necessary information may then be conveyed in the form of patterns of fixed lights and moving lights, the latter carefully specified to replicate faithfully all the relevant apparent movements of aircraft. Daylight, with its associated variations in climate, visibility and light intensity, generally requires some form of projection in simulation. The representation of the aircraft themselves can be by various principles, from toy aircraft to electronically-generated aircraft shapes. The options and associated problems have been considered in relation to the feasibility of a simulated air traffic control tower for the purposes of controller training[122]. Many solutions are costly, grandiose and sophisticated; the technological implications of some solutions have been evaluated[123].

# CHAPTER 8

# DISPLAYS

## 8a PHYSICAL DIMENSIONS

Comprehensive guidelines on the factors which affect interactions between visual displays and their users can now be compiled. A human factors checklist of factors is provided as Appendix 1. This is careful not to quote figures. The human factors specialist has to be cautious when judging the applicability to air traffic control contexts of sources of human factors data which do cite figures. These are seldom derived from, or intended for, air traffic control. A recent handbook[124] was originally written for visual display terminals in the newspaper industry, where the tasks are different, the people are different, the physical environment is different, the displays themselves are different, and the extent of teamwork is different from air traffic control. Furthermore, some of the figures cited can be traced to relevant ergonomic studies, but others appear to represent the opinions of the authors; the strength of the evidence on which recommendations are based varies greatly, but the text does not make this clear. The moral is plain: do not apply data from handbooks uncritically in an air traffic control context without obtaining specialist human factors advice on how the data should be interpreted.

In air traffic control, major changes in information displays are taking place, comparable in magnitude and human factors implication with the replacement of conventional instruments by cathode ray tube displays in aircraft cockpits. Three kinds of display, grossly different in their dimensions and orientation, may be found in air traffic control workspaces:

(1) Luminous electronically generated displays, for individuals or groups, mounted horizontally or vertically, showing radar information, tabular information or topographical information, in pictorial, graphic, alphanumeric or symbolic form, usually but not necessarily using a cathode ray tube, with some variability of content which is automatic and some at the controller's discretion by means of a keyboard or comparable input device.

(2) Wall-mounted displays, often of more general or summarised information, driven by electronic, projected or mechanical means, luminous or non-luminous, employing a wide range of coding conventions and various methods of updating, but not normally under the control of individual controllers.

(3) Non-luminous displays based on flight strips, which are pieces of paper, one for each aircraft at each reporting point, printed automatically or prepared manually by the controller or an assistant, housed in strip holders on a board, and moved about manually; and other displays of information such as maps, charts and job aids which are also in the form of hard copy.

The first of these is most recent; the trend is for it to dominate and ultimately replace the second and third kinds of display.

At one time, the ambient lighting requirements for the three kinds of display were fundamentally incompatible, mainly because information on electronically generated displays could not be perceived in bright ambient light. Advances in display technology have led to the development of visual display units which can be used in ambient lighting up to or above that of office lighting standards, and similar ambient lighting standards can now prevail in air traffic control centres and rooms given modern equipment. Some problems may remain in towers, since even the best displays can become difficult to read if direct sunlight is allowed to fall on them.

The general location of displays should be settled as part of the workspace design, and is not solely, or even primarily, decided by display factors. The main influences on the decision are the tasks, the physical environment, the communications, the extent to which individual roles are intended to be autonomous or team functions, the envisaged content and utilisation of other displays, especially wall-mounted ones, and accessibility. These factors determine broadly the information required at each operating position, its approximate level of detail, and whether it should be displayed permanently, temporarily but automatically, or temporarily at the controller's behest. The size, shape and positioning of each display depend on engineering constraints, cost, and commercial availability, on how many displays there will be and on the relations between them, on whether each is for one individual only or shared, on the amount of information to be portrayed and the methods of coding, and, in the case of radar displays, on the region to be depicted and the preferred scale. Ambient lighting requirements are borne in mind lest they pose problems which have no solution: as far as possible, the dimensions, location and orientation of the displays are specified first to suit the task requirements, and the ambient lighting is adjusted to be compatible with the display requirements, rather than vice versa.

For displays of tabular information, limits are set by the planned capacity of the system. Provision is made to display information about a maximum number of aircraft at any one time, and the information about each aircraft is standardised. Such displays commonly are intended to meet a specification of a maximum number of lines of data and a maximum number of characters per line. Required character sizes and spacings can be derived from display characteristics (especially contrast), ambient lighting, method of character generation, viewing distance, and minimum eyesight standards, to arrive at the character dimensions needed to ensure legibility under all circumstances in that environment. From this, the minimum display dimensions can be derived. Not uncommonly, this exercise has the effect of making everyone think again, because in air traffic control the tendency has always been to try to cram too much information onto displays. The options are:

(1) To reduce the amount of information to be portrayed.

(2) To increase the number of displays if there is space for them.

(3) To reallocate tasks and roles so that it is possible to put some of the information on other displays.

(4) To keep all the information but specify a larger display than was originally envisaged.

(5) To keep all the information but recode it in ways that use less space.

(6) To improve the contrast of the characters or redesign them to retain their legibility at a reduced size.

(7) To adjust the level or spectrum of the ambient lighting if this could improve legibility.

(8) To re-examine the planned viewing distance and see if it could be reduced (e.g. from about 750 mm. to 450 mm.)

(9) To raise the minimum eyesight standards for operators.

These are options to be considered; in any given circumstances, not all of them will be feasible, and some may not make a significant contribution on their own, but only in conjunction with others. The kinds of solution also depend greatly on the severity of the problem - whether each display dimension would have to be increased by 10% or 100% in order to accommodate to the required legibility standards all the data thought to be necessary.

The initial impression from many modern air traffic control workspaces is that the radar display is very large. A diameter of about 550 mm. is not unusual. This is far in excess of the normally recommended size for an information display even with a viewing distance of 750 mm., and in air traffic control the viewing distance is often 450 mm. or even less. The larger the radar display, the more difficult it becomes to accommodate within the workspace the radar display itself and other displays and their associated controls at near optimum positions, or to provide ambient lighting which does not lead to any glares and reflections from any radar display.

Nevertheless, the large radar display can convey some advantages. Often the controller uses only a segment of it most of the time, and this segment is of the same order of magnitude as the recommended maximum display size for an operator to view the display as a whole. Therefore the large display does not necessarily lead to frequent large eye movements and extensive display scanning. It does provide a context for the radar controller's task, so that he can see impending traffic and gauge some of the longer term consequences of his proposed actions when controlling the traffic which is his direct responsibility. The display when large can be set up permanently and does not have to be re-centred whenever the focus of interest changes substantially. Although the smearing associated with re-centring and long persistence phosphors is a problem which modern technology is in the process of resolving, nevertheless even with the best displays the change of visual framework and orientation associated with re-centring the display is still sufficiently disconcerting to be avoided whenever possible.

A further advantage of the large display is that an extensive region which includes all the radar evidence directly and peripherally relevant to the controller's tasks can be depicted at a reasonably large scale. Although any loss of radar information or impairment of performance by reducing the scale is almost invariably negligible, yet most controllers express strong preferences for as large a scale as possible since they believe it improves their performance, particularly in judgments of range, bearing, separations, and optimum sequencing of traffic.

There is however, the implied assumption, which is potentially hazardous if wrong, that a larger scale implies greater positional accuracy and perhaps greater reliability in the data. This impression can be pernicious: a large display and a large scale for the displayed radar information should not result in the depiction of data at spuriously high levels of accuracy. It is misleading, if data are accurate to a kilometre or so, to present them on a display on which differences of 100 metres could readily be discriminated. A large display can help to show that data are accurate when they really are, but can fail to show when data are inaccurate.

One practical advantage of a large radar display is most apparent in heavy traffic when it is most needed. The size of the alphanumeric characters which form the labels on a radar display is a function not primarily of the size of the display but of other factors such as their method of generation, the ambient lighting and the operator's viewing distance; as a result, the larger the display, the less severe the frequency of label overlap and its associated problems becomes. The advantages and disadvantages of a large radar display are therefore finely balanced. Perhaps the point of most significance in terms of safety is that the display must not, at its normal expansion setting, convey the impression that the information on it is very much more accurate than in fact it is.

## 8b LAYOUT

Display layout can be considered in three respects: the positioning of displays in the furniture in relation to each other (considered in Chapter 7c); the layout of displays in association with controls (considered in Chapter 9e); and the broad principles for the layout of information within each display, considered here.

Many principles for the layout of information on air traffic control displays can be derived from two main sources, guidelines in human factors handbooks and traditional air traffic control practices. The flight strip exemplifies the latter. Its traditional layout has generally been retained when displays of electronically generated tabular air traffic control information have replaced flight strip boards, although in principle this change provides an opportunity for the radical recasting of the layout of information. With regard to radar displays, the fact that a radar display provides a plan view of a region imposes major constraints on the flexibility of layouts that can be adopted; the main issue is the extent to which layouts can conform with the principles inherent in a plan view without becoming cluttered by additional alphanumeric or symbolic information.

Secondary radar displays have now largely superceded primary radar displays in air traffic control. Where they have not, the problem of maintaining the identity of each blip or track in relation to other data sources, usually in the form of flight strip boards, remains. It requires elaborate cross-coding between two information sources where the principles for information layout can be grossly different, the one giving a plan view, and the other providing a list of aircraft in a sequence determined by time order, direction of flight, height, destination, or some combination of these and allied factors. Although the tasks consequent upon this cross-coding could be cumbersome and in many respects were inevitably inefficient, they were not totally devoid of advantages: primary radar gave some indication of the qualitative aspects of information such as the strength of the signal or its propensity to fade, and the amount of active participation in tasks entailed by cross-coding, although often of a routine nature, had the incidental benefits of helping the controller to build his picture of his traffic and of reinforcing his memory of it.

Secondary radar presents tracks and dots which have been smoothed and appear more stable. It offers much greater flexibility than primary radar in terms of the additional information which can appear on the radar display. This has led to much discussion on what the content of the label on a radar display should be. Much information could be shown, at the cost of making each label large, cluttering the display, presenting information which is not often used, and introducing potential sources of confusions, for example between digits which show height and other digits which show speed.

Label overlap is a serious layout problem on radar displays, partly because a priori it is most likely to occur when it can least be tolerated. Label overlap occurs when two or more aircraft are quite close together, and the greater the traffic density the bigger the problem becomes. When aircraft are close together and the traffic is dense it is most important to read the label of each aircraft correctly and to establish the identities, heights and speeds of the aircraft concerned. It is therefore important to make each label as small as possible and to lay out label positions to minimise label overlap. One possible approach to the problem is to move labels automatically if they are about to overlap, for example by putting one or both at the end of tag lines or by alternating their presentation every two seconds or so. A facility for the controller to move individual labels or specified categories of labels can be provided, with manual or automatic reversion of the label positions once the aircraft have separated. The controller may perceive a series of labels as a single traffic flow and thereby verify that a smooth flow is being maintained with no opening gaps or closing separations within it. If he can perceive streams of aircraft in this way he can also verify that the streams are safely separated from each other. This function is facilitated if the controller can structure a series of labels as a visual entity. Where the label is always in the same position relative to the aircraft, the controller may tend to use the labels to judge relative positions, bearings, or even speeds of aircraft but if he does this, the selective movement of some but not all of the aircraft labels in relation to their track positions in order to prevent label overlap could clearly become potentially misleading, particularly if the controller forgot that he had moved labels selectively. The layout of labels on the display may therefore convey far more information to the controller than it is intended to and this must be borne in mind when the facilities for repositioning labels are being considered.

As far as possible, the layout of labels should follow a logical principle which facilitates their comparison with other data displays about the same aircraft, although it is the layout of the latter which generally has to be adjusted to the layout imposed by the radar display and by the route structures depicted on it. Proposals are sometimes made to introduce small tabular information displays in regions of the radar display not in regular use, often with the provision that this additional tabular information could be deleted from the radar display or moved elsewhere if need be. These further data could keep the labels themselves at a more reasonable size or could obviate the need for the controller to look away from the radar display every time he needed certain categories of further information. While the addition of small tabular displays within the radar should not be ruled out entirely as a matter of principle, it can only have limited value without causing clutter; if there is a need for it, the relevant electronic data displays may need replanning to make it easier to find the requisite information on them. Proposals of this kind also raise the more fundamental question of the extent to which it is desirable for the controller to come to rely almost exclusively on his radar display and not to have to look at other displays very often.

Major layout problems tend to arise with tabular air traffic control information on electronic data displays. Such displays have a pre-planned capacity to match the planned maximum loading at the work position. This sets the number of rows of tabular data. Additional rows of data may be required for several purposes - to readback the information being entered, to show additional information requested about designated aircraft, to provide scribble lines, or to allow the compilation and use of extra tables of data for specific purposes. These additional roles must be differentiated clearly by their layout from the main tabular data, by means of gaps to provide visual separations, different layouts for the additional and for the main data, separate headings or labelling of the additional data, or different coding conventions in the two parts of the display.

A dilemma with tabular displays of air traffic control information is that they almost invariably function efficiently when traffic is light and when they therefore contain few rows of data, but that the busier the traffic is and the fuller the displays become with data, the more they impose a search task on the controller to find the data he needs, just when he has least time to devote to searching for data, and the more errors due to misreadings and misalignments can arise, just when there is least time to detect, correct or handle the consequences of errors. The layout of tabular data should therefore be chosen to minimise search, to prevent misreadings, and to eliminate visual misalignments as far as possible. Nevertheless, the layout must not follow these principles slavishly and unintelligently without regard to the content of the information being laid out, since it is desirable to use the layout to promote and strengthen the visual structuring and grouping of data in logical and efficient ways for task performance. Flight strips employ differently coloured paper for eastbound, westbound and crossing traffic. Individual flight strips can be offset physically on the flight strip board. Such principles impose a layout structure which can be used to aid memory. These are sound human factors principles, to the extent that comparable equivalents are needed on electronically generated displays of tabular information.

The air traffic control information on tabular displays is normally grouped under headings such as aircraft identity, type, route, destination, expected times at reporting points, actual and cleared heights, and whether the aircraft is level, climbing or descending. The information under many of these headings is in alphanumeric forms that can appear superficially similar. To avoid confusion it is necessary to give the headings themselves on the display. Since it is much easier and more logical to put all the information under the same heading in a column with the heading at the top rather than in a row with the heading at the left or right, the equivalent data about aircraft, such as their heights, generally appear in a single column under the appropriate heading. All the information about each aircraft appears in a single row. To establish rules for the spacing between rows and columns, handbook data can generally be followed, with some extra allowance for the thickening of luminous characters attributable to the method of their generation. If the row of data is long, some replication of the most vital information within the row may help to prevent misalignments - a favoured form is to put the aircraft identity at both ends of the row of data about it. Technical limitations in the generation of characters, coupled with the planned display capacity, also influence the layout.

Within a row of data, misalignments can be minimised by lines of dots linking separated items, and by other conventions such as depicting a whole row in a different colour, font, or size of characters, or underlining it. Some of these methods, such as the use of a different colour or underlining, may not only make a row stand out visually but also impose a visual structure and layout on the whole display. Blocks of data, readily distinguishable visually, can be formed horizontally, vertically or in both dimensions by lines, dots, gaps, changes of colour of the characters or of their backgrounds, differences in typeface, case, or size, or other discriminable attributes such as different height/width ratios of characters. Many of these conventions can become much too obtrusive for most purposes, and prevent the user from seeing the tabular information on the display as a whole. If the intention is simply to break up the display visually to facilitate searching and to discourage misalignments during the scanning of rows of data, then the simplest method is to leave somewhat larger gaps than normal between certain rows, with a larger gap about every third, fourth or fifth row, preferably where the display content provides some logic for introducing a gap rather than at the same position in the display regardless of the display content. Almost any visual coding dimension can be used to help to structure the layout: in general, the aim is to provide a structure strong enough to be discernible but not noticeable enough to be disruptive. Gross changes, such as colour coding, thick lines, or gross brightness differences are generally excessively obtrusive to be suitable solely to structure the layout.

In general, the same layout principles should always be followed throughout, and not varied for apparently trivial reasons. They must therefore be chosen to remain applicable whatever the display contents. Occasionally it is possible to use the layout itself as an information coding, but this requires great caution. For example, if information on eastbound and on westbound aircraft is laid out differently according to different rules, this may certainly facilitate the distinction between eastbound and westbound traffic, but it can engender confusion in tasks which require data about both. It is better in making such a distinction to rely on other coding conventions, such as colour, symbology or the offsetting of a row slightly, rather than alter the layout of the whole row of data.

One of the most difficult problems of layout arises with the labelling of displays such as touch wire displays, touch pads and plasma panels, when they also function as data input devices. Commonly such displays function in many respects like a keyboard but the electronically generated label that describes the function of each key position and appears beside it varies during a sequence of keyings. Sometimes the variability depends solely on the position in a sequence and if, for example, at a particular position in the sequence the keyboard always functions to enter numerals, the position of each numeral in the keyboard can be learned and eventually the man may enter it without having to look at the display label. However, in the normal rest position these displays often present a list of aircraft identities which are not constant and not in the long term learnable. Each entry sequence is started by touching the appropriate identity, usually in the form of a callsign, and this would normally be in the system for use for a period of only a few minutes. As an aircraft leaves the controller's area of responsibility and a new aircraft enters it, callsigns drop out or appear. Various principles can be followed in the layout of the labels of callsigns on a display which functions as an input device. A callsign may remain in the same location as long as the aircraft remains under control. When an aircraft callsign is removed all the other callsigns could be moved up so that the callsigns always tended to fill the same part of the matrix of rows and columns, normally starting from the top left position. A new callsign could always be added at the end of a list or it could fill up an existing space where one had dropped out. These alternative have different implications for learning, for search, and for errors in identity. The problem is complicated if there are more aircraft callsigns than spaces available for them, so that some have to be presented on a second "page" which the controller must call down and scan when he has searched the first page in vain and which replaces the first page and uses the same touch sensitive panel. The layout of callsigns on displays of this type needs to be studied. The optimum answers to the above questions are not known. Existing tentative evidence suggests that it may be best to keep each callsign in the position originally assigned to it and to put new callsigns at the end of the list rather than to fill in gaps in the list. Eventually the end of the list is continued as a new beginning. This principle should not be extended so that two "pages" are ever used unnecessarily.

The information layout may also have to make it easy to discriminate between certain basic categorisations of information. Examples are static and dynamic information, and information which refers to status or to events. The layout of information may also influence the functions of it, for example by preventing confusions between actual and predicted information. The numerous possible functions of displayed information (cf. Appendix 1) should be borne in mind when decisions are taken on how it is laid out. As far as possible the principles of layout followed in different contexts, such as for wall-mounted displays and displays for individual operators, should be the same or at least logically compatible. It is desirable that the principles of information layout are self-evident from the layout itself so that the user is not unnecessarily mystified about what they are and can use the layout principles to find the information that he needs.

## 8c INFORMATION CONTENT

The information content to be presented to the controller is initially established from the objectives, job descriptions, and task analysis or synthesis. These not only permit the specification of the information needed, but also guide its grouping and collation onto displays. Information which must be used in conjunction with other information is distinguished from information used independently. Knowledge of human capabilities and limitations and of current air traffic control practices can then be applied to determine the appropriate level of detail of information, in terms of the time available for tasks, the standards of performance to be achieved, and the knowledge which the controller can be presumed to possess.

From such beginnings, the specification for the information content for each display is derived. From tasks, guidance can be obtained on the information which is permanently or temporarily displayed. From the nature of the information, for example whether it is static or dynamic, mandatory or advisory, essential or optional, warning or confirmatory, important or trivial, quantitative, qualitative or status, etc, guidelines can be derived on its desirable relative visual prominence and on appropriate methods for its depiction. From its location, and its use by groups or individuals, suitable formats can then be suggested.

Because there are so many tasks and roles in air traffic control, no general specification for the information contents of displays can possibly meet every air traffic control purpose. The content of each individual controller's displays therefore depends on what his job is. It is not self-evident, but has to be deduced. Even when the general guidelines to determine information content are clear there may not be agreement on exactly what should be presented. An example concerns the labels on secondary radar displays. Clearly the most vital information is aircraft identity in some form: the general preference seems to be for aircraft callsign because then the identity on the label beside the appropriate track on the radar display corresponds with the identity announced by the aircraft pilot when contacting the controller and used by the controller to contact the pilot. The use of callsigns therefore avoids cross coding which can be a source of errors, delays and extra work, but would be necessary if for example, a four digit code was used. An electronically generated identity on the radar for each aircraft track replaces the plastic "shrimp boats" of primary radar displays, and incidentally introduces the option of having vertical rather than horizontal radar displays.

Radar provides a two dimensional plan view, on the basis of which many air traffic control tasks can be done, including the control and monitoring of traffic flows, the maintenance of safe separations, the interweaving, crossing and amalgamation of streams of aircraft, the detection and resolution of potential conflicts, the sequencing of aircraft for final approach, the detection of navigational deviations from the planned route, etc. For most of these tasks, one further item of information on the radar display would be of great assistance, to the extent that if it is not shown then the controller would have to obtain it by searching his flight strips or electronic displays of tabular information. This further item is the height of each aircraft. Even better is height plus an indication of whether each aircraft is level, climbing or descending. Therefore aircraft labels on radar displays commonly show height.

Beyond this point, the desirable information content of a label on a radar display starts to be much more debatable. Much information could be shown, at the cost of making each label larger, cluttering the display, presenting information which is not often used and introducing potential confusions, for example between digits showing height and digits showing speed. The more information appears on the label, the greater the problem of label overlap becomes. Although it is clear what the total information content must be for tasks, the allocation of items of information among various displays is a matter of striking the optimum compromise between conflicting benefits and disadvantages.

Two further considerations influence the specification of the information content of air traffic control displays. One is the tendency for the individual workspace to be fully occupied or over-occupied with displays which can be difficult to accommodate and which contain so much information that they can become cluttered and difficult to interpret. The other is that air traffic control displays must do more than convey information and their contents must therefore foster the efficient performance of many other tasks by the controller. These further functions are mentioned in Appendix 1 in relation to task demands. They cannot be fulfilled unless the information content of displays meets their requirements also. A comprehensive task analysis or synthesis should show this, but it does not always put sufficient emphasis on them or recognise some of the new roles which the display must fulfil because of changes at the man-machine interface associated with advances in display technology and the progressive dissociation of the man from his real task of controlling aircraft.

The information content of air traffic control displays is not interpreted in a naive and untutored way. Those who view air traffic control displays in the course of their work already know a great deal about air traffic control. To someone with no knowledge of air traffic control much of the information content of air traffic control displays is incomprehensible. The fact that the knowledge of air traffic controllers is taken for granted when the information content of their displays is specified must not obscure its importance. Displays do not normally contain information about air traffic control procedures or instructions, nor are detailed legends provided, as for a map, which define the meanings to be assigned to all the symbols and information categories portrayed. It is presumed when the information content is specified that the controller knows what all the displayed information means, what his tasks are, what rules, standards and conventions he must follow, what the objectives of air traffic control are and what constitutes safe, orderly and expeditious control of air traffic. The information content of the displays must therefore be matched to the controller's training and knowledge. Since far more air traffic control information could be portrayed than can be depicted on displays, there is a tendency not to portray information all the time unless it is needed, countered by the preference of the controller to see all the information that can possibly be made available to him, or at least have access to it. It is very important in the specification of information content of displays to ensure that the assumptions about the controllers' knowledge are correct. It would be a serious mistake to present information on the assumption that the controller will know what it means, only to discover that he cannot fully understand it.

Three kinds of human factors problem are of particular importance in relation to the information content of air traffic control displays:

(1) The unnecessary presentation of information which the controller already knows should be avoided, but sufficient information must be provided to serve as a frame of reference for him so that he can see how to apply what he knows to the interpretation of the information content of his displays.

(2) The specification of the information content of displays must not make too many assumptions about the controller's knowledge since otherwise vital information will be lacking; the controller's training should therefore be examined before the information content of his displays is finally specified.

(3) The information content of the controller's displays should be in a form and at a level which is compatible with his knowledge and experience, and in particular the information content should facilitate his recall of relevant knowledge when it is needed.

A major potential advantage of the direct participation of experienced controllers in the specification of the information content of their displays is their ability to relate the displayed contents to their professional knowledge.

The information content of displays should foster the controller's learning and understanding. To learn, he needs to be able to see the consequences of his own actions, both to discourage less successful procedures and strategems and to entrench those which are near the optimum. Although some knowledge of results can come from others - supervisors, colleagues, pilots - most must come from the information content of displays which are the basic means of conveying information to the man about the system, its current condition and the state of progress.

Data about the system and about what is happening in air traffic control terms are therefore necessary for man to improve by learning, but they also form part of the information content of displays for other reasons. The amount of knowledge of the system and its functioning needed by the controller in order to apply his basic skills to it in the optimum way is a matter of debate. Currently, most air traffic controllers do not know much about the hardware or software of the system, to the extent that they may criticise the system designer for failing to achieve what he never intended. As wholly manual tasks are gradually replaced by tasks where man-machine interactions in various proportions are essential, evidence has accumulated that the man needs to understand the functioning of at least some aspects of the machine quite thoroughly before he can achieve the most safe and efficient air traffic control while using it. While the information displayed cannot be adequate to tell the man all he may need to know about how the system is functioning, and therefore he must acquire a considerable understanding of the system before he can use it properly, nevertheless it is taken for granted that the information content of the displays must contain some data about the system itself, such as its serviceability. As long as an envisaged role for the man remains that of manual intervention and task performance in the event of system failure, insofar as this role is feasible it follows that the information displays must be able to indicate such a failure, and preferably its extent, its cause, and the automated and manual functions which can still be performed.

A major difficulty is to predict what the information content of the displays would be if the system were to fail in a way in which it had never failed before. In highly automated systems, very many kinds of failure can occur, all of which are likely to be rare and unfamiliar. In the event of a failure, the man may have no way of knowing what has occurred or what its implications are, except by the information content of the displays that remain to him. In certain instances of failure, there may be no information content, or the dynamic information may freeze in its condition when last updated. This may indicate a failure, but not its nature or extent or the most appropriate course of action.

The information content of displays derived from data stored and collated in a computer can be seriously deficient in qualitative information. The strength of processes such as task analysis and synthesis is their efficacy in defining the quantitative information required; a weakness can be their inadequate coverage of its qualitative aspects. The information content of displays should include in some form some cues to the quality of the data portrayed - its accuracy, the frequency and magnitude of its updating, and the extent to which it should be trusted. A secondary radar display, or a tabular information display of air traffic control alphanumeric data, provides no visual distinction between accurate or inaccurate data, between data which are up-to-date or are out of date, or between data which should or should not be trusted. Here the problem is not simply to recognise that the information content of the air traffic control display should incorporate some qualitative information of these kinds; it is also a problem of portrayal, since widely acknowledged and accepted visual conventions to depict even gross differences in information quality are not to hand, though they are badly needed.

In air traffic control and elsewhere, various forms of automation are beginning to pose a problem now which will become more severe in future, and which directly affects decisions about the information content of displays: if certain aspects of systems are too complex for the man to understand, and are designed to function automatically, it seems probable that even his most well meaning and well informed attempts to intervene might do more harm than good. If it is suspected that the man may misinterpret the contents of information displays in this way, one solution is to withhold the information from him by not presenting it on his displays. Not the least of current problems when deciding what information should be presented to the man is to consider what he could possibly do with it, and whether any of his misunderstandings from an inadequate appreciation of its significance could be so potentially dangerous that the information must not be presented at all. This kind of problem is already being faced in the context of other large man-machine systems such as nuclear power plants and chemical processing plants and advanced aircraft cockpits, and it seems likely to arise in air traffic control. It is also clear that any apparently simple solutions to it are likely to prove far too facile.

## 8d VISUAL CODINGS, INCLUDING COLOUR

This section is concerned with the main visual psychophysical variables which can be employed to code the information on air traffic control displays. Where applicable, it includes some indication of appropriate applications and limitations of each coding variable.

### Dimensions

Perhaps the most basic distinction is between point, line, area and volume codes, which with some slight simplification, can be described as codings in no, one, two or three dimensions. In air traffic control, information based on this distinction is confined almost entirely to radar displays and ancillary map displays: on displays of tabular information, the uses of points and lines tend to be limited to the visual structuring and alignment of other data.

#### Point

A point on a radar display denotes the location of an item; a point alone cannot convey much further information, and it needs to be embedded in, or associated with, further codings if information about the nature of the located item has to be presented to the controller. Different categories of information cannot be conveyed by points alone. At least as a coding points have the advantage that they do not occupy much space!

#### Line

Lines are often used extensively for coding on radar displays, as straight lines or curves, and as continuous lines or lines segmented in a variety of ways. A line, used to depict an aircraft track, can show position, heading, approximate speed, and, if associated with a point or symbol, direction of movement. A line can also serve as a tag, to associate the position of an aircraft with further information about it.

Lines are employed to depict boundaries, for example where there is a change of air traffic control responsibility, and to depict linear features such as coastlines. Circular lines, in the form of range rings, connect points that are equidistant from a designated position. Pecked lines may be used as a kind of electronic ruler to assess distances. Line coding has been tried, but with less success, to depict height by a column, particularly in attempts to include a perspective view of three dimensional traffic on a two dimensional surface. A further use of line coding has been to extend it ahead from a current position to show the predicted routes of an aircraft and future positions.

If more than one meaning may be assigned to a line on a display, these meanings must be clearly distinguished by combining the lines with other codings, of which colour and segmentation are likely to be the most successful. Contrast may also be varied in association with line coding, but line thickness, a successful coding on some hard copy, is seldom suitable for electronic displays.

#### Area

A series of lines are the usual method of depicting an area, by outlining it. The commonest types of area depicted on air traffic control displays concern airways or air corridors, danger zones, and regions within which some flying restriction, such as a minimum altitude, is in force. Line codings depicting different kinds of areas must themselves be conspicuously different. If other codings are combined with lines and areas, the meaning of each combination must be unique. The distinction in meaning between lines which differ in brightness or colour, for example, must correspond to differences in meaning between any other symbols or information which also differ in the same way in brightness or colour. This principle is vital: to ignore it can be potentially dangerous. Further important principles are that any differences between lines must remain clearly discriminable under the most adverse viewing conditions and must never be near the visual threshold, and that the magnitude of the visual difference resulting from the codings should bear a reasonably close relationship to the operational significance of the difference which it depicts.

#### Volume

Apart from experimental three dimensional displays, codings by volume are not used in air traffic control. They should not be confused with area or linear codings that may be employed in attempts to depict three dimensional space on a two dimensional surface. Height information about aircraft in plan view exemplifies three dimensional data on a two dimensional display.

### Shape

Shape coding is by far the commonest coding employed for information on air traffic control displays. Usually it takes the forms of alphanumeric characters or symbols.

#### Alphanumerics

There are various national and international standards for the design of alphanumeric characters, but most of these are intended for non-luminous characters with good contrast with their backgrounds and full flexibility in their depiction. Electronically generated characters generally have restricted flexibility, and sometimes technological limitations can impose serious constraints on their legibility. In air traffic control, alphanumeric characters have the great advantage that they can often conform closely to the content of the visual or verbal message received in alphanumeric form (e.g. callsigns, heights, speeds, reporting times, etc), and therefore alphanumerics can obviate much cross coding.

The extent to which alphanumeric characters can differ is illustrated in Figures 8 and 9. The aim in the design of any set of alphanumeric characters is to make them as legible as possible and as discriminable as possible from each other, within the limits set by context of use, physical environmental viewing conditions, and principles for character generation, such as the use of a 7 x 5 dot matrix. Occasionally, these limits become so severe that a full set of characters, all of which are sufficiently discriminable to meet operational requirements, cannot be generated, although with technological advances this difficulty has become much less common in recent years. Indeed technology has now advanced so far that there can no longer be any valid excuse for tolerating poorly discriminable alphanumeric characters on electronically generated air traffic control displays; many good character sets are available, and poorly discriminable characters can be hazardous.

The height of alphanumeric characters on air traffic control displays may not agree with handbook recommendations, especially for characters on radar displays where compactness is sought to minimise clutter and label overlap. Air traffic controllers have high eyesight standards. The characters in Figures 8 and 9 would require different heights to ensure legibility. It is therefore not possible to give a single recommended height for alphanumeric characters on air traffic control displays, regardless of other factors: sources which do should be treated with scepticism.

The principles to test for the discriminability of alphanumeric characters are fairly standard: they include the progressive degradation of characters or viewing conditions to discover their margin of safety, the measurement of errors which occur during task performance, and the emphasis on known sources of confusion to check that none of them is prevalent. Examples of known common confusions are between O and Ø, between S and 5 and 8, between I and 1, etc. The quirks of a particular method of character generation may result in confusions between characters not normally confused with each other. The compilation of a grid in which the presented character is compared with the reported character[125] reveals particular confusions which may have to be tackled as specific artifacts of the particular character set and require ad hoc solutions. Sometimes in designing individual alphanumeric characters it is advantageous to exaggerate somewhat the most salient features of each, as a means of enhancing their discriminability from each other. Characters which are to a slight extent caricatures of themselves can appear odd when drawn at a large scale, but acceptable and in no way exceptionable when presented on an air traffic control display at a small size, including the slight visual thickening and blurring of characters often associated with cathode ray tube displays.

Shape coding is also a basis for symbols, which are used on air traffic control displays of tabular information and on radar displays. The use of symbology in air traffic control is nevertheless quite limited compared with its use in other contexts such as air defence systems, and therefore the visual problems which can arise from combinations and superimpositions of symbols do not normally occur in their severest forms on air traffic control displays. Proposals for elaborate symbology codings in air traffic control are made from time to time, but seldom reach fruition.

In shape coding, there is a potential clash between the requirement to maximise the discriminability of each symbol, and the requirement for an unambiguous name or descriptor for each symbol. There may be no obvious name to denote a gawky irregular shape which in fact is highly discriminable from its background and from all others: as a consequence it is discarded in favour of other shapes (triangle, square, circle, octagon, etc) which may in fact be less discriminable from each other but have the advantage of an unambiguous, universally known, and recognisable name. This property of alphanumeric characters as shapes, that each has a name, is so often taken for granted but perhaps is their major advantage, to the extent that alphanumeric characters are retained and efforts are made to improve them even when they are poorly discriminated, because they can be designated so unambiguously. They differ grossly in certain visual dimensions such as symmetry, but nevertheless are viewed as a distinct shape category, as are symbols with equally familiar names.

Symbols which are not inherent meaningful in this way are more readily confused with each other, and although they may be easily discriminated if they are present on a display at the same time, confusions can nevertheless arise if they have to be referred to in order to convey information to others. Certain combinations of shapes, and of symbols in particular, with other codings such as size, brightness, colour or flashing, are usually possible without impairing the controller's ability to recognise the shape, but attempts to combine one symbol which denotes one meaning with another symbol which denotes another meaning into a single symbol intended to convey the meaning of both may render both the original symbols and the combined one unrecognisable. The visual principles involved, though often cited as the basis for symbol sets, must always be employed, if at all, with extreme caution. It is best in air traffic control to keep to simple inherently meaningful symbols such as arrows, with a few easily named shapes to denote major categories (preferably with shape as a redundant coding combined with another coding dimension). Certain symbols, such as asterisks, should be used very sparingly: they have a commonly recognised name but no inherent meaning in an air traffic control context so that their significance has to be learned and remembered. Symbols which have neither an obvious unique name nor an inherent familiar meaning should be avoided if at all possible in air traffic control.

Size

Size as a coding dimension is not used much in air traffic control, but it can be very useful. Normally information on air traffic control displays is presented as compactly as practicable for safe and efficient use. Therefore there are few opportunities to employ size coding by reducing the size of items of information: its usage must therefore be confined mainly to increases in size. The selective use of increases in size can make the required items of information stand out well without disrupting everything else excessively. Only one increase in size is usually practical, or at the most two in very rare circumstances. Size is more effective as a relative than as an absolute coding. It may be readily apparent that items of data, such as labels, characters or rows, are not all of the same size when they are present on the display together, but much more difficult to tell, if all of the presented items are of the same size, which of several possible sizes they in fact are. Size as a coding must always be used sparingly. Differences in size should be related to the importance of the distinction drawn; if an item is very large it must be very important indeed. Size as a coding dimension can also be useful when applied to the gaps between items or blocks of items, rather than to the items themselves. Differences in the size of gaps may designate clearly differences in the degree of association between data in different blocks.

Texture

Texture as a coding is not applicable on most air traffic control displays or on electronically generated displays, where subtle differences in surface texture within symbols may be difficult to represent. Only gross differences in texture, as between outlined and filled symbols, may be worth considering, and then only if there is a compelling logic which makes the respective meanings assigned to different textures obvious.

Contrast and Brightness

Contrast is a main determinant of the possible uses of brightness as a coding dimension. In addition, most electronic data displays impose some limitations on the different brightnesses that can be generated. For information on air traffic control displays in a modern environment with ambient lighting approaching the standards recommended for offices, and with display surfaces which do not have high reflectance, a contrast ratio between luminous characters and their background of about 8:1 is generally suitable. Contrasts greater than about 10:1 tend to show some disadvantages and higher contrast ratios per se convey no benefits. Ratios below about 6:1 may begin to produce difficulties or occasional misreadings in some circumstances, although ratios as low as 3:1 may sometimes be tolerable for certain kinds of non-essential information which are meant for reference and are deliberately intended to be unobtrusive. To maintain legibility the size of characters may have to be increased if their contrast is poor: even so, increased size can compensate for reduced contrast only within narrow limits.

These contrast ratios are guidelines: there is no need to follow them slavishly, and due regard must always be paid to the effects of particular display characteristics or physical environmental conditions. However, any use of brightness as a coding should not incur gross violations of these guidelines for contrast, and the differences in brightness must be clearly discriminable. The implications are that only two brightness levels can normally be employed, and that brightness is usually, though not necessarily always, used to introduce a few items of more important information at a higher brightness than the standard one, rather than to present items of less importance at a lower brightness level than the standard.

A recent problem, an artifact of technical achievements, is that the background of a modern cathode ray tube can sometimes become so textureless as to contain no visual surface perceivable to the viewer. High contrast items of information can therefore appear to be floating in space within the display rather than resting on a surface. This problem can be aggravated by colour coding, which may make differently coloured items of information appear at different visual distances, an effect which is merely disconcerting and not sufficiently regular or controllable to render these apparent differences in visual distances useful in their own right as a coding dimension. Since textureless backgrounds are often associated with excessive contrast, the best human factors solution is usually to degrade the background so that some surface texture is perceivable, or to use the ambient lighting to impose a just perceivable visual surface on the display.

On luminous air traffic control displays, the convention is to have bright characters on a dark background. The concept of inversion in this context therefore refers to dark characters against a light background. Its meaning for luminous displays is therefore the opposite to that for non-luminous displays such as hard copy where inversion generally refers to bright characters against a dark background and dark characters are the norm. As a coding, inversion can be effective in principle if used sparingly and with a realistic appraisal of the consequent problems that have to be overcome. One of these is that characters on luminous displays almost certainly must be thickened and may have to be redesigned or increased in size to retain their legibility when they are inverted and become dark characters against a light background. Another consequent problem is that the extensive use of inversion increases grossly the total light output or luminous flux from the display as a whole: this can create extensive patches or areas of the display which seem, and are, excessively bright in relation to the other sources of light within the workspace. Extensive use of inversion as a coding can therefore upset a careful design intended to bring the various light sources into harmonious balance. Thus, if used properly and rarely, inversion can be an effective coding dimension for air traffic control displays: if misused or applied in ignorance of the consequential effects that have to be allowed for, it can render information illegible.

Colour

Probably the most attractive and most studied coding for air traffic control displays and for displays in many other contexts in recent years is colour[126,127]. On non-luminous displays, colour is really three codings, hue, value and chroma, which can be varied independently. Technological principles or limitations preclude the independent manipulation of these three dimensions in luminous displays. Colour display technology has advanced greatly in recent years, and will continue to do so in the near future. This has two implications: one is that any current application of colour coding is likely to become technically obsolete in a short time; the other is that there is a risk of introducing colour coding in a form dictated by what is immediately feasible in the present state of technology rather than what would be ideal or most efficient for air traffic control. It is seldom possible with current technology to portray related information on several adjacent air traffic control displays with a different technological basis in the same colour, yet this might be an effective usage of colour on air traffic control displays.

One compelling reason for introducing colour is because it is available. Another is that people like it so much. These may in themselves be sufficient reasons for introducing colour displays into air traffic control, but it is unlikely that the introduction of colour coding will bring marked benefits in task performance, efficiency or safety at the present time. The reason is not that colour is ineffective; indeed as a coding it can be highly successful. Rather the reason is that alternative monochrome codings, selected with care, can usually be equally effective. For example, colour coding can help to counter the effects of label overlap on radar displays, but it is not the best way to deal with label overlap. Also, colour, being highly influential as a visual coding, can predominate visually over other codings which are also present, and should therefore be reserved for distinctions of major significance. But colour comes late to air traffic control radar and electronically generated displays. Distinctions of major significance, essential to air traffic control tasks, are already in existence in monochrome, using codings which have become familiar to users, the effectiveness and safety of which have been proved.

Colour must always be used in the same way throughout to make distinctions on only one dimension. The present options for using colour coding are:

(1) To wait until a new and vital distinction is needed in air traffic control information, and to consider the relevance of colour coding to it.

(2) To use colour to make a distinction not hitherto made, which tends to imply a trivial or optional usage which has not hitherto been essential in air traffic control.

(3) To reinforce by colour an important existing distinction currently made by a monochrome coding by using colour as a redundant code and depicting the distinction in colour as well.

(4) To replace an existing familiar important monochrome code with colour coding and to use colour as a non-redundant code.

(5) To use colour coding in a partially redundant way, by combining or sub-dividing distinctions embodied in more than one existing monochrome coding.

In practice, it is almost impossible to use electronically generated colour coding in a wholly non-redundant way, since for technical reasons colour differences are invariably confounded with differences in brightness and in contrast in current real-life applications of colour coding. The currently preferred monochrome colour for luminous air traffic control displays is usually green. This is partly because it lies in the most sensitive part of the visual spectrum, and in terms of contrast is often better than yellow or white (with excessive contrast) and than red or blue (with too little contrast).

If colour is used for a single clearly defined purpose, then the usage of colour can be optimised for it. In air traffic control, these circumstances never apply. The coding must serve several functions in different air traffic control tasks, and any particular application of a coding therefore tends to foster some tasks and to hinder others. Numerous possible applications of colour coding on air traffic control displays have been suggested[126]. They include:

(1) Distinctions between eastbound, westbound and crossing traffic.

(2) Distinctions between aircraft controlled by a specified individual controller or controlled by others.

(3) Distinctions of aircraft according to their height.

(4) Distinctions between actual information and predicted information, or between current and future states.

(5) Distinctions according to the nature of the air traffic control service provided or offered.

Colour coding would probably succeed for any of these applications for certain tasks, at the cost of hindering other tasks, but the very fact that so many uses have been seriously considered suggests that colour coding is not obviously uniquely suitable for any particular application. Logically, perhaps the favoured distinction would be between eastbound, westbound and crossing traffic on a controller's display, since his flight strip information is, or was, colour coded according to this convention, and therefore the controller is familiar with it. While this usage can facilitate the controller's ability to perceive as a single visual entity on a radar display a stream of aircraft flying along an airway in the same direction, it may not facilitate the detection of potential conflicts between opposite direction traffic, the conflicts requiring most urgent attention, since this would require the cross-referencing of data in different colours which may be more difficult to perceive as items to be compared when they are in different colours than they would be when in monochrome.

In principle, colour coding facilitates search tasks, but this holds true only if the colour of the sought item is known beforehand. If an item of information in a tabular air traffic control display changed, and, because it had changed, was coded in a different colour until the controller acknowledged that he had noted the change, whereupon it reverted to normal, this usage of colour coding would facilitate search. However, to code the changed item in a larger size, at an increased brightness, or by flashing, would all achieve comparable results in monochrome. Similar considerations apply to the coding of information needed for emergencies. Colour can succeed about as well as alternative monochrome codings.

Two kinds of advantage for colour as a coding may however be postulated for consideration. One is that, if the same colours can be generated on different displays, the cross-reference of information on different displays all relevant to an emergency or particular problem could be helped if all the relevant data could be presented temporarily on all the displays in the same colour, a colour not employed for any other purpose elsewhere. The other putative advantage is that although colour coding may not of itself improve the performance of tasks at the time when they are done it may facilitate the subsequent recollection of them and of the information that was present.

The general guideline that three or four colours only should be used on displays is reasonable for most air traffic control applications, and particularly for categories of dynamic information. For background information, at lower contrast levels, many more colours can be used. A topographical map or a projected moving map display illustrate the subtlety and complexity of colour coding that can be employed successfully if the format is appropriate and the coding conventions are clearly understood or self-evident. Many colours can be employed in semi-pictorial applications, such as the depiction of boundaries and danger zones, as long as they are all discriminable and are not obtrusive enough to become confused with dynamic information about individual aircraft.

It cannot be emphasised too strongly that the efficacy of colour as a coding does not depend primarily on colour at all but on contrast. A red character against a green background can be very difficult to read if the contrast ratio between character and background is nearly 1:1. The need to maintain recommended contrast ratios when employing colour coding is of overriding importance.

Colour combines quite well visually with most, but not all, other codes. It can often be used in conjunction with shape, size or brightness. With point information, colour is just about useless, and with lines its value is limited. Attempts to combine colour with inversion can be so ill judged as to produce classic demonstrations of how colour coding should not be used. On the whole on air traffic control displays, it is best when using colour coding not to attempt to colour both information items and sections of the background as distinct from the whole background. If this is attempted, the legibility and aesthetic qualities of the outcome can be grossly different from what would be predicted. Sometimes for example, a successful application of colour coding to a row of data on a tabular air traffic control display is to vary the chroma and value but not the hue within the row: an instance would be pale unsaturated blue alphanumerics against a dark saturated blue band as background. Never introduce this kind of combination of colour coding based on theoretical visual principles only, without checking to see what it would actually look like.

Stability

One way to draw attention to information on a display is to move it or change its state. Care has to be exercised when this is done; a movement or change glimpsed peripherally for an instant, which is no longer there by the time the observer can look at it directly to determine what has moved or changed, can be irritating and lead to time consuming data checking. The use of movement as a coding also depends on the display phosphor, with long persistence, movements have to be relatively large and infrequent to curtail smear. With a short persistence phosphor, movements of labels and tracks can be in much smaller increments, can give an impression of continuity, and can therefore convey greater positional accuracy. Coding should not be by movement alone, and dynamic information should be portrayed differently from static information so that the two can always readily be distinguished. Methods of generation of data on air traffic control displays which can induce any form of spurious apparent movement should be avoided.

Flashing or blinking of items of information can be an effective way of drawing attention to them, but is distracting if it persists. Flashing or blinking can be used to denote the occurrence or imminence of a change, but should be cancelled automatically, or by a simple manual function, whenever the required action has been initiated. The recommended flashing or blinking rate is about two cycles per second, with the duration of each flash or blink being approximately as long as the duration of the gap between consecutive flashes or blinks. Flashing as a coding must be used sparingly, to draw attention to information of importance. As a general guide there should not normally be any visible flashing items of information on a display while it is in use. Flashing should be an occasional and selective coding. It is not inherently meaningful, and is best employed to draw attention rather than convey information. Different frequencies of flashing are not recommended as a means of drawing distinctions. The differences have to be gross to be reliably discernible and interpreted correctly.

All the codings discussed above refer to visual differences in the coded information itself. It is also possible to code distinctions by the inclusion or exclusion of additions to the information, while keeping the information itself constant. An example already mentioned concerns the addition of asterisks or similar symbols to distinguish designated items of information from others. Underlining is a further example. Additions to symbology can become quite complex. For example, a box may be drawn electronically around the aircraft label on a radar display to denote that the aircraft has strayed from its planned flight path by more than a defined tolerated margin; the box may be retained as long as the aircraft remains in this condition; part of the box may remain to denote that a revised heading has been issued and to act as a reminder that the controller's task is not yet complete; the whole box may be removed only when a final instruction has been issued to the pilot to return to normal navigation.

Very many additional codings are possible. To choose the most appropriate one, the task is studied and the precise information to be conveyed is established. In most circumstances, a conventional coding dimension is preferable if it will suffice, but occasionally an unusual tailor-made additional coding may convey the required information in the most directly meaningful way, with a visual prominence commensurate with its operational significance.

Absence of Information

The absence of information can itself be a form of coding. If all is well, or a facility is not in use, this can be implied by showing nothing. As a principle, this reduces visual clutter, and it is commonplace in the coding of control labels and in the coding of displays which show serviceability states for maintenance purposes. However, it is better to show important operational information positively: this not only indicates its presence but also acts as a reminder.

Most air traffic control displays need to contain so much essential information, to be coded as succinctly and compactly as possible in order to minimise clutter, that there is little likelihood of any substantial amounts of unnecessary information appearing on them. The problem is rather to ensure that all essential information is present or readily available. Compactness of coding is therefore a great practical advantage. Also it is prudent to consider using redundant rather than non-redundant codes for air traffic control information wherever practicable. It may be impractical in the case of much alphanumeric information, but redundant codings for purposes of categorisation are often feasible, and where they are they should be adopted.

8e LEGIBILITY AND READABILITY

In common parlance, these concepts are often treated as interchangeable. In human factors terms they are not, but represent separate and successive phases. Most of the effort devoted to the coding of information on air traffic control displays is intended to achieve legibility, which is a prerequisite for readability. If characters look similar enough to be confusable with each other, this represents inadequate legibility. The means for enhancing legibility of characters depend partly on the way in which the characters are generated, but they normally include:

(1) The improvement of brightness and of contrast between characters and their background, so that the contrast and brightness are neither too low nor excessive.

(2) Adjustments to the size of characters, generally but not necessarily by increasing their size: characters generated by dot matrices in particular are not necessarily made more legible by making them bigger.

(3) The optimisation of the spacing between characters within a word, between words, and between rows of characters.

(4) The design of individual characters to minimise the visual similarities between them, to emphasise the most distinctive features of each, and to render them more visually harmonious as a set.

(5) The prevention of conditions known to degrade legibility, such as the overlapping of characters.

In tests of legibility characters are viewed and reported, often under conditions in which they are deliberately degraded by reduced contrast or restricted viewing times. The purpose is to prescribe conditions under which errors in the discrimination of characters are more likely to occur in order to gather sufficient data to compare alternative character designs in terms of the incidence of errors associated with them. Errors in discrimination or identification are also categorised by character. Certain characters are more likely than others to be confused with each other[125]. Particular attention is paid to the specific errors predicted as most probable and to those which actually occur associated with each character in a known character set. With alphanumeric characters, containing a set of 26 letters and 10 numerals, whether an "3" is confusable visually with an "8" or a "5" or both or neither, or with another character altogether, depends on specific details in the design and method of generation of each character. Which potential confusions are operationally significant depends on details of the tasks. With symbols, the extent of errors arising from failures in legibility depends more on the choice of symbols; for example, a square and a circle may be highly discriminable as symbols, but the inclusion in the same set of symbols of a visually intermediate symbol such as a hexagon or an octagon may not only lead to poor discriminability of the additional symbol but may also degrade seriously the legibility of the square and the circle, both of which may be confused with the hexagon or octagon though not with each other.

Methods that rely on degradation of the viewing conditions for assessing legibility may be ergonomically defensible but logically dubious. If the degraded viewing conditions will not arise in real life in air traffic control, the legibility errors which occur under operational conditions may not necessarily be those found under the more artificial circumstances of the laboratory. The rationale therefore has to be proved before findings from legibility studies in simplified laboratory settings can validly be applied in real life. Sufficient is now known about legibility, its criteria, methods of measurement, influences, standards and findings, for the legibility of any given character set, and the particular sources of potential decrements within it, to be established by a competent human factors specialist by inspection and the application of known principles, without recourse to experimentation except to verify the correctness of the conclusions and recommendations in a few particular instances. There are however, certain circumstances where this does not hold true and the human factors specialist will wish to conduct practical evaluation trials to measure legibility: these circumstances occur with novel methods of character generation or non-standard environmental viewing conditions. In relation to legibility, it must not be presumed without verification that findings for non-luminous displays will apply to luminous ones, or that findings about one type of luminous display such as cathode ray tubes, will apply to others such as plasma panels. The legibility requirements of certain kinds of display, such as electroluminescent panels, may be unique to that display type so that separate studies of legibility must be conducted using them.

Whereas legibility is concerned with perception and is measured by tests of detection, discrimination or identification, readability is concerned with cognitive aspects, and is measured by tests of cognitive functions such as learning, comprehension and memory. The subject-matter for laboratory studies of readability is usually written text of some kind, although the variables within it are often perceptual. If the legibility is inadequate, this affects readability, and in many respects there is no point in studying readability until all the material proposed for use in a readability study has been shown to be legible; otherwise, a failure in comprehension, attributable to inadequate legibility, may erroneously be ascribed to poor readability of the text.

Because readability is assessed in terms of comprehension, it is more common to talk about the readability of the design of the whole text or character set, whereas legibility can and does vary a lot between the specific characters within a character set and legibility is often discussed in terms of individual characters and symbols. Sometimes the pattern of eye movements, measured by an eye movement recorder, is enlisted as an index of differences in readability, and similar techniques, applied slightly differently, can be used to assess legibility also. Although different text designs may impose detectable differences in patterns of eye movements while they are being read, this may in turn be of little practical significance if the differences do not have any measurable cognitive correlates.

Because of the nature of air traffic control, displays, as distinct from instructions and job aids in the form of hard copy, seldom contain any substantial quantities of text intended to be continuously read, and therefore most of the standard tests of readability cannot be applied directly to the information on an [illegible] traffic control display. The main ways of assessing the readability of such information include:

(1) Measures of the search patterns which the information imposes, and of variables in it associated with perceptual differences (legibility also affects these measures).

(2) Measures of task performance with particular reference to the information which must have been read for the task to be performed, and to the errors, omissions and delays which occur.

(3) Measures of the extent of understanding and comprehension of the material read, related to the time required to read it, or measures of the amount read and understood in a given time.

(4) Measures of recollection of what has been read, related where relevant to the time spent in, or required for, the reading.

Comparative measures of alternative ways of presenting the same information, based on assessments of comprehension and time required.

(6) Measures of specific errors and delays, to try to trace whether their origins include inadequate readability.

(7) Measures of texts known to be highly readable in other contexts, to assess their adequacy and readability under air traffic control conditions.

Because the controller knows a great deal about air traffic control and can deduce information often without reading the display at all, there can be a problem, in assessing readability, of disentangling the presented information from other information already known to the controller but not actually read.

Layouts, formatting, display contents, and display coding, as well as legibility, are among the display variables which can affect the readability of information on air traffic control displays substantially. Readability studies often include deliberate specifiable variations in these dimensions, and measures of their cognitive consequences. In the case of legibility, it is usually possible to determine when an approximate optimum has been achieved, because the few residual errors are nearly random and could not be substantially reduced by a few specifiable changes. A comparable judgement, that near optimum readability has been achieved, may not in fact be possible; all that can be said is that the readability attained is operationally acceptable, will suffice to meet the air traffic controller's objectives, and does not seem to be improvable by any specific suggestions that can be made. This does not imply that readability could not be further improved, but that it is not possible to specify the maximum attainable level of comprehension of the material or the fastest rate of reading while retaining full comprehension. Therefore if the optimum readability has been attained, it cannot be recognised; if further improvements could be attained, they might not be recognised either. What would constitute perfect performance can be specified for legibility but not for readability.

8f RELATIONS BETWEEN DISPLAYS

Compared with the basic flight instruments in an aircraft cockpit, the displays within the workspace of an air traffic controller interact less closely with each other, but nevertheless they are not wholly independent. Different air traffic control displays have tended to evolve separately, in accordance with air traffic control system designs, traffic demands and technological advances. Primary radar displays have given way to secondary radar, on which additional information, mainly alphanumeric or symbolic, has in its turn evolved. Manually written flight strips have been replaced by automatically printed flight strips, and latterly by electronically generated displays of tabular information corresponding to flight strips. Displays of various kinds, notably those which double as input devices because they are in some way touch sensitive, have also been developed independently. Technological changes, coupled with the recasting of the controller's roles, have influenced the need for general wall-mounted displays of air traffic control information, and led to changes in the contents of such displays, often generated according to novel principles. On the whole, these and other display developments have not been related closely to each other from their incipient beginnings, but the task of relating and reconciling them has been left late, on the assumptions that it can be done and that major modifications to the displays themselves would not be a precondition of successful reconciliation. In some contexts, none of these technological changes has been made, and the equipment for air traffic control is still primitive.

Two separate aspects of the relationship between displays deserve consideration: firstly, their positioning within the workspace; secondly, the user's integration of their displayed contents.

Some problems in the relationships of the displays within the workspace originate if such factors are not considered in detail from the outset but are settled when decisions about display size, user's functions, and the approximate display content have already been reached. The problem of trying to pack too many displays into a workspace wh[illegible] if it is to meet the normal requirements imposed by reach distances and viewing distances is too sma[illegible] accommodate them all, cannot arise in the form which it usually takes in air traffic control unless [illegible] problem of display positioning and the relations between displays is treated as secondary. The decision on the size of a radar display, for example, can, and must, have a major influence on where other displays can be put, on what their viewing angles will be, on whether they can be alongside or above each other, and on how high up they may need to be placed in the console, regardless of what their contents are. A different order of priorities, assigning greater importance to the relationships between displays, would result often in a workspace that looked very different. This is not to say that greater importance should be assigned to display relationships - indeed, on the whole, it probably should not. The intention is rather to point out that because of various decisions taken about individual displays, and because of the persistent tendency to try somehow to fit into the limited workspace all the displays decided individually to be necessary, there is often very little flexibility remaining within which to optimise display relationships. The implications for all displays therefore need to be spelled out more clearly at the time when decisions about each one are taken.

Problems about the relationships between displays in terms of the integration of their contents are partly determined by where they are in the workspace as well as by what they contain. The positioning of displays should influence their contents. One obvious example is that displays above eye level should not include any information that must be consulted frequently. Collectively, the displays must contain all the information necessary for tasks. The controller has to obtain all the information he needs in the most efficient way from the various displays. Presuming that information categories have been allocated to various displays sensibly in relation to the technical limitations and purposes of each, and that within each display the format, coding and design of the information content have been devised competently, the main aim is to make the information on different displays as compatible as possible so that it can be collated quickly and efficiently with a minimum of fuss, confusion or error. This means that:

(1) Different displays should wherever possible incorporate the same principles of layout; if different principles are followed they must be related in ways that are self-evident.

(2) An information coding used to denote a specific information category on one display should be used to make the same distinctions on all other displays, and never for anything else.

(3) The visual appearance of related information should reflect the closeness of the relationship by the degree of its visual similarity.

(4) Information of great importance on one display should be portrayed to denote this and equivalent information on other displays should be portrayed in the same way, or at least in an associated coding which saves search time and is reserved for equivalent urgency. For example, the information required to solve an urgent problem might be flashed at the same rate on all displays. If information which is urgent is coded on some displays in a distinctive colour, a similar colour should be chosen for related information on other displays with a colour capability, and on monochrome displays there should be some means of drawing attention to related information of equivalent importance, a means which is reserved for the same uses as that of the particular colour on the displays with colour capability, and is not also used for other functions unrelated to those coded in colour elsewhere. There should not, in other words, be different confoundings of codings on different displays. If there is, errors are almost inevitable because the meaning then depends on the display on which the information happens to appear.

(5) Wherever possible, conventions should not clash. This can be difficult to achieve in air traffic control where information on a radar display is in plan view and information related to the same aircraft on a tabular information display, or as a set of labels on a data input display, may be set out according to a different principle. There is no ideal simple way to resolve this difficulty. Any solution must lead to certain anomalies. Of overriding importance is that there must be some principle which the controller knows of, understands and can use, to relate the information on one display to that on every other display without fruitless searching. The least flexible display is the radar. Therefore the simplest solutions may tend to follow the principles which it embodies. Even if its principles cannot always be followed (and for some purposes such as listing aircraft in height order or according to destination they may be wholly or partly inappropriate), the data on another display must never be laid out in an apparently random fashion in relation to the data on the radar display. There must be some guiding principle so that the controller knows where to begin looking on the other display for the data which he needs, with a good prospect of quick success.

## 8g THE QUALITY OF DISPLAYED INFORMATION

In air traffic control, as in many other contexts, there has been a progressive change from analogue to digital information. This, coupled with improved display technology, has had two main human factors implications regarding the quality of the information displayed. One is that displays often contain far less qualitative information than they once did, although the consequences of this change may be difficult to determine. The other is that the user tends to ascribe high quality and reliability to clearly portrayed and aesthetically pleasing displayed information, yet there need be no close relationship between information quality and the way in which it is portrayed.

The reduced role of qualitative information on air traffic control displays has occurred partly because no standardised coding conventions have been evolved for use to denote the quality, reliability, validity, accuracy or similar attributes of displayed data. Radar displays perhaps exemplify best the reduction in qualitative information. The primary radar displays of the past, more familiar in air defence than in air traffic control contexts, were subject to clutter, permanent echoes, fading, and poor signal-to-noise ratios. Individual blips, and the tracks which they formed, differed greatly in the ease with which they could be discriminated. The operator could glean from the primary radar display a great deal of qualitative information about whether a track seemed likely to disappear, or had a propensity to fade, or was heading for clutter, or had a poor signal-to-noise ratio, or seemed near the limit of the range of the radar under the prevailing conditions, and, for these or other reasons, depended on data of poor quality or uncertain provenance. Knowing the quality of the data, with associated evidence on its propensity to vanish, become uncertain or become misleading, the controller could allow for this in his division of attention, his allocation of resources and his decision making.

It is impossible to tell, from looking at a modern radar display, anything about the quality of the data from which it has been derived. A symbol may denote the position of an aircraft which represents the carefully weighted average of positions sensed from several radar heads, each giving highly reliable information; or it may denote the position sensed by a single radar head in a dubious state of serviceability: in both cases the radar display would look the same. The controller may not even know which radar head, with its particular idiosyncrasies of coverage, is in fact in use to provide the display. In the absence of such qualitative information, the controller cannot in any way respond selectively to take account of differences of which he has no knowledge. This may not necessarily be important, provided that the system design and its procedures have compensated for the controller's recognised loss of qualitative data: however, it can become highly important if the absence of qualitative data has not been fully appreciated, and failures can be sudden, mystifying and hazardous, rather than predictable, of known aetiology, and largely circumvented. The practical options are therefore to plan tasks so that qualitative information is not needed, or to put qualitative information back onto displays.

Perhaps more insidious as a problem is the ascription of quality to clarity. A radar display on which the position of each aircraft is shown precisely and crisply, using points, lines, symbols and alphanumerics with good contrast ratios and sharp contrast gradients so that the light from luminous characters does not seem to spill over or blur, is perceived as containing information the location and description of which must be known precisely because they are depicted precisely on the display. The fact remains that the radar must show the position of the aircraft somewhere. There may be no means for denoting in visual terms that the data shown so surely on the display are in reality not trustworthy. For some purposes this may not matter; in others it may be vital. The height information about each aircraft on the radar display may be presented in exactly the same way, as three digits within the label of the aircraft, although the quality of the height information may vary substantially from one aircraft to another, to the point where a defect is suspected. If the portrayal of the data remains impeccable, it is all too easy to presume that its quality is of a high order, and that all is well.

In a crude form, the units in which information is expressed convey something of its quality. Separations which cite data to the nearest 10 miles obviously are based on much poorer data that those expressed to the nearest 0.1 of a mile. The air traffic control practices and procedures which are followed depend so much on the quality of the information available that some notion of it can be deduced from examining them. But positive indications of quality, and especially of lack of quality, rather than deductions about it should be taken more seriously on modern air traffic control information displays.

## 8n NEW DISPLAY TECHNOLOGY

The purpose of this section is not to give a detailed description of the current, still rapidly developing state of modern display technology[126], but to note some human factors implications which can arise when these technological developments are introduced into air traffic control. Cathode ray tubes have themselves evolved greatly, and some of the commonest human factors consequences, such as excessive contrast, textureless backgrounds, limited choice of colours and over-saturation of those offered, have already been mentioned. Plasma displays, light emitting diodes, and electroluminescent panels are examples of display types which have been used in, or evaluated for, air traffic control. Various forms of television display are under active consideration or in use. Displays which also function as input devices form a further category.

The human factors issues which these and other developments raise can be subsumed under the following headings:

(1) How far do the recommendations given in human factors handbooks and in related literature for the coding and presentation of displayed information apply to the new technology?

(2) What coding dimensions can be varied and controlled, and what range of options is therefore possible in the content and portrayal of displayed information?

(3) What are the limitations of each new display principle, with particular reference to any which do not apply to other forms of display generation?

(4) What can go wrong with the display, and what would the display look like to the user if it became faulty?

(5) What advantages are claimed to justify the introduction of the new display technology into air traffic control, and what is the substance of these claims in terms of the nature and strength of the evidence purporting to support them?

(6) What sources of human error or confusion will the new technology bring or reintroduce; what is their operational significance, and how can their effects be minimised?

(7) What form of evaluation of the new display principle is required to strike a fair balance in appraising it, so that its advantages can be confirmed and quantified, and also any disadvantages can be identified and assessed?

Any innovation in display technology usually has committed advocates who believe that it brings major benefits and are keen to see these benefits realised wherever possible. Air traffic control is often considered as one of many possible areas of application. The human factors approach to such innovations is often perforce critical, not because human factors is in principle antagonistic to technical innovation (such an attitude would be foolish) but because far more thought has usually been given to its benefits than to its possible disadvantages, so that to obtain a fair judgement it is necessary to redress the balance somewhat, particularly since any unforeseen disadvantages may prove very difficult to circumvent once the innovative display becomes an integral part of an operating air traffic control system. Human factors must also weigh an innovative display against the human factors benefits and disadvantages of the alternatives to it. As a result, the human factors specialist sometimes seems particularly keen on comparative evaluations so that alternative displays can be thoroughly examined in terms of safety, efficiency and the errors they may engender.

A technological advance does not necessarily convey human factors benefits, in displays or elsewhere. If it leads to particular human factors difficulties, these may prove insuperable. It is unlikely that the full human factors benefits of an advance in technology will be realised immediately in the form which the innovation first takes as it is being developed. Therefore it is normal for some improvements to be effected by the application of human factors principles to technological innovations.

# CHAPTER 9

# CONTROLS

## 9a LOCATION OF CONTROLS

Controls are the main means for the man to convey information to the system or the machine. The controls that are provided largely determine the responses which the man can make to system states or machine events, the actions he can initiate, and the choices available to him. Task designs, and the functions envisaged for the man, set the control facilities to be provided. Their location, type, sensitivity, and interactions with other controls and displays determine the efficiency with which the tasks can be performed, and many of the errors that can and will be made.

The broad principles for the location of controls are derived from task requirements and from relevant human capabilities and limitations, couple ith a knowledge of the control options technically available and the characteristics of each. These principles are applied during the design of the system and the workspace, the allocation of functions and the development of the console profile, using appropriate anthropometric data. These combined factors then set the limits within which any residual problems in the location of controls must be resolved. Sometimes further constraints are imposed, such as the specification of all control panels in standard dimensions so that they are interchangeable.

Before the limits imposed by the workspace design, reach distances, and the need for certain controls to be shared, have been fixed, it is essential to establish that there will be room within the workspace for all the controls which must be accommodated to enable the tasks to be done. If the available space is insufficient for all of them, fundamental revisions may be needed. The following options may be entertained:

(1) Re-examination of the preferred control types to see if they could be replaced by more compact controls for which there would be sufficient room.

(2) Combination, amalgamation or removal of certain control functions, again to reduce the space that the controls occupy.

(3) Reallocation of functions so that some, with their associated controls, are removed from the overcrowded workspace.

(4) Re-design of the workspace or the consoles to provide more surfaces to house controls within reach.

(5) Re-location of controls to extend the usable workspace, by employing controls which can be used at greater reach distances, on different surfaces, or with the non-preferred hand.

Until it has been established that all the controls can be fitted into the space available, and until the amount of unused or unallocated space has been gauged approximately so that the degree of flexibility in the location of controls can be estimated, it remains premature to tackle the human factors problems of the optimum location for each control with respect to the relative importance of its functions.

Given that the controls can all be housed, each can be allocated a provisional location. This is an interactive process, with trade-offs of benefits and disadvantages. The fundamental principles are that the proposed location for each control must take account of the proposed locations for all others, particularly those with which it is functionally associated, and that each control must be positioned appropriately in relation to the display or displays to which it refers. Within the limits imposed by these principles, the basic allocation of controls, or groups of controls such as panels, to surfaces is relatively straightforward.

The most important controls should all be located on the main console shelf, positioned so that there is room for appropriate support for the elbow, wrist or hand wherever the task or the type of control requires this. Controls which are specific to a particular display and not in common use should be positioned near the display. Controls, such as light pens, which have to be picked up, held and put down and have special requirements to avoid operator fatigue if they are in frequent use, should not be adopted if alternatives without these support problems will suffice; if they are used, there must be room for appropriate elbow or other support, and somewhere convenient to put the light pen when it is not in use. Controls which are combined with display surfaces are the most difficult to locate satisfactorily: generally the best position for them is towards the rear of a sloping shelf, but sometimes they must be treated primarily as displays and positioned accordingly if the controls are not used frequently or if the control functions change so much that they cannot be remembered and therefore the operator generally has to look at them whenever he uses them. This solution is never ideal in human factors terms; frequent use of such a device can lead to insuperable problems of wrist and arm support.

The broad allocation of controls to surfaces having been completed, work to determine the precise optimum location of each control or panel within the surface can then proceed. The design of the workspace, console and surfaces should ensure that the controls are all comfortably within the recommended reach distances for the smallest operator. The precise location of each control takes account of various further factors, including actuation forces, the direction of movement of the control, the control depth in relation to shelf thickness, the use of the control by the preferred (right) or non-preferred hand, and its intended use by one controller only or by more than one. Tasks are examined not only because they determine the relative amount of use of each control, but also because they indicate the most probable sequences in which different controls will be used. These sequences and frequency of usage should if possible influence the location of controls in relation to each other. This is perhaps most obviously important for specific associated controls within a single control panel, but it is also important when controls in different panels often have to be used in a regular sequence and it may be particularly important for controls intended to be used together or in conjunction employing both hands. Such controls need to be located in positions on the shelf which facilitate two-handed operation.

For all but the simplest tasks, the location of controls is always a matter of compromise. Even with simple tasks, such as those employing a single keyboard, an optimum layout for each key in relation to the others is seldom achievable, since the optimum varies with task details. In air traffic control, the tasks are complex. Controls located in the optimum positions for any single task are unlikely to remain optimum for any other tasks. This is not as important operationally as it may seem: the practical implications are that efficient task performance relies considerably on the man's adaptability, and that training to attain full proficiency in all tasks may be somewhat prolonged. Of greater practical importance than the fruitless quest for the optimum location for every control may be the avoidance of a seriously inappropriate location for any one of them. Controls which require excessive reaching, uncomfortable postures, operation with inadequate support, excessive force, or unusual sustained effort are generally in the wrong place, and should be located elsewhere.

## 9b CONTROL TYPES

The range of controls used for air traffic control tasks and therefore found in air traffic control workspaces is very limited. Controls which require major effort to operate or which are bulky are intrinsically unsuitable. Controls near the front of the shelf must be of limited depth so that they do not restrict thigh clearance but can be housed entirely within the thickness of the shelf; otherwise they must be at the side of the shelf. For most jobs in air traffic control, numerous controls are necessary. Since the workspace is limited, compact controls have to be chosen and placed as closely together as is permissible without impairing performance or generating errors.

The control types in air traffic control are generally restricted to the following, which are considered in turn:

- Push buttons, especially in multiple use in the form of keyboards and panels of keys.
- Touch sensitive display panels, combining display and keyboard functions.
- Switches and knobs, especially for occasional uses.
- Continuous controls, such as joystick, rolling ball or cursors, for functions such as position marking on displays.
- Plugs, sockets and other controls mainly for communications.
- Foot switches.

### Push Buttons

Push buttons or keys are the commonest control in air traffic control now and they will become even more prevalent in future. In principle, a button or key should have two settings, on and off. It is used to enter a single designated unit of information, a description of which is associated with each push button, in the form of a label within it illuminated when the push button is activated or a label scribed or engraved beside it. If the label can be changed, electronically for example in accordance with its position in an input sequence or depending on the task being performed, then in practice a single push button can be used to enter a variety of units of information but each of these units is normally predetermined by sequence and order rather than at the discretion of the operator, and the push button still functions as a control with two settings only, one of which is variable. Push buttons are an efficient way to enter data which are digital and pre-set.

It is essential to indicate whether a button or key is in operation or not. If its function is a change of state (e.g. equipment switched on; range rings shown; larger size radar display label selected; etc) then it should be possible to tell the state selected by looking at the push button or key: it should not look the same in both its possible states. It may remain depressed, or be internally lit, or acquire a different label, but it must look different, so that it is immediately obvious to the user what state it is in. If its function is to enter an item of data, it will generally be one button or key in a row or column of keys or in a keyboard, and it may be activated more than once in rapid succession. Here the essential information that the key has been successfully activated must be given immediately whenever it is operated, by some discernible event on a display and also by the feel of movement of the key against a firm stop.

The operator should be able to feel the movement of the key whenever he operates it, so that he does not have to look at it to tell whether he has operated it or not. Typically a force of some 300 grams should be required to operate it, and its travel discernible, at least 3 mm., with a sudden obvious resistance at the end of travel and no suggestion of sponginess. A just audible click, to denote contact, can be helpful, especially during learning, and even when fully proficient. An operator using a keyboard with which he is very familiar does not normally look at it much, and the absence of a click when it fails to operate may be by far the most effective way to let him know when something is amiss.

The optimum spacing between keys within a keyboard depends on functions. For an alphanumeric keyboard, used to enter substantial amounts of data, the aim is to make the keyboard as a whole as compact as possible to minimise time-consuming finger, hand, and arm movements while operating it: this implies that the keys should be close together. However, if the keys are too close, the probability of activating the wrong one or of striking more than one at once is increased: this implies that keys should be kept apart. The optimum compromise for keys in a row is to have a centre to centre distance of some 18 mm. between adjacent keys in the same row, which includes a space of about 5 mm. between the adjacent keys themselves. These figures are approximate. The gap between keys in a column, or between adjacent rows of keys, can be slightly greater, particularly if the rows are stepped and lie on a tilted rather than a horizontal surface. For functional keys, essentially used one at a time and relatively infrequently, their size and the spacing between them may be increased, these increased dimensions being helpful sometimes to group and code the functions. In particular, a larger or more separated key may denoted a function of particular significance, or one which initiates or terminates a sequence of keyed functions.

The tops of keys should not be so shiny that the finger can slip over them or that they reflect ambient light. The tops should be slightly concave, but preferably not embossed, except as a coding to make certain rarely-used but vital key functions discriminable by touch, not from each other but from standard unembossed keys. A key should not have any sharp corners or edges. Elaborate codings are not suitable for keyboards: they take much longer to learn and do not necessarily lead to greater speed of input. Chord keyboards, whereby a function is designated by the activation of two or more keys concurrently, can be effective in air traffic control if used sparingly but they are more difficult to learn, they introduce their own crop of errors, they require a great deal of very careful pre-planning, and they do not necessarily repay in terms of increased speed and efficiency of input. Being more compact in principle, they offer an option which may have to be considered in air traffic control if there is no other way to accommodate all the necessary functions within the shelf space. They can be highly efficient, but at considerable cost in design, software and training.

The standard (QWERTY) keyboard has gradually come into favour as the preferred layout for an alphanumeric keyboard in air traffic control, and it seems likely to become more firmly established. Although it is far from ideal in ergonomic terms, the extra time required to become proficient at it, compared for example with a keyboard in alphabetical order, is not large, and the learning transfers to other standard keyboards in widespread use, such as teletypes and keyboards for word processors, provided there is no gross disparity in the separations between keys.

A trite but important aspect of keyboards is that if controllers are allowed to smoke or take drinks to their workspace, sooner or later tobacco ash will fall on the keys and drink will be spilled on them: they should therefore be designed to withstand such predictable hazards.

Touch Sensitive Display Panels

Touch sensitive surfaces take various forms. Some, such as touchwires[129] have been used in air traffic control for some years; others are in the development stage. For most of them, air traffic control represents one of many potential applications of the technology.

Touch sensitive surfaces generally function as both displays and controls. Either they are on the shelf and can be operated by touch alone in some circumstances, or they are intended to be viewed while being operated and may be positioned either as a normal display or on the shelf. Various kinds of touch sensitive surface bring their own particular human factors problems, the solutions to which do not generalise, but the human factors problems which they have in common, in addition to those concerned with workspace, can be expressed in general terms.

(1) By touch alone, it is not possible for the operator to tell what is being entered. Therefore it is necessary to indicate this clearly to him either by electronically generated labels at the appropriate positions within the touch sensitive surface itself, or by similar labels on another display with which the touch sensitive surface has an obvious one-to-one relationship.

(2) There is no equivalent of a key to feel. Therefore if it is important that the operator touches the surface in the correct place, something must be introduced to give him feedback that he has done so. This may be a wire as in touchwires, a protuberance or surface bulge, a series of engraved lines, a marker on the touch sensitive surface or on another display, or a label on the touch sensitive surface if it is intended to be viewed while being operated. In the last case, it may be necessary to offset the label somewhat, either to allow for parallax or to enable the label to be read while the surface is being activated. If this is so, the label has to be slightly above the sensitive region which it designates. Some independent information regarding the input being made with the touch sensitive surface must be provided as a condition for the operator to be able to learn to become proficient when using it.

(3) The input with a touch sensitive surface has no moving parts. Therefore there can be no direct evidence from this source that an input is being made successfully or has been successfully completed. Feedback is vital to the operator and must therefore be provided in some other way, even by auditory clicks. The preferred method is to show on a display what is being entered as it is entered. The touch sensitive surface may itself change, for example by showing a different set of options as a means of indicating the completion of the previous input, though this change will not necessarily indicate that the previous input was correct.

(4) The region which is touch sensitive for a particular function should be apparent. It should not be possible to touch any position and activate more than one function. If it is possible to touch a position and activate no function, there must be some feedback to show why, so that the operator knows which way to move his finger to activate the intended function. The operation of the touch sensitive surface must be consistent. Once the required kind of touch, in terms of its pressure, duration, etc., has become familiar, it must always succeed. Any suggestion of arbitrariness in the functioning of a touch sensitive surface, so that it sometimes functions and sometimes does not in unpredictable ways, will guarantee slow and inefficient performance, negative attitudes towards it and a lack of smoothness and proficiency in its use. The options which the touch sensitive surface presents must always be unambiguous. If for any reason it does not function, the reason must be clear to the operator so that he can see what he must do to activate it as desired.

Switches and Knobs

Other discrete controls common in air traffic control include switches and knobs. Most of these are used for occasional functions, for setting up displays or for selecting facilities. Switches may be two or three position single switches, or rotary switches. In either case, there should be a firm stop at each possible position of the switch and it should never be possible to set the switch inadvertently between positions. Each position for the switch should be clearly labelled. It must always be possible to tell at a glance the position at which the switch is set however many positions there are, to see how many settings of the switch are possible, and to know whether the switch has been activated or not. Standard guidelines in human factors handbooks should be followed to achieve these objectives. The function of each switch should be made as self-evident as possible by means of its positioning in relation to other displays and controls, and its labelling. Knobs have comparable functions to rotary switches in air traffic control workspaces, and the same guidelines apply to them. Their settings must each be clearly marked, and the position at which the knob is set should be immediately obvious from the shape of the knob and from the engraved settings for it, and should not appear to alter with viewing position. The shape of knobs can be varied so that knobs with different functions have different shapes and are discriminable from each other visually and by touch.

Some controls seldom have any relevance to air traffic control or are too cumbersome. Thumbwheels are not generally suitable for setting in air traffic control data. They take too long, and can be a source of errors and misreadings. Light pens are also generally unsuitable, being best for drawing or for tracking moving objects, neither of which are functions commonly needed in air traffic control tasks. Light pens have the serious disadvantage of being awkward to time share with other controls, since they have to be picked up and put down every time they are used. Continuous usage of a light pen demands firm support for the arm or elbow to forestall fatigue; such support requires free shelf space which is not always easy to provide in air traffic control workspaces.

Continuous Controls

There is a requirement for continuous controls in many air traffic control tasks. The main options are joysticks, rolling balls (track balls), and cursors. All share the problem of striking the best compromise between speed of movement and accuracy of positioning: this decision on gearing probably has a more important effect on the performance achieved than the choice of type of continuous control. In air traffic control, the rolling ball seems to be the most favoured continuous control. Equally good performance in air traffic control tasks can usually be obtained from a well-engineered joystick, which has the advantage, if it is linear, that it is possible to tell by looking at it the approximate region of the display where the associated marker can be found. The problem of losing the marker or of its reappearance at the opposite side of the display does not arise with a linear joystick. With a well constructed joystick, rolling ball or cursor, suitably geared, it is possible to achieve impressive performance and the operator can make very small movements indeed, of the order of 0.1 mm., which may not be visually discernible. If accuracy is required, the gearing should be set so that the limits are perceptual rather than an artifact of the control type and its sensitivity: in other words, if an error can be seen, it can be corrected. Such a degree of accuracy is seldom needed in modern air traffic control systems where the speed of movement of a continuous control is generally of more practical significance than accuracy of marker positioning. The question of gearing is discussed further in the next section.

Plugs and Sockets, etc

Though not controls in the conventional sense, several further items used and handled by the controller should be designed and located to facilitate their effective manipulation at his workspace. His telephone, for example, must be compatible with his headset where both may have to be used at once, and the telephone should be positioned to be in easy reach, so that he can view other essential information while using it, and so that its cable does not get in the way of anything else. Its location and installation are an integral part of the workspace design, and should not be an afterthought. Similar considerations apply to the sockets for headsets, which should grip the plug firmly and have an unmistakable feel to indicate that the plug is home. The plug should be released without tugging. It should never be possible to plug a headset into a socket not intended to house one. Extra sockets, for listening in, supervision, on-the-job training, maintenance checks, etc., should be clearly distinguished from standard ones if they have a different specification or are intended for different purposes.

Foot Switches

A further type of control found in air traffic control workspaces is the foot switch. This, if required, should serve an on-off function, rather than one which provides continuous control or has to be pressed for a long time. From Figures 1, 2 and 3, it will be apparent that the decision to include one or more foot switches has major implications for the console profile and the seating design, since it is not usually practical to incorporate a large adjustment in the foot switch itself, and the optimum eye position may have to be sacrificed to allow people with grossly different body sizes to use the foot switch in comfort. Generally there should only be one foot switch per position, and since that foot switch can serve only one function, the arguments in its favour are probably outweighed by the ergonomic problems its presence engenders. If a foot switch is present, it is essential to provide a clear visual indication for the operator of its state of activation, since he cannot see it directly.

9c CONTROL SENSITIVITY AND FUNCTION

The importance of control type as a determinant of efficiency can sometimes be overestimated. The residual differences between alternative control types may be quite small if they are appropriate for their function and the operators have become fully proficient in using them. The importance of control sensitivity and gearing is as consistently underestimated; incorrect sensitivity can set severe performance limits and engender errors.

Although sensitivity as a concept can be applied to discrete controls, for example to keys which require excessive force to be operated or which are triggered by the slightest brush, it is generally applied to continuous controls, and especially to their gearing, which is the amount of movement of a display marker per unit movement of the control. Optimum sensitivity varies with the task and especially with requirements for speed or accuracy. For most tasks and gearings, speed is obtained at the cost of accuracy, and vice versa; the closeness of the negative relationship between speed and accuracy varies with the control type - it is much closer for a rolling ball than for a joystick. Efforts to achieve both speed and accuracy lead to various strategems, such as coarse:fine ratios to give more than one gearing, and non-linear gearings so that large or fast movements of the control produce proportionately greater movements of the marker than small or slow movements, or than those produced by a linear control. Generally in air traffic control great sensitivity is not needed because great accuracy of marker positioning is not needed. The marker is moved to designate an aircraft or character or label, and does not have to be positioned with the degree of accuracy required if it has to be centred on a point. Therefore for most air traffic control applications a relatively small movement of the control should produce a large movement of the marker. For a joystick, its total arc of travel would normally cause the marker to traverse the entire display. For a rolling ball, rapid spinning of the ball should never be needed. It should always be possible to reposition the marker to the required level of accuracy within a second or so. If it is not, then either the gearing is wrong or the need for such high accuracy in positioning should be questioned.

Air traffic control functions using controls can be classified under the following general headings:

(1) Setting up: for two settings use a push button, toggle or switch.
for three settings use a three-position toggle switch or rotary knob.
for more than three settings use a rotary selector or knob, which includes an "off" position.
If the settings are very numerous (more than about 10) do not attempt to get them all on a single rotary selector. The necessity to have them all on the same control should be questioned by considering whether all the settings really are on the same dimension. Separate controls should be used for different dimensions. All settings should be labelled.

(2) Designating positions on a display: use continuous controls such as joysticks, rolling balls or cursors or a touch sensitive surface if low levels of accuracy would suffice. Continuous controls usually require push buttons to be operated when the marker is at its designated position.

(3) Selection of states or facilities: for two states use push button or toggle switch.
for more than two states use a rotary switch or a row or column of push buttons.

(4) Data entry: use push buttons in the form of a keyboard or touch sensitive surfaces. Perhaps there may be direct voice input in future.

(5) Data retrieval: use functional keyboards, touch sensitive surfaces or continuous controls in conjunction with push buttons. Again voice may be used in the future.

9d INTERACTIONS BETWEEN CONTROLS

The first requirement is that the user must not mistake one control for another. This problem arises between controls of the same type which should therefore be distinguished from one another by their appearance (size, shape, colour, texture, etc.) unless they are intended to be used as a group (for example, four controls with the same alignment indicate that all is well). Every control should have some label or designation to indicate its function, partly as a memory aid, but also to discourage random exploratory tinkering when there is nothing to do. Although not general practice, it can be useful if certain controls are also distinguished by the way they feel when they are operated, particularly if it could be hazardous if adjacent controls were mistaken for each other. They might therefore require a different force to operate or have a different travel distance. However, if this problem arises a more fundamental cure is called for: similar controls should not be adjacent if the operation of one in mistake for the other could be hazardous.

The ways in which controls will be used, including their normal sequence of usage, should be reflected in the workspace design, in the choice of control types and sensitivities, in their positioning in relation to displays, and, for frequently used controls, in their relative positioning on the shelf. Unwanted interactions between controls have therefore to be foreseen and prevented, rather than cured after the equipment has been installed. Many air traffic control tasks involve the concurrent or consecutive use of more than one control. Although tasks should be designed to minimise the need to change from one control to another, a certain amount of changing in air traffic control is inevitable. The main guiding principles in considering the interactions between controls include the following:

(1) Minimise gross hand and arm movements when changing from one control to another.

(2) Employ controls which are in a state ready for immediate use and do not have to be picked up and put down or moved or switched on before they can be used.

(3) Do not have controls with gross differences in sensitivity, so that one requires large movements and another small, fine adjustments.

(4) Do not employ together controls which impose gross differences in the pace at which they can be used.

(5) Minimise the total number of different types of control within the workspace.

(6) Ensure that there are no incompatibilities between controls in their expected directions of movement.

(7) Do not employ within the same workspace controls which demand very different forces to operate them.

(8) Use the layout, engraved lines, colour codings, and other devices to show visually the presence of important links between controls.

(9) Use mechanical or electronic interlocking to prevent any deliberate or inadvertent operation of controls together or in succession which could be operationally dangerous or could damage equipment. Do not rely solely on human memory but assume that every possible combination of control will sooner or later occur and positively prevent those combinations which for any reason must not happen.

## 9e CONTROL DISPLAY RELATIONSHIPS

As far as possible, the workspace design and the location of controls and displays in relation to each other should make the functions of each control self-evident to an experienced user and should render the interactions between controls and displays obvious. There has been a failure in task design, workspace layout, control specification and labelling, or training, if a control is provided but never used, or consistently used inappropriately either because it is unsuitable for its intended function or because the user does not know or understand what its function is, or because it has no obvious association with any displayed information. Control-display relationships are intended to foster the efficient and safe use of the control, to help the man to select the correct control and to remember what it does, and to make it easy to carry out each function efficiently.

Several principles can be followed to realise these objectives:

(1) Position controls beside the displays to which they refer. This guideline is easier to implement for rarely used controls than for those in frequent use, since it may be incompatible with the provision of adequate wrist, arm or elbow support during the manipulation of the control. When task requirements and the conventions for movement (see 3 below) permit, controls for a display should be beneath it or to the right side of it (assuming a predominance of right-handed operators), so that information on the display is not obscured by the viewer's arm whenever he activates the control.

(2) Replicate display layouts in control layouts. This principle applies in most extreme form to touch sensitive surfaces which are also controls. But if, for example, touchwires within the display are replaced by a keyboard on the shelf, while the electronically generated labelling remains unaltered, the layout of the keys should replicate the layout of the labels with which they remain associated. Their relative positioning must be retained; their absolute spacing need not be, so that the optimum spacing between adjacent keys should be that recommended for keyboards rather than that of the labels on the display.

(3) Follow the standard conventions for display movement in relation to control movement. These include:

the direction of movement of the display and the control should be the same;
the control should, where possible, be in the same plane as the display, with its axis of rotation at right angles to that plane;
display movements should be proportional to control movements, or conform to another easily learned relationship between them;
control movements which are clockwise, to the right, forward, or up should be associated with increases.

Toggle switches are awkward because there are two contrary conventions - down for on in the UK; up for on in the US: it is best to follow the local convention wherever they are used.

(4) Use similar codings for displays and the controls associated with them. This is most readily done by employing the same labelling on both, the same typefaces on both or the same colours on both. The more the controls look like the related display contents, the more readily they can be associated with them.

(5) Show links between controls and displays visually by engraved lines or similar means. This principle is most applicable in air traffic control to displays for purposes such as maintenance and fault finding rather than for air traffic control itself, but as a principle it can be successful even in air traffic control if used sparingly and not too obtrusively.

(6) Follow the same conventions for control-display relationships consistently throughout the workspace, with as few different conventions as possible.

(7) Tie display changes directly to control movements, so that the relation between them seems causal to the operator, and the display provides immediate confirmation that the control is being activated.

# CHAPTER 10

# COMMUNICATIONS

## 10a TRANSMISSION OF INFORMATION WITHIN THE AIR TRAFFIC CONTROL SYSTEM

Communications in air traffic control have seldom been studied in their own right in human factors terms, with scientific measurements of the effects of known and specified variables in communications on controller performance or system efficiency. Rather, communications facilities, often in elaborate form, have been provided as an essential prerequisite for the study of other aspects of system performance, particularly in air traffic control simulations. As a result, communications in air traffic control constitute a relatively neglected human factors topic.

The transmission of information within the air traffic control system presupposes a sender (man or machine), a recipient (man or machine), a communications channel between them, and information in a form suitable for transmission. The subject matter of human factors studies of communications therefore includes in principle:

(1) Attributes of the sender which affect the information that can be sent.

(2) Attributes of the recipient which determine the information which can be received.

(3) Characteristics of the transmission channel, such as its capacity and the changes, distortions, or failures in information transmission which it can induce.

(4) Characteristics of the information transmitted, including its form, content, pace and compatibility with the communications facilities.

Since information can be sent or received by either a man or a machine, its communication can take four main forms:

(1) Man to machine (generally sent by using controls).

(2) Machine to man (generally sent in the form of information on displays).

(3) Man to man (generally in the form of speech).

(4) Machine to machine.

This last category is not usually of direct human factors concern, except where the machine processes the information in some way for human use (for example by collation, summary, tabulation or selection) in ways which the man may not appreciate and which are beyond his intervention. Under the heading of man to man communications are included the use of R/T and telephones, even though these are intervening machines, the characteristics of which as transmission channels may introduce substantial, though largely predictable changes between what is sent and what is received. Man to man communications also include hand-written pieces of paper, such as manually prepared flight strips.

A further four-fold independent classification of air traffic control communications distinguishes between messages from air to ground, ground-to-ground, ground-to-air, and air-to-air. This last is the least important category for air traffic control purposes, although it is not irrelevant. Pilots may acquire a picture of the traffic near them from overhearing messages sent to others, and this picture may be a valuable safeguard whenever the quality of the air traffic control itself is suspect for any reason.

From the point of view of system design, communications deal with channels and their routeing. The design of the network of communications also depends on the tasks, the quantity and nature of the information, the predicted utilisation of channels and the balance between available funding and resources on the one hand, and on the other hand, tolerance of overloading, of delays, of garbling, and of the characteristic sources of degradation of information associated with alternative methods for transmitting it. In simulations not intended to study communication channels as such, their provision is usually ample, and controllers often remark on the comparative ease of establishing contact with pilots whenever and wherever required. In real life, communications are often subject to gross variations and deficiencies in quality and accessibility. Some channels may be so notoriously unreliable, and some places or people so consistently difficult to contact, that ad hoc procedures have sometimes been evolved to circumvent or by-pass such highly fallible communication channels.

If information is sent by means of controls, or received in the form of display contents, the communications seem to the man to be an inherent part of the display or the control. If the overloading of a communications channel renders a control temporarily inoperative or if information garbled during transmission appears unintelligible on a display, these events are interpreted respectively as a faulty control or a faulty display, rather than as inadequacies of communication, even though there may be nothing amiss with either the controls or the displays. The user may take communications facilities for granted until they fail or become overloaded. When they do, his frustration may make him particularly antagonistic towards them because he seems, and often is, powerless to counter their failures.

The aspect of communications which to the controller is most dominant is speech. Since in this chapter communications are considered primarily in human factors terms, much of its content is therefore concerned with speech in air traffic control. However, speech is no longer the main means for the transmission of information within the air traffic control system; in a modern system far more information is transponded and gathered automatically, and in the future this trend will be accentuated, for example when data derived from satellite-based navigation systems are employed for air traffic control purposes. Therefore communications in air traffic control must not be equated with speech.

Changes and limitations in communications can often have much larger effects on system efficiency and on task performance than changes in controls or displays. The decrements in performance attributable to the non-optimum design of the alphanumeric characters on a display, or to the wrong type or sensitivity of a control, may be much smaller than those attributable to inadequate communications, particularly since the latter may produce effects which are cumulative. There always seems to have been some reluctance to conduct valid studies of the implications of communications on system efficiency, particularly since the variables and their effects may not be observable [illegible] controllers. Detailed issues, such as the intelligibility of spoken words [illegible], have attracted more experimentation than broader issues, [illegible] form, between [illegible]. As a consequence, relevant human factors [illegible] factors consequences of proposed changes in communications [illegible]. Hypotheses [illegible] systems[14] and to computers and computer languages[15], as long as [illegible] is verified empirically and not assumed.

An increasingly important aspect of communications in air traffic [illegible] machine system [illegible] of the time [illegible]. These [illegible] computer systems, and [illegible] by the man to the computer. [illegible]

[illegible]
Data entry, [illegible].
Prompting, in which the computer [illegible].
Commands, [illegible].
Queries, which enable the man to retrieve [illegible].

There are now numerous publications which give guidance and human factors recommendations about these dialogues. All should be treated circumspectly in relation to air traffic control. Many of the recommendations in different publications cannot even be reconciled with each other. They were often based initially on specific studies of equipment and dialogues which are already obsolete. The guidelines were derived from many contexts, but they seldom included air traffic control. Theoretical generalisations abound. In human factors terms, far too little is known about the optimum development and usage of man-computer dialogues to warrant such confident and unqualified recommendations about them at the present time. Changes, developments and improvements are very rapid.

A policy for air traffic control can nevertheless be stated. Human factors recommendations about dialogues in the literature can be helpful if they are used as a source of insights and suggestions to be verified in air traffic control contexts before they are considered for operational use. Also, more credence should be placed on recommendations supported by data from several completely independent sources, than on recommendations based solely on a single source or context, no matter how reputable it may be. The increasing sophistication of the users of man-computer dialogues as these become more familiar to them should also be allowed for in considering optimum man-computer dialogues for the future.

10b TRANSMISSION OF INFORMATION BETWEEN AIR AND GROUND

Positive air traffic control cannot take place without some means for transmitting information from air to ground and from ground to air. Prerequisites for any air traffic control system are a set of rules which all users subscribe to, and knowledge of the traffic pattern and of the individual aircraft within it. Traffic control entails facilities for positive intervention in the form of instructions issued to individual aircraft, either by pre-planning and the allocation to each aircraft of a time when it begins to follow a preset procedure (such as a slot for departure, or a designated height and route for crossing the Atlantic) or by requiring tactical manoeuvres (such as the avoidance of conflict with another aircraft or the sequencing of aircraft preparatory to their final approach to an airfield). Insofar as the communication with all aircraft in the system is incomplete, the air traffic control service is itself incomplete.

Initially much of the transmitted information in air traffic control was in the form of speech. On the basis of what was said, the controller wrote down what he wanted to remember and used that information as the basis of his air traffic control decisions and instructions. This procedure became more formalised with flight strips. When the communications channel interfered with voice transmission sufficiently to make the spoken message uncertain, this was apparent to the receiver who could ask for it to be repeated or request specific information to verify the parts of the message about which he was uncertain. There is no equivalent to this function of asking for a message to be repeated when data are transponded automatically. Usually the controller cannot diagnose suspect data; if he does, he cannot ask for it to be sent to him again, or ask many questions about it.

When radar information was added, in the form of a continuous plan view of the traffic, initially the radar picture contained some information from the sweep about the rate at which it was updated and the way in which it was communicated, and some information from the signal-to-noise ratio about the reliability of the data. Comparable information is absent from modern secondary radar displays which portray information of apparently high quality but give little or no indication of the communication channels in use, of the accuracy of the data, of the rate of transmission and renewal of information, or of the serviceability of the communication channels themselves.

These points apply with similar force to modern tabular displays of air traffic control data. It may be possible to glean from them some notion about accuracy and transmission rates, but there is no indication of the amount of processing the information has undergone, of the quantity of transmitted data from which the presented information has been derived, or of the state of the communication channels themselves. In fact, now and in the future, quantities of transmitted data and transmission rates may increase vastly, but this may have little significance for the controller while the appearance of his displays, and their contents, remain unchanged. Changes in information transmission, especially from air to ground, may therefore be of much less consequence to the controller than their true importance warrants. The gain from them may remain largely technical, in the absence of direct guidance for the controller about them.

With increased amounts of transmitted information go demands for more communication channels, for revisions in the allocation of frequencies, and for better means of changing frequencies. Problems with human factors implications for air traffic control include the overloading of a channel in heavy traffic just when overloading is least tolerable to the controller, the sequencing of verbal messages to the controller on a single channel into an order to take some account of their operational priority, and the specification in air traffic control terms of the amount of information actually transmitted and the amount of redundancy in it.

10c SPEECH AS A MEDIUM OF COMMUNICATION

Although aural communication is important in aviation, the main emphasis in recent studies of speech has been on voice messages in the cockpit with its characteristic background noise[132]. Conditions in air traffic control are different. The outstanding characteristics of speech in air traffic control are its flexibility, complexity, immediacy, and freedom from restrictions. Compared with displays and controls, with their preset formats and functions, speech can be flexible and unfettered. In a system context, such as air traffic control, this is not necessarily a boon. Rules, conventions, formats and terminology have to be imposed and standardised to try and ensure that spoken air traffic control messages are universally intelligible and compatible with the system. When they are, speech becomes comparable with other ways of sending information, to the extent that comparisons are actually made. In the past, this has occurred mainly when it is proposed to replace spoken messages with automatically or manually transponded information using controls and displays. For certain functions in the future, the latter may in turn yield to automated speech synthesis and recognition, though not retaining the full potential flexibility of speech between people. The technical complexity of the sounds in speech has emerged from attempts to recognise them automatically, which generally entail frequent sampling of numerous phonetic and other parameters to achieve recognition of even a very limited vocabulary in a known voice.

A potential attraction of direct man-machine communication by speech is its immediacy and naturalness as a form of human communication, which makes the alternatives, such as keyboard data entry, seem indirect and cumbersome by comparison. In certain respects, this impression can be misleading. Speech is not necessarily more efficient, quicker, or more direct than its practical alternatives. Some tasks, such as the control of a cursor, apparently become more difficult and unwieldy if the commands must be in verbal form; others, such as the matching of complex visual patterns can neither be done nor described effectively and comprehensively in verbal terms. However, much air traffic control information is expressed in the form of words, and speech must therefore be a potentially advantageous way of communicating it. In the case of very rare events and circumstances, for which no provision has been made in the system design because the possibility of their occurrence was never foreseen, speech may be the only means of communicating essential information, which is sufficiently free from restrictions to be employed both to describe the rare occurrence and to formulate and express the actions required to deal with it.

In common with other means for conveying information, speech has its own characteristic sources of error and confusion. Most of them are predictable in general terms though not in specific instances. Just as the kinds of error which will be made using a particular keyboard for a known task can mostly be predicted by examining the keyboard layout in relation to the task for which it will be used, so the kinds of error which will occur in spoken messages can mostly be predicted by relating the message formats and contents to the consequent probability of known common phonetic confusions, taking into account the technical characteristics and distortions of the communications channels themselves. Because many of the sources of potential confusion in spoken air traffic control messages can be identified, it is possible to reduce their incidence, though never to eliminate them, by designing messages so that these sources occur as rarely as possible.

In a man-machine system, spoken messages are outside the system in the sense that it cannot receive them directly or integrate them in their spoken form with other sources of information or with stored data. Consequently, information which is spoken has often to be entered into the computer additionally and separately, in order to update the stored information and to ensure that computations based on stored data take account of the content of spoken messages. To the controller, to speak and to key in the same information can constitute unnecessary duplication of tasks, the more irksome the busier he becomes. Such chores can be interpreted as compensations for machine deficiencies. The replacement of speech by keying, or the replacement of keying by speech because of the successful automated recognition of speech to permit direct voice entry, both offer prospects of progress, and means for reducing duplication of effort.

Speech intelligibility can be assessed by establishing whether the speech has been heard correctly, but it is more commonly assessed in terms of understanding. Background noise affects hearing rather than remembering. Similar sounds may be confused with each other, or their order of occurrence may be misinterpreted, either of which can have serious consequences in air traffic control. Poor signal to noise ratios affect the intelligibility of speech adversely, and impair the listener's confidence. Standard speech discrimination tests can be used to diagnose an inadequate speech channel, but not to predict the specific problems encountered by experienced controllers listening to air traffic control messages spoken over that channel, since the ability to use a noisy channel improves with practice and familiarity, and the differences between individuals and between groups in their acquired ability to use a noisy channel can be substantial. The gain from repeating spoken messages heard against noisy backgrounds may be more in confidence than in hearing or in understanding. Noise does not affect all frequencies equally. Most noise interferes with higher frequencies more than lower ones. Intelligibility can often be improved by frequency modulation or by speech compression techniques to reduce the bandwidths.

For most practical purposes, speech is best treated as a single information channel; it is potentially confusing to try to listen to two or more people speaking different messages concurrently. In air traffic control this is a practical problem, with direct speech, speech over R/T, and perhaps speech over a telephone as well. If more than one source of speech must be heard, it is usually better to direct one source to each ear, since this helps the listener to distinguish them. The ability to perform such dichotic listening tasks declines with age. Although the successful presentation of more than one source of speech at the same time is easy to achieve technically, this does not resolve the associated human factors problems which centre on understanding rather than on hearing, on the need for frequent attention switching, on the involuntary distracting effects of new messages, on the need to listen and understand before the relevance or irrelevance of the spoken information can be established, and on the increased potential for confusion, omission, transposition and mishearing associated with the reception of different spoken messages at the same time. Therefore, wherever possible, it is best to design the air traffic control tasks and functions to prevent the simultaneous occurrence of spoken messages from more than one source at the same time, or, if this cannot be done, to permit the controller to suppress or delay whichever message he does not want to hear, if he finds that the interference between them impairs their intelligibility, as it is likely to do.

To a naive listener, speech in air traffic control, particularly speech over a noisy R/T channel, sounds unintelligible. In the correct interpretation of speech, much reliance is placed on the training, knowledge, experience and special skills of the controller. The corollary is that findings about intelligibility of speech obtained in the laboratory or in applied contexts other than air traffic control should never be presumed without verification to be applicable to air traffic control.

10.4 QUALITATIVE ATTRIBUTES OF SPEECH

The full importance of the qualitative aspects of speech may be recognised only when they are no longer present because speech as a medium of communication has been replaced by some form of automated transponding of data. It is then too late to restore the qualitative information that speech conveyed.

When the spoken information required for tasks is examined, quantitative air traffic control information naturally receives most emphasis. It is clearly essential for task performance. Speech has other attributes that convey information: pace, pauses, repetitions, structure, phrasing, and in particular selective feedback in the form of individual spoken responses. On the basis of these qualitative attributes and responses, each speaker in an air traffic control conversation makes judgements about the other: about his competence, his calmness, his confidence, his professionalism, his reliability, his probable workload, his emotional state, and whether he has really understood the information sent and perhaps formally acknowledged.

The soundness of these judgements based on qualitative information may be uncertain when gauged impartially and scientifically, but to those who make the judgements they are the basis of many actions and decisions. A message may be repeated, even though it has already been correctly acknowledged. An emergency in the air may receive the pilot's full attention because he has judged that the controller is calm, competent and reliable and can be left to institute appropriate ground-based procedures on his own initiative. A controller may diagnose uncertainty or inexperience in a pilot from the content and manner of his speech, and pay more attention than normal to the needs of that pilot, perhaps by allowing extra air space for unpredictable manoeuvres. Messages sent in a language judged not to be the native language of the listener may be spoken more slowly, more distinctly, and in a more standard format than normal. Messages sent to a listener who is judged from his responses to be very busy may be shorn of inessentials and superfluous pleasantries. Spoken information of vital importance, or which is very unusual, may be confirmed and reconfirmed until both speaker and listener are completely satisfied that it has been heard and understood correctly.

The true impact of such qualitative attributes of speech, and of the actions they lead to, on safety is uncertain. On balance it seems very likely that they do improve safety; certainly the belief is strong among many controllers and pilots that safety is enhanced by judgements based on speech, and that these judgements are usually correct. When speech is replaced, wholly or in part, by transponded data, no such judgements can be made, or the opportunities for forming them are severely curtailed. The information contained in the qualitative aspects of speech is lost without speech. It has no equivalent in automated transponding of information, in man-computer dialogues, or in automated speech synthesis and recognition. Perhaps the consequences of these attributes of speech should be more thoroughly explored, to establish exactly what is lost when speech is no longer possible, and whether what is lost needs to be replaced.

Information gleaned from these qualitative attributes of speech is not necessarily beneficial to air traffic control efficiency or safety. The examples quoted above of types of messages which might be thought to promote safety can be countered by further, but fewer, examples where the judgements formed on the basis of speech may potentially distract from safety, usually by stifling further speech. A curt response may discourage further verbal communications; an apparently obvious confirmation may not be carried through; an action which should have been queried by the controller may go unchallenged; the controller may not venture to issue a reminder which could be construed as casting doubt on the pilot's competence - in short, spoken messages likely to invite a rebuff may not be sent when they should have been[133]. But they will not be sent either when speech is replaced by automatically transmitted data.

While there are many instances when spoken messages between controller and pilot have led to confusions and misunderstandings which would not have arisen in the absence of speech and which would therefore be removed as sources of error if spoken messages could be dispensed with, it is very clear that the form of data transmission that replaces speech, whatever that form may be, will bring its own quota of confusions and misunderstandings, many of which may be predictable if the form is a familiar one but may not be if it is novel. The apparent findings of comparisons between speech and its absence, and their respective consequences for efficiency and safety, often need to be tempered by a hard-headed appraisal of the true benefits and penalties of change.

There is some evidence, much of it from experience of automation in Flight Service Stations, that there may be some potential benefits in certain circumstances when speech is replaced by man-computer dialogues, provided that the dialogue has been correctly designed. In particular, if the man does not understand information he has received, he may be more willing to ascribe his failure of understanding to inadequacies in the computer and ask for clarification or repetition of the information than he would be to admit to someone else that he does not understand what he has just been told. It may be important, in designing dialogues, for the man to be able to blame the machine for any deficiencies of understanding that may arise regardless of where the true blame should lie. His efficiency and his collaboration, may depend on the ascription of his failures and misunderstandings elsewhere while he gains experience and learns to overcome them.

In communications between controllers in the same workspace, speech is supplemented by the information obtained from seeing the speaker directly, and from knowing him. This includes manner, gestures, personality, and relative status, all of which influence the interpretation of spoken words. In recent years, the information communicated non-verbally has become a major area of study in its own right [88], but the usual caveat must be entered here about extrapolating findings from elsewhere to air traffic control.

10e AUTOMATED SPEECH RECOGNITION AND AUTOMATED SPEECH SYNTHESIS

In automated speech recognition (also known as direct voice input) the controller enters data into the computer by speaking, instead of by keying it in or using another control. In automated speech synthesis, the computer conveys information to the man by speaking to him in a synthetic voice, instead of presenting information to him on a display or changing the state of a control. The requisite technology for both these applications is now available in principle, although a great deal of further development seems necessary before either could be introduced into operational air traffic control. Initial applications to air traffic control training seem more probable. Direct voice input has reached a stage of being as good as a keyboard for the entry of certain categories of air traffic control data [60].

A great deal of research, particularly into automated speech recognition, is being conducted currently in many countries, although the effort does not seem to be well co-ordinated. The possible applications appear to be very numerous. The most promising ones require a limited vocabulary which can accommodate every message without being extended, a series of clearly defined options, material which can be expressed in forms similar to menus, and a structure for each message that includes an unambiguous beginning and end and discrete identifiable intervening stages that can be sequenced according to definable logic or algorithms. Much air traffic control comes near to meeting these requirements, although perhaps not as near as other potential applications such as automated booking systems. Nevertheless the concepts merit examination in human factors terms for air traffic control applications.

Some formidable technical problems have still to be overcome. In air traffic control it would probably be necessary for each controller to pre-record the whole usable vocabulary in any automated speech recognition, and to identify himself, perhaps by speaking his name, as soon as he came on watch so that the appropriate package would be used to compare his speech patterns with his pre-recorded ones, match them, and recognise his messages accordingly in terms of matched syllables, words or phrases. The auditory patterns to be matched would not necessarily correspond to words in the dictionary sense of the term, but might be phrases spread over a second or two if these were of standard pattern, or might even be parts of a word. Much work has still to be done to partition air traffic control messages into verbal units which facilitate pattern matching and which minimise errors and mismatches. The extent to which the messages themselves, the sequence of items of information within them, their phrasing, and even the introduction of pauses within them, would have to be standardised, taught, and rigorously adhered to, would have to be established. Perhaps the controller would have to learn to speak in a particular way - another imposition on him to circumvent technological limitations!

Certain problems in automated speech recognition arise for which solutions must be found before any application to air traffic control can be seriously contemplated. One problem concerns any air traffic control message which contains a sequence of more than two numerals, e.g. 220, 245, etc. Such sequences are very common in air traffic control. In automated speech recognition, the first and last numerals can usually be recognised successfully, but the middle one, articulated less clearly and embedded in, and overlapping with, the others, cannot. Problems such as the distinction between "to" and "2", or between "for" and "4", have to be resolved by a combination of context, priorities, and pattern matching. The common cold can alter the voice so much that the computer may make frequent errors in matching the same voice with and without a cold.

In some respects, the ideal might be a system, where it was not necessary to pre-record all the spoken data because the words of a new speaker could be recognised by the machine just as they are recognised by other human beings. However, while such a development seems a prerequisite for the successful development of a direct voice input automated booking system for use by the general public, it may not be so advantageous in air traffic control where the use of pre-recorded material coupled with the need for positive identification of the speaker by the computer may provide an effective safeguard against unauthorised tampering with the system.

Human factors is concerned with the solutions to the technical problems of automated speech recognition and automated speech synthesis. It can apply the extensive body of knowledge about common phonetic confusions and sources of error to help to resolve ambiguities. The potential human factors implications of automated voice recognition and synthesis go far beyond proving the technology, minimising errors and expanding the vocabulary. What would it be like to spend the working day talking to a machine that talks back when there is no-one else there? Perhaps the man would come to prefer talking to a predictable, friendly and docile machine than talking to real people, and eventually shun other people. Perhaps the man might treat other people as he treats the machine and they would resent it. Perhaps the man would become able to work effectively only in isolation, and not as a member of a collaborative team. Perhaps the characteristic errors associated with automated speech recognition or synthesis in air traffic control cannot all be adequately detected, resolved or avoided. Perhaps the man would treat the machine as a toy, particularly if he had to be at his workplace for long periods with few air traffic control tasks to do; he would play with it, experiment with it, and try to test it to its limits, with dire consequences for its reliability or even for the efficiency and safety of the air traffic control system. Perhaps he would come to rely on the machine so much that he could not control aircraft traffic without it.

In addition to proving and improving the technology of automated speech recognition and synthesis, we should ask such questions. It is essential to find acceptable answers to them before the idea of introducing extensive automated speech into air traffic control is seriously adopted. It is desirable to be able to predict all the potential human factors consequences first.

10f CO-ORDINATION AND LIAISON

Co-ordination and liaison are inherent aspects of the communications within an air traffic control system. There are other aspects ju inherent, such as handovers, which tend to be discrete events rather than on-going activities. The term "co-ordination" usually, but not exclusively, refers to the activities of controllers when the handling of air traffic by one controller impinges or will impinge on the rightful responsibilities or activities of another controller. Some examples may clarify this point. Two controllers who are in control of different aircraft in the same airspace at the same time must co-ordinate their activities very closely and continuously to maintain safe separations and smooth traffic flows: it is dangerous if either acts independently. A military controller wishing to route an aircraft across a civil airway must co-ordinate this by agreeing a crossing height and approximate time with his civil colleagues in charge of the airway. The departure time and climbing profile of an aircraft departing from a small airfield to enter or transit the terminal area of a larger airport must be co-ordinated before departure with other controllers concerned, who may include an inbound controller, an outbound controller and a controller handling other local traffic just outside the terminal area.

The denser air traffic becomes, the smaller the region which is the responsibility of a single controller tends to be. The requirements for co-ordination increase not only because there is more traffic, but because there are more frequent transfers of responsibility for each aircraft. Further partitioning of the regions of responsibility becomes at some point self-defeating, when the additional co-ordination workload exceeds the reduction in workload of other kinds. Co-ordination requirements therefore set major limits on system capacity, and on the peak number of aircraft that each controller can handle at once. This is one of the main reasons for the disparity between the number of aircraft handled by a military controller or by a civil controller in regions where military and civil control are not integrated; the former usually has much more co-ordination to do. Hitherto, co-ordination practices and procedures have changed relatively little; much of the work has still to be done by the man, and the changes wrought by automation have been relatively small: this may be the explanation for the paucity of studies of co-ordination problems, compared with those dealing with displays or controls.

The form and extent of the co-ordination required in an air traffic control system are largely set by the system design. Main influences are the divisions of control responsibility, the extent to which tasks are performed by individuals or by teams, the planned traffic handling capacity of the system, the balance between strategic and tactical control procedures, and the nature of the air traffic control service. Obviously, co-ordination of traffic approaching a terminal area is more intensive, more frequent and more urgent than that of traffic in mid-ocean beyond radar coverage. Co-ordination problems feature prominently in workspace design. Decisions on whether displays will be individual or shared affect co-ordination methods greatly. A planning and executive controller in a team may sit side by side (in the UK) or back to back (at some Eurocontrol facilities). The consequences are major in terms of the controller who becomes overloaded first, the form which co-ordination takes, and communications directly or via equipment such as telephones. The extent to which co-ordination can be altered once the system becomes operational is very limited, without altering manning levels, divisions of responsibility, facilities, workspace design, or the system design itself.

Co-ordination should be studied more in its own right in human factors terms. Often the priorities appear to require the co-ordination procedures to be fitted to other changes in aids, facilities, routeings and procedures, so that measures are taken of how much co-ordination there has to be for the air traffic control system to function properly, rather than plans laid of how much co-ordination there ought to be for effective air traffic control. A policy on co-ordination, considered as one of the starting points for air traffic control system planning, might prove helpful. Studies on effective and safe ways of reducing co-ordination, and the human errors associated with it, are also needed.

10g THE LANGUAGE AND TERMINOLOGY OF AIR TRAFFIC CONTROL

Air traffic control, as other disciplines, has evolved its own technical terms. Its vocabulary contains few neologisms: most words have been adopted from common currency and given a narrower technical meaning specific to air traffic control when used in that context. Many technical terms in human factors and applied psychology have similar origins. They therefore share with air traffic control the problem that words used in their technical sense may be misconstrued by anyone familiar only with their everyday meaning, so that their true significance and implications may not always be appreciated. An essential part of the stock-in-trade of the experienced controller is his familiarity with, and correct usage of, the technical meaning of air traffic control terms. An essential aspect of interdisciplinary collaboration on air traffic control problems is constant verification that when controllers and non-controllers are working together they are not inadvertently ascribing different meanings to technical air traffic control terms, and thereby unwittingly engendering misunderstandings about what is being agreed. In extreme instances, such terminological confusions can lead to subsequent accusations of bad faith if they are not recognised.

Air traffic control messages are rarely given as sentences. Much of the recent interest in linguistics, and the theories and constructs which have evolved from it, has little direct relevance to the language of air traffic control. The standard language for international air traffic control is English; a consequence is that controllers whose native language is not English may know only the technical meaning and not the more general meaning of many of the terms that they use. There is also an increased likelihood of confusion and misunderstanding when unusual air traffic control circumstances and problems arise, since the terminology needed to describe and resolve the problem adequately may be unknown to a controller with limited command of English.

To some extent, spoken air traffic control messages can expand or contract to fit the time available for their transmission. In light traffic densities, courtesies may be exchanged and sociable conversations conducted, which are omitted if the controller or pilot has no spare time for such niceties. In heavy traffic densities, spoken messages may be shortened, pruned in number, quickened in pace, and acknowledged in abbreviated form, so that more messages can be transmitted on a single channel in a given time. One consequence of these trends is that measures of the occupancy times or utilization of information channels and frequencies may not in themselves reveal much, without concurrent records of the nature and content of the information sent, of the incidence of superfluous and redundant messages, and of occasions when the channel was in use but not for sending air traffic control information.

Computer languages are used for air traffic control software, and therefore air traffic control terminology must in certain respects be compatible with them. The nomenclature for queries, menus, commands and other forms of man-computer dialogue must not only be reconcilable with the language of air traffic control but must actually employ technical air traffic control terms wherever they apply, since to use any other terms, or to use air traffic control terms in their non-technical sense, could be misleading.

Two aspects of the terminology of air traffic control deserve specific comment in human factors terms because of their different implications for the expected incidence of human errors. One concerns the allocation of callsigns to aircraft. These are the means by which aircraft are generally identified in air traffic control. It is vital for safety that aircraft should not be misidentified, and that as far as possible the callsigns of different aircraft should not be similar or readily confused. Therefore it would be expected that in the allocation of callsigns to aircraft, all prudent and reasonable steps, though not obsessionally pernickety ones, would be taken to try and minimise the occasions when aircraft with similar callsigns could be in the same airspace under the control of the same controller at about the same time. Obviously this could not be achieved perfectly worldwide all the time, but a firm policy to try to achieve it should render the presence of aircraft with similar callsigns on any air traffic control display simultaneously, quite rare. In fact the actual allocation of callsigns has the opposite effect, and well-nigh ensures that aircraft with callsigns which could readily be confused with each other will be under the concurrent control of the same controller far more often than would be expected by chance. Positive proof that this practice is potentially unsafe is hard to come by - it is not easy to determine what would constitute proof in statistical and scientific terms - but many controllers worry about callsign confusion, and in human factors terms the principles for the allocation of callsigns should be re-examined, with a view to reducing the potential for confusions, and the similarities between callsigns of adjacent aircraft.

In contrast to callsigns is the other aspect of terminology relevant to human error - the evolution and adoption of the standard ICAO alphabet (page 35). Before the final choice of words for the ICAO alphabet was made, there were numerous practical tests of the acoustic properties of the chosen words and of alternatives; their intelligibility against noisy backgrounds was tested; their meanings (or lack of meanings) and their connotations in various languages were examined; the low potential confusability of each word with every other word in the set was checked; the retention of the intelligibility of each word when spoken by a non-English speaker who might mispronounce a vowel or consonant or misplace an accent was verified. All this work did not show that the words of the ICAO alphabet could never be confused with each other: a very noisy channel can ultimately defeat even the most dedicated efforts to enhance intelligibility. What the work did show was that this set of words was about the best that could be devised for the purpose, and that no alternative set would be likely to achieve any gross improvements in intelligibility.

## 10h AIR TRAFFIC CONTROL PHRASING AND MESSAGE FORMATS

It is possible, but not likely, that substantial improvements in the efficiency of air traffic control could be attained by recasting its phrasing and message formats, but in all aviation contexts it is always potentially hazardous to change without good reason any message formats which have become familiar and trusted as inherently safe. Over the years, most of the sources of actual and potential ambiguity in air traffic control phrases and message formats have been identified and resolved. It is always possible to find more, and for a standard message, used in safety on thousands of occasions, suddenly to contain an ambiguity in exceptional circumstances. The rare misinterpretation of messages which employ phrasing and formats which have been used many times in the past in safety leads occasionally to a tragic accident, but such ambiguities are now rare. Although they can never be wholly eliminated, the best safeguard against them is to adhere strictly to the tried and true formulae which have served so well for many years. The probability of ambiguity and misinterpretation becomes very much higher whenever non-standard words, phrases, formats, content, or sequences are used. To recast phrases in order to resolve ambiguities, far from absolving spoken messages from errors would undoubtedly engender a new crop, which would gradually emerge in daily use, first in the form of common confusions to be resolved and then in the form of typical ambiguities associated with progressively rarer circumstances. To have sources of confusion at all in air traffic control messages can be potentially hazardous. To eliminate them entirely from messages spoken by human beings is beyond reasonable expectation. The aims are therefore to try and minimise their occurrence as much as possible, and, having accepted that on rare occasions confusions are inevitable, to attempt to minimise the adverse consequences which any single source of confusion can engender.

Many classifications of the information in air traffic control messages have been attempted. There have been few recent attempts, perhaps because the process has proved to be unrewarding and unenlightening in the past. Findings have been obtained, but they have generally been confined to what would be predicted without experimentation, and the practical steps that should follow from them have been far from obvious. The lengths of spoken messages in air traffic control tend to vary with the speaker's familiarity with the language. Ground to air messages are longer than air to ground ones. A classification of air traffic control messages into the categories of information, instructions, confirmations, and requests, assigns a preponderance of the first two categories to controllers and of the latter two to pilots. Messages expressed either in the form of sentences or in more abbreviated air traffic control forms can be compared, and in both cases the essential information is embedded in longer conversations which could be shortened substantially; however it is not necessarily safer to do so.

Communications influence workload, and a reduction in speech, or more succinct phrasing or formats, would in principle cut workload and free more time for other tasks, but this apparently self-evident assumption has not been confirmed on the rare occasions when it has been tested. Significant relationships between air traffic densities and phrasing, formats, and amounts of communications can be established, and can be shown to afford reasonable predictions over a fairly narrow band of air traffic densities, but the sheer flexibility of air traffic control communications, in their content, pace, and adaptation to the time available and to changing circumstances, makes any extrapolations of these relationships to grossly different traffic densities precarious and largely invalid, just as it can render measures of channel occupancy times nugatory.

The consensus of human factors evidence therefore suggests that it would be inadvisable to tinker with the well established current air traffic control phrasing and message formats without good reason. Further minor anomalies and sources of confusion can be expected to emerge, and be in need of correction from time to time. However, the problem arises when existing practices do not fit new technology. Perhaps the ultimately successful application of automated speech recognition and synthesis to air traffic control would require the abandonment of traditional phrasing and message formats altogether. It may be that really effective menus or options can never be presented in the air traffic control terms which are used now. It is possible that the way to efficiency in air traffic control is to make each work position more automated and more autonomous and in the process scrap altogether the transmission of substantial amounts of air traffic control information in verbal form, and with it the associated difficulties in phrasing and formats. Certainly in contexts other than air traffic control, inefficiency is often associated with a needless reliance on essential verbal communications, especially when the amount of such communication is closely related to the task demands. Nevertheless it is wrong to see the reduction of verbal communications as an end in itself, bound to bring other benefits in train.

A few principles can be enunciated again:

(1) Always employ standard phrasing and formats, even when it seems pointless, unnecessary, overcumbersome, or excessively time-consuming to do so.

(2) If in doubt, check, repeat, and check again, even at the cost of a rebuff or sarcasm, both of which are much less important than air safety.

(3) Do not try to pass too much information at once, particularly if the whole message contains more than one set of potentially similar numerals or other items.

(4) When heavily loaded, and at other times, take care not to cut off the beginning or end of a message, either verbally or by a switch, but be sure that you hear the whole message and that the whole of your own message is heard.

(5) Do not skimp on acknowledgements, repetitions, confirmations, or other means for ensuring that the message in its entirety has been received and understood, and that there is no room for misinterpretation.

(6) Do not include in messages any implication that there ne  be no further communication for some considerable time, unless the circumstances, such as trans-oceanic flight, warrant this as a matter of routine. Light traffic, or being busy, are examples of circumstances which do not warrant this implication.

(7) Speak at a regular pace, without gross variations in pitch, and be sure that the end of each phrase or sentence is not spoken more softly, more quickly, or at a much lower pitch than the remainder of the message.

(8) Never assume anything; if you are not sure, no matter how obvious the question may seem, ask it and make sure.

## 10i INFORMATION QUANTIFICATION AND REDUNDANCY IN AIR TRAFFIC CONTROL MESSAGES

Many attempts have been made to classify and quantify air traffic control messages. None has proved sufficiently encouraging, practical or helpful to be adopted as standard. Sometimes the purposes of classification or quantification have been obscure.

A simple method is to measure channel occupancy times, and the relative and absolute frequencies of usage of various channels in the communications network. Occupancy times approaching 100% for any channel point to actual or incipient overloading if they persist for any appreciable time, and in many circumstances average occupancy times above about 50% can be construed as indications of overloading. High occupancy times of channels can occur in light loading, as a means of passing the time. Occupancy times need to be supported by further data on the content of the messages passed, before they can yield useful findings. Sometimes, with occupancy times around 50% in particular, a great deal more information can be transmitted by curtailing unnecessary verbiage and by increasing pace and succinctness, without much increase in the measured channel occupancy times.

Messages can be classified according to the various fourfold categories mentioned in Section 10a. They can also b  classified in terms of the air traffic control agencies involved. Messages may be between radar and planning controllers, between sector controllers, between agencies controlling different regions, categories or levels of airspace, between military and civil controllers, between domestic and internationals centres, between ground movement, approach, departure, terminal area, or en route controllers, between controllers and supervisors, between controllers and assistants, and so on. They may be categorised under psychological concepts, such as information, question, confirmation, acknowledgement, instruction, etc. They may be classified as essential or inessential; as related or unrelated to displayed information; as introductory, appropriate, inappropriate, or irrelevant. They can be classified as identity, height, heading, destination, route, time at reporting point, climb, descent, emergency, and so on. All the above kinds of classification of air traffic control information have at some time been examined as a means of specifying air traffic control messages, and suggesting what they should consist of and how they ought to be changed.

Attempts have also been made to trace the flow of information through the system, to discover how and whether essential information is delayed or distorted, and to effect improvements and measure those attained. For many purposes, this approach may be most likely to furnish practical findings that can be implemented, but it is highly empirical, does not usually rest on any firm theoretical support, and generally implies that the whole exercise has to be repeated following any major recasting of the system, since its effects on the flow of information may not be deducible from first principles and have to be measured once again.

A method for the quantification of information which has often proved efficacious in other contexts, and has the incidental benefit of assessing the amount of redundancy in messages also, is the use of information theory, in which all the information transmitted in converted to "bits", standard units of information comparable to those employed in digital computers. Because with this technique all information can be converted to the same units, comparisons can then be made in an objective fashion in terms of the relative efficiency of various channels in the amount of information successfully tranmitted through them in unit time. Any aspects of air traffic control messages which can be converted to quantifiable digital form can in principle be treated in this fashion, though it requires a great deal of work for highly skilled specialists. The qualitative aspects of air traffic control messages often cannot be converted into information theory terms with comparable precision, although information theory does not fail totally to take account of qualitative information and can make some allowances for it.

Even if the effort is made to try to apply information theory to air traffic control messages, there are considerable difficulties in interpreting the findings and in deciding what practical steps would actually succeed in improving the efficiency of air traffic control messages. The main finding is that there is a great deal of redundancy in air traffic control messages. Many of them could be pruned very drastically and still in principle convey the same information. Technically much redundancy is present; it does not follow that there must be benefits in reducing it. Redundancy may be in the form of confirmations and repetitions which enhance safety. Redundancy may be in the form of speech by the controller which sounds as if it is little more than waffle but is in fact vital, either to give him thinking time, or to allow him to perform some essential activity without being interrupted by other pilots while he is doing it. The application of the concepts of information theory to air traffic control reveals the great complexity of air traffic control information as well as the high levels of redundancy in much of it. Although the practical steps that should follow are not always clear, the techniques of information theory can be illuminating in revealing many of the functions served by air traffic control messages, and in pinpointing their essential core of indispensible information. Also the amount of redundancy has to be quantified in some terms before the need for all of it can be evaluated.

# CHAPTER 11

## THE SELECTION OF CONTROLLERS

### 11a TWO UNRESOLVED FUNDAMENTAL ISSUES

The presumptions behind selection are that everyone is not equally fitted for air traffic control work and that everyone cannot be trained to perform air traffic control tasks equally well. The aim is to select those most capable of learning to become controllers, most able after training to do air traffic control tasks, and most likely to remain willing and able to make air traffic control their career. If the wrong person is selected, much time, effort and resources are wasted, and much personal anguish may be caused if an individual, perhaps after years of training, must reluctantly face the facts that he will never become a controller, that his years of effort have been wasted, and that the training he has received does not equip him for any alternative employment. Meanwhile someone else, who might have been more successful, has been deprived of the opportunity to become a controller and perhaps of a successful air traffic control career. From every point of view therefore, the process of selecting the most appropriate people to become controllers should be as fair, valid and successful as it can possibly be.

Yet at the heart of this process are two fundamental issues which must be tackled and resolved before the selection process can be optimised or substantial further progress in selection can be made. These issues have been fudged or evaded, partly because they are difficult to deal with but also because they could have unwelcome political or administrative consequences. The first concerns the relationship between selection and training: the second concerns attributes unrelated to air traffic control but nevertheless deemed essential in controllers.

Put oversimply, the correct balance between selection and training depends on whether controllers are born or made. There is no dispute that the experienced controller relies heavily on his abilities, skills and knowledge. There is debate on the respective roles of innate qualities and of acquired ones.

The argument that assigns more importance to selection runs somewhat as follows. A relatively rare combination of innate abilities and attributes is an essential prerequisite for a good air traffic controller. Quite a small proportion of those who apply to become controllers would be expected to possess all these abilities and attributes. Many people could never become successful controllers, no matter what training they receive, because they lack the essential innate qualities. If this argument pertains, any successful selection procedure would be expected to be elaborate and would reject a large proportion of applicants but emerge with an elite, almost all of whom could be trained to become controllers since they are known from the selection process to possess the required combination of abilities and attributes. In these circumstances, selection becomes very important, and failures at the end of training can most readily be ascribed to faulty selection. A controller would be successful primarily because of his innate abilities and attributes which provide the indispensible potential for successful training. The main way to raise the quality of controllers would be to improve the selection procedures.

The contrary argument that assigns more importance to training runs somewhat as follows. The innate abilities and attributes essential in a successful controller are few and prevalent. Most people, with above average intelligence, a reasonable educational standard and good physical and mental health especially in eyesight, hearing and emotional maturity, could be trained to become good air traffic controllers. Provided they meet these straightforward criteria, few applicants need be discarded during selection. If this argument pertains, selection procedures should be simple since this will suffice for the few essentials, and further specific attributes beyond these are unimportant. Since most people with these general attributes could become satisfactory controllers, selection itself is relatively unimportant. The main determinant of success at the end of training is the training itself, and failures should be ascribed to training rather than to selection. A controller is successful primarily because of what he has been taught, has learned and understood during training, in the forms of knowledge, experience and skills. His ability as a controller is learned. It is not primarily a matter of innate attributes or potential.

Many controllers might themselves incline to the view that their innate abilities are important and assign a predominant influence to selection. Other controllers, and perhaps many management staffs and some human factors specialists, might support the idea that training is more important and that highly specific innate attributes are not. Both groups of protagonists have to rely on belief and anecdote to bolster their views. Sound scientific evidence does not exist because the necessary research has not been done. It is overdue. In the meantime, much effort and resources may be expended on the development or improvement of a selection procedure which has little relevance to air traffic control; or comparable effort and resources may be devoted to the development and improvement of training, which must ultimately be a profitless exercise if the wrong people have been selected.

Work to define the priorities and relationships between selection and training in air traffic control is urgently needed. One possible conclusion is that much effort on both selection and training in air traffic control is wasted, simply because suitable candidates in sufficient numbers never apply to become controllers. The attraction and recruitment of applicants would then take priority over both selection and training, as the first human factors problem to be solved. There are gross national differences, and sometimes differences between civil and military experience, in the ease with which air traffic controllers can be recruited.

The other fundamental unresolved issue, often particularly applicable to military air traffic control, is the confounding of the selection of controllers with the selection of future military officers, managers or programmers. In effect, the individual must satisfy more than one separate selection procedure. The attributes needed for success in one may bear little relationship to those needed for success in another. When those who satisfy one selection procedure are rejected because they fail in a separate one, this reduces the supply of eligible candidates, sometimes drastically, and complicates the validation of each procedure. This can result in muddle.

Controllers commonly contend that those who manage them fail to understand them but that if all management staffs were drawn from experienced controllers their needs would be adequately understood. In practice, this does not follow. Those appointed to management posts, where they have to take account of fiscal, political, procedural, and other constraints which the controllers themselves remain unaware of and do not wish to be associated with, often seem to their erstwhile colleagues to desert their former air traffic control interests and loyalties as they settle into their new roles. The managerial jobs are different, as are the attributes needed to do them well. A practical consequence is that a selection procedure designed only to choose the best possible controllers would almost certainly differ from one designed to chose individuals who could be both successful controllers and future managers of controllers, or one to choose individuals who could be both controllers and programmers. This issue of the exact requirements of selection in air traffic control needs to be faced and resolved.

11b SUPPLY AND DEMAND

The nature of the selection process must depend greatly on the public image of air traffic control as a profession, and the consequent willingness of people to apply to become controllers. If no-one can be recruited, the question of selection does not arise. If the only applicants are obviously inappropriate, it still does not arise. The most urgent problem then concerns recruitment policy and the reasons why air traffic control is so unattractive. The greater the number of applicants, the greater the need for selection. The greater the number of applicants who all meet or exceed the minimum agreed standards, the more refined the selection procedures must become to distinguish the most suitable candidate from others who may be nearly but not quite as suitable. Air traffic control has an additional selection problem, in well qualified applicants who wish to become controllers but who nevertheless see air traffic control as second best, having failed an aircrew selection procedure.

The supply of applicants may be curtailed if numerous candidates are rejected on grounds irrelevant to air traffic control. The lack of prospective managerial or software writing skills provides a few examples. Much more common are poor officer qualities among candidates for military air traffic control. This constraint can become serious enough to convert an adequate supply of candidates into an inadequate supply. A measure of the problem could be obtained by disentangling the reasons for rejecting individual applicants. The need for controllers to be officers is an emotive and contentious issue that cannot be avoided if it is blocking adequate recruitment.

When the number of air traffic control applicants who meet the basic criteria far exceeds the number required, a two stage procedure may have to be implemented as a practical necessity when the costs and resources needed to put all candidates through the full selection procedure would be prohibitive. The first selection stage, often based on the information obtained from application forms, must be straightforward to achieve its objective of a substantial reduction in the number of candidates, but if it is cursory or invalid it may inadvertently reject many of the best candidates, a deficiency which cannot be subsequently remedied. It is therefore important to establish the true validity of the first stage of any two stage selection procedure. A corollary is that the content of the initial application form may have to be revised drastically, and perhaps expanded, if it may be used not only to establish that each candidate meets the basic general criteria, such as age, health, education, etc, but also to permit a preliminary sift of the candidates apparently best qualified.

Selection is complicated by fluctuating demands, particularly if they are unpredicable or sudden. Various allowances can normally be made when predicting future demands. These include the proportion of candidates who will complete their training successfully, the prevailing or predicted attrition rates among controllers, predictable retirements, changes associated with the opening or expansion of control facilities and towers or the closure of existing ones, changes in manning levels because of new equipment, procedures, traffic demands or policies on hours of work, rostering or grading, changes in training and retraining commitments, and so on. Because of the length of training, and because newly licenced controllers cannot fulfil all air traffic control jobs without further experience, predictions of expected demand have to be made several years ahead. Such predictions are usually quite accurate, except when unusual circumstances intervene, most commonly in the form of such gross changes in national policy as a total ban on recruitment. On the basis of expected demand, training courses are planned in terms of their frequency and the numbers on each course. Supply and demand are matched as closely as possible so that there should neither be trained controllers for whom there is no work, nor insufficient controllers to provide a full air traffic control service.

Wherever possible, the balance between supply and demand is smooth, so that the requirements for training are fairly constant over short periods and the organisation of training can thus be more efficient. This smoothing also means that the probability of a candidate's acceptance or rejection should not fluctuate grossly over short time periods for reasons that are irrelevant to him and are beyond his control. The aim is to make the selection criteria and standards as consistent as possible so that all candidates selected meet them but the borderline between acceptance and rejection changes only slowly if at all. Ideally the selection criteria are held constant and fluctuations in demand that cannot be smoothed away are countered by variations in such factors as recruitment publicity.

The most serious consequence of gross changes in demand at short notice occurs when there are also recruitment difficulties. The only way to obtain a sufficient supply of candidates for training is to lower the selection standards. Whether the selection criteria are specific or general, and employ many or few assessments, if they have validity it is self-defeating to lower them: the result may be the rejection of a higher proportion during training, the prolongation of training, or the licencing of less able or less safe controllers, none of which are desirable consequences. However if the selection criteria were initially poor and of dubious validity, little extra penalty may be incurred by lowering them.

Once the vagaries of supply and demand have been reconciled, if necessary by including an initial selection on the basis of the contents of the application form, the full scale selection procedure is followed with a sufficient number of candidates to yield the numbers ultimately required, allowing for known or estimated attrition rates for every reason at each subsequent stage between selection and full licenced or journeyman status a· an air traffic controller. These subsequent stages include:

(1) Candidates who pass the selection procedure but do not present themselves for training.

(2) Candidates who fail or leave at some time during training.

(3) Candidates who fail at the end of training.

(4) Candidates who complete training successfully but never practice as controllers.

(5) Candidates who start to practice as controllers but leave for any reason before they have become fully experienced and fully independent as controllers.

The later the stage at which individuals fail or leave, the larger the resources devoted in vain to them, the greater the benefits if they had never been selected, and the more difficult the decision to leave for each individual. A productive role for the human factors specialist, especially if he is seen as impartial and independent, is to conduct formalised interviews with those who leave to explore their reasons for doing so.

11c THE IDENTIFICATION OF RELEVANT ATTRIBUTES

The first stage in devising any selection procedure is to examine current and future tasks in terms of the human qualities which are or may be relevant to their successful performance. Just as job descriptions and task analyses are needed to specify the equipment and the workspace, so they are also needed, in conjunction with evidence about the workspace, the equipment and working conditions, to determine relevant attributes in selection, and to guide the planning and implementation of training. The evolution and proving of a valid selection procedure involves a great deal of careful and painstaking human factors work, much of which is comparatively routine in the sense that it requires the application of known and proved procedures and techniques, rather than innovative or radical ideas which may sound more valid than they are. Some selection techniques which possess face validity (so that their predictive value for air traffic control seems plausible both to selectors and to candidates) may lack true validity: evidence of validity must therefore depend on much more than commonsense. Selection techniques which employ interviews need to incorporate defined dimensions for assessment, and not rely on hunches and ill-defined non-specific impressions, whether favourable or not.

Many kinds of attribute may be sought in selection. Some refer directly to aspects of task performance, such as manual dexterity and verbal fluency. Others concern mental attributes such as a quick appreciation of problems, a good well organised memory, a high level of intelligence, or the ability to reason, to predict or to deduce. Others concern the organisation of mental attributes - the propensity to be distracted, the ability to time share tasks effectively, the choice and management of available resources, or the ability to judge how important and urgent each problem is. Others are more social attributes, such as the ability to work collaboratively as an effective member of a closely integrated team, the insight to judge when others should be consulted and when they need not be, the ability to listen to speech by R/T, telephone or colleagues, the acceptance of the need for rules, conventions and standards, and the willingness and ability to absorb and subscribe to the ethos of air traffic control as a profession and to act accordingly to be fully acceptable as a colleague. Still others deal with physical attributes of individuals such as adequate colour vision, eyesight which can reach required operational standards if necessary after correction, good hearing, fitness, and emotional stability. Other individual attributes include being within acceptable age limits, not being addicted to drugs or alcohol, not being exceptionally tall, short or obese, and possessing the required educational qualifications. Sometimes a further attribute that is sought is experience, knowledge or stated interest in aviation in general or air traffic control in particular. A long list of attributes can be compiled. Although there is a core of essentials (reasonably high intelligence; minimum educational qualifications; adequate mental health; adequate physical health, vision and hearing; physical fitness; appropriate age; etc), there are considerable national differences in the attributes of controllers which receive most emphasis in selection and in the forms of assessment employed in the selection itself. Biographical data, interviews, tests, and simplified air traffic control tasks are the commonest methods for obtaining the basic data used in selection.

In air traffic control, selection is of controllers as such, rather than of a controller of a particular type, except that civil and military selection criteria and procedures may differ. Generally selection is not used much to prejudge the kind of air traffic control for which the individual is best suited. In countries where the training of all controllers is relatively standard, it makes good sense to use training rather than selection as a guide to the allocation of controllers to appropriate jobs on completion of their training, rather than to prejudge their job when they are selected. However in countries where controllers are recruited mainly for particular facilities from the outset, it may be advisable to question the universal applicability of a single selection protocol for this purpose. It is reasonable to expect that a proven and validated selection procedure should not only select good controllers but should also indicate the kind of air traffic control most appropriate for each individual.

If a selection procedure is based on a thorough analysis of tasks, equipment, workspace, facilities, responsibilities, and conditions of employment, a relatively short list of testable attributes of predictive relevance is likely to emerge as a basis for validation. An alternative approach, based on a different perception of how scientific methods should be applied to selection, may also be adopted: this involves far less finesse and insight, more resources and testing time, less human factors commitment, and more statistical computation. It requires the measurement of almost every conceivable attribute that can be quantified and correlated with air traffic control proficiency, whether or not there is any logical basis for linking the two or any rational or theoretical connection between them. Methods akin to this have in fact been adopted. The advantage is that any factor with predictive value is unlikely to be missed. A disadvantage is that, at least initially, a few factors may seem significant by pure chance. Also, correlations may be mistaken for causes, or the imputed direction of a causal connection may be the reverse of the true one. The justification for the predictive value of a relationship may be purely empirical, a mathematical correlation with no feasible explanation. A measurement may then be employed because it seems to predict, although no-one knows why.

The more this latter approach is adopted, the more scope there is for the intercorrelation of measures, to establish which are independent of each other and which appear to be different measures of the same thing. Some overlap among measures is always expected, such as a relationship between general intelligence and educational qualifications. The intercorrelation of measures is encouraged by the development of automated methods for comparing the variables within a stored data bank, although the work required to gather the data can be formidable, and there is the risk of invalidating some measures by trying the candidates' patience too far, particularly in the absence of face validity.

It is debatable how far human factors should become involved in exploratory work on the correlation of variables where predictions depend solely on mathematical relationships devoid of psychological insight, explanation or theoretical justification. This kind of approach can lead to muddled thinking. Efficiency as a controller may be correlated positively or negatively with numerous factors, but to contend that all such factors must in principle have predictive value for selecting controllers is fallacious. For example, some of the measured attributes may have been caused by being a controller; if those who failed had been selected instead they too would have evinced the same correlated relationships.

Age is important in selection. In many countries there has been a change of policy so that older people, no matter what their qualifications and experience, are not eligible for selection as controllers. At one time ex-aircrew with many years of experience were eligible, but their attrition rates and failure rates during training proved too high. The maximum age now for recruitment is usually between 23 and 30 with a minimum age of between 17 and 21 [27]. There may also be a minimum legal age at which a controller can take sole responsibility. The interacting effects of age and of experience, which tend to act in opposite directions, are complex to disentangle [134]. It certainly becomes more difficult to train a controller as he gets older, and his peak, without allowing for the factor of experience, occurs on average when he is quite young, around thirty. Thereafter, increased experience may counteract the effects of age: the extent to which it does so varies greatly between individuals. Some show little or no deterioration in their ability as controllers for many years; some burn out when quite young, for reasons which are often obscure, but which are sought from time to time with a view to incorporating measures of them during initial selection if possible. It may become more difficult for an older controller to adapt successfully to evolutionary or revolutionary changes in the design and operation of the air traffic control system, because he cannot learn new skills as well as he could when younger, and because he cannot break old habits so easily and, being older and more experienced, he has more old habits to break.

## 11d PSYCHOLOGICAL TESTS

In principle, appropriate psychological tests should prove useful and valid in the selection of air traffic controllers. In practice, numerous tests have been tried in different countries at various times. On the whole, psychological tests have not fulfilled their promise in air traffic control assessments. They have not failed, but their predictive value, though positive, has generally been low. Efforts to devise and validate suitable single tests or test batteries continue, in the belief that further improvements in selection should still be attainable if only the right tests could be found or constructed. The most extensive work on the selection of air traffic controllers using psychological tests has been done in the United States; fortunately a historical account of the main research programme has recently appeared [135].

The psychological test with the best predictive value at an initial stage of selection in air traffic control is likely to be a test of general intelligence, but this kind of test is not used extensively perhaps because it would tend to duplicate the evidence from other criteria such as educational attainments. The fact remains that controllers must be of above average intelligence, probably with a minimum IQ of 115 or thereabouts, so that for purposes of initial selection a test of general intelligence, with its well established norms and often with procedures for automated scoring, is not to be disparaged. Although the requirement for minimum educational qualifications may in some respects overlap with that for intelligence, the predictive value of a test of general intelligence may be commensurate with that of educational attainment for initial selection. Thereafter, intelligence may be a poor guide. Those with the highest intelligence may not necessarily prove to be the best controllers; in the United States those with the highest educational attainments are certainly not the best controllers [136]. This raises the question of why most countries continue to choose applicants with educational qualifications far above the minimum, when there appears to be no evidence to justify this practice.

Deductions from the nature of air traffic control tasks suggest numerous testable attributes likely to be advantageous in a controller, and therefore worth considering in air traffic control selection. These include the following: numerical ability, arithmetical reasoning, verbal fluency, abstract reasoning, spatial reasoning, directional judgements, dial reading, analogies, and manual dexterity. Research on the predictive value of these and other attributes has extended over more than twenty years. There are difficulties in establishing their true validity, because many independent criteria, essential for validation, may themselves lack both objectivity and validity, but this difficulty is not confined to psychological tests for it applies with equal force to any alternative selection procedure which might replace them. Even so, the predictive value of psychological tests in air traffic control selection hovers above the borderline between usefulness and irrelevance. For most tests, it is not so low that the test can be dismissed out of hand as having nothing to offer, nor so high that it can be included permanently in a selection procedure with confidence. The predictive value of several tests collectively can be better than that of any one test, especially with weightings to maximise the validity of the tests collectively, but as each further test is added to the test battery, the extra predictive value that each test adds diminishes until a point is reached where the time and effort required to administer, score and interpret the test are not repaid by a worthwhile improvement in predictive value of the battery as a whole.

Because of the basic requirements which must be satisfied by any individual before he or she can be eligible for selection as a controller, the sample to whom the selection tests for air traffic control are administered is far more homogeneous than the general population, and the differences between individuals in the dimensions pertinent to selection are already small and circumscribed. As a consequence, any measure which can differentiate reliably between individuals in the sample must itself be highly sensitive, reliable and valid. It is inevitable that coefficients between test scores and criterion measured must be lowered by this restriction of range. Nevertheless a valid selection test must still be satisfactory within these constraints, which are not confined to tests. Perhaps what is needed is greater insight and skill in devising psychological tests sensitive enough to be effective, since the results to date, while disappointing in their immediate practical value, offer sufficient encouragement to suggest that valid tests could be devised with persistence.

More problematical is the place of the personality test in air traffic control selection. Its role hitherto has been as a diagnostic clinical tool, to detect individuals about whom fuller data should be gathered, rather than as a test in its own right or as one of a battery with a scoring criterion or cut-off. A personality profile or pattern, or the avoidance of extreme personality scores, has been sought, but not assessments on dimensions likely to have specific significance for air traffic control. Yet there would seem to be some measurable personality dimensions as potentially relevant to the selection of controllers as the more familiar cognitive, motor and skill attributes. Perhaps a controller should be able to work effectively as a member of a team, be emotionally stable and not become over involved, be able to tolerate and remain unaffected by stress, be able to reach and abide by decisions, and even be somewhat obsessional in following rules and procedures faithfully. While it is unlikely that a single optimum personality profile for controllers can be specified, nevertheless dimensions which look particularly apposite seem worth exploring further. Different measures of personality, such as the classification into type A and type B personalities, have been taken to try and predict the individual controller's propensity to show symptoms of stress, but the common finding in other professions, that the type A personality - the ebullient, thrusting, highly active and highly motivated person with ambitious goals - is more susceptible to stress, has not been replicated among controllers, for reasons which await a satisfactory explanation[137].

One testable factor of relevance which has emerged more recently and may be pertinent to air traffic control concerns the ability to share tasks. There is some evidence of the independent existence of such a factor, regardless of the nature of the tasks being shared, though not of how extensive it may be in each individual. It is not yet known whether an individual's apparently enhanced task sharing ability in some tasks applies to everything he does. The ability to remain aware of the general situation and of other pending problems no matter how demanding a specific problem may become, is clearly relevant to air traffic control. Attempts are made to instill it during training. To some extent, the success or failure of these attempts may be predictable in terms of this task sharing ability.

In considering the role of psychological tests, it is fair to conclude that their status in air traffic control selection is broadly comparable to their status in other contexts. Some measures, notably those concerned with personality, have been devised originally for application to clinical rather than occupational problems; a personality test specially devised for occupational use would probably offer better prospects of practical utility and validity. Social and legal attitudes towards psychological tests have changed in some countries in ways which affect air traffic control applications, so that the social context within which the psychological tests were originally devised has been replaced by new and more questioning social attitudes towards them, to which the psychological tests must adapt so that they can survive. The future of psychological testing in general is currently a matter of debate and reappraisal.

## 11e THE ROLE OF AIR TRAFFIC CONTROL TASKS AND KNOWLEDGE

Whereas the employment of psychological tests for the selection of air traffic controllers examines attributes which occur generally in human beings but are thought to have a particular relevance to air traffic control although the tests of them were not originally designed as air traffic control measures, simplified air traffic control tasks are intended specifically for air traffic control selection. They rarely have norms for the general population but only for controllers but they attempt to measure directly some attribute of air traffic control, usually in a rudimentary form and disentangled from its air traffic control context so that the simplified task can be done by a candidate with no knowledge of real air traffic control. These simplified tasks generally possess high face validity in that they seem sensible and plausible to candidates. Two distinct kinds of tasks can be distinguished: one concerns knowledge or experience of aviation, air traffic control or particular air traffic control functions; the other requires the actual performance of tasks based on aspects of air traffic control or ostensibly derived from it.

When air traffic control began, many of the people who became controllers had aircrew experience. It seemed logical that a knowledge of flying and of the tasks of aircrew would be helpful in a controller in charge of air traffic. For a long time, the practice persisted of favouring in the selection of controllers those with aviation experience of some kind. In some countries this practice was endorsed as national policy. Over the years the evidence has gradually accumulated that the only previous aviation experience which confers sufficient advantage to be included in selection procedures for controllers is previous experience as an air traffic controller. Experience or knowledge of other aspects of aviation, including flying experience, confers no benefits. Obviously, the more experience a man has had, the older he is likely to be when he applies to become a controller and so age might be a confounding factor in this finding; but even when full allowance is made for age, the finding still remains the same. The scientific support for the inclusion of any tests of aviation knowledge and skills in selecting controllers is at best very tenuous, although its face validity is high and it seems so reasonable. The burden of proof should therefore rest with those who advocate its inclusion: there is ample evidence that it does not contribute usefully to the selection of controllers.

It is important that this point is not confused with an apparently similar one. It is not being argued that the controller does not need to learn about other aspects of aviation during training, including flight deck experience and perhaps obtaining his private pilot's licence. This is an essential part of his professional knowledge and he must therefore be well versed in it. The point is that if, for whatever reasons, he knows about this beforehand it does not increase the probability that he will become a good controller, and he should not therefore be selected on that basis unless he has previous direct experience as an air traffic controller.

Selection procedures for controllers have often included one or more tests representing air traffic control problems, generally but not always in static form. The task has usually been to determine whether a depicted situation, or proposed changes in it, would violate specified rules, usually concerned with separation standards expressed as times or distances, with conflict detection or resolution, or with sequencing or flow control. The general experience with these air traffic control tests has been much the same as that with the psychological tests: they have enough predictive value to be seriously considered for inclusion in a selection battery for controllers, and sometimes slightly more predictive value than psychological tests have, but they do not have so much predictive value as their face validity might lead one to expect. The impression remains that this aspect of selection merits re-examination at the present time, particularly with respect to the use of micro-computers to generate simple dynamic tasks which can be presented and scored automatically at very low cost. These micro-computers offer high face validity, and great flexibility in the generation and validation of suitable air traffic control material.

A further use of air traffic control tasks in selection might be to facilitate the allocation of those selected. Although extensive efforts have been made to try to provide guidance from the selection procedure itself on the kind of air traffic control jobs for which each candidate may be most suited, only limited progress has been made, and much of that has been in the form of different proposed cut-off points in test scores for various options[138]. This too would seem to be an aspect of selection on which definitive work might yet be done.

Although aviation interest, particularly an interest in aircraft and flight, has been dismissed as a useful major contribution to selection procedures for controllers for lack of supporting evidence, there may nevertheless be a case for treating it seriously. An interest in aviation as such may not affect a controller's ability but might well affect his motivation, his attitudes, and his tolerance of air traffic control work. In particular an interest in aviation may sustain his alertness and the belief that he is doing a worthwhile job throughout the long hours when he is on duty but there is very little work for him to do. While he waits, the man with aviation interests may have greater satisfaction because he is doing a job that is intrinsically interesting to him, especially if he is in the surroundings of a tower, where the runways, taxiways, aprons, airport buildings and parked aircraft may have some fascination for him. If such a boon can come from an abiding interest in aviation, it may well be worth having.

## 11f THE VALIDITY AND RELIABILITY OF SELECTION PROCEDURES

A recurrent theme in attempts to devise any selection procedure for controllers is the difficulty in establishing criteria for its validation. Some independent definition of the attributes of a good air traffic controller is required in order to gauge whether the selection procedure is providing them. Preferably the validation criteria should be sensitive enough to permit correct decisions on whether a change in the selection procedure has been beneficial and on the prospects that further worthwhile improvements in the selection procedure may be attainable. The notion of a good air traffic controller is at best a nebulous concept, which becomes even more elusive with efforts to express it in quantitative measurable terms for validation purposes.

The main sources of criteria for validating an air traffic control selection procedure include the following:

(1) Progress during training, as measured by assessments, tests and instructors' judgements.

(2) Final assessment and initial allocation at the end of training.

(3) Supervisors' assessments of on-the-job performance.

(4) Peer ratings of on-the-job performance.

(5) Career advancements, promotions, and responsibilities.

(6) Incidents that lead to investigations or official enquiries.

(7) Participation in refresher or retraining courses, and the attainment of additional professional qualifications.

(8) Attrition rates, and reasons for leaving.

It is usual to choose a few of these sources and amalgamate them in some way to derive a single composite criterion against which the whole selection procedure, itself an amalgamation of weighted measures, is validated, or against which each test or assessment within the selection procedure, or proposed for addition to the selection procedure, is validated individually. The way in which the sources are chosen and the weighting accorded to each in the amalgamation of them, depend partly on the strength of evidence for an optimum weighting and partly on the purpose of the validation. In the absence of any adequate basis in which the characteristics of a good controller could be expressed in quantifiable terms, a more modest aim may be to select those candidates most likely to complete their air traffic control training successfully and to go on to become controllers. Most weighting would then be given to training and attrition factors. However, if the emphasis of the selection was to find controllers potentially suitable for management posts, the selection criteria should then be weighted in favour of supervisors' assessments and career advancements.

Controllers themselves, in peer ratings, are often in substantial agreement about which of their colleagues are the best controllers. They have difficulty in putting their reasons into words. Air traffic control instructors often have firm views, formed quite early in the training course, about who will ultimately succeed and who will fail. They too have difficulty in formulating their reasons verbally. Both these types of judgments are made by well-informed people on the basis of evidence which they believe to be present, though hard to quantify. If it is indeed present, more persistent efforts should be made to identify and measure it, since it is not being included in current selection procedures but should be. However, if in the case of the instructors it is spurious, based on superficial impressions of no scientific worth which may rapidly become so entrenched as to become self-fulfilling prophecies, then such premature judgments must be firmly discouraged, and no discriminatory activities must be based on them. In either case, this propensity to form early judgments needs thorough study, the outcome of which should lead to practical action.

Existing criteria for validating air traffic control selection are inadequate. The vagueness about the attributes of a good controller, the subjectivity of many of the judgments on which the criterion measures ultimately depend, and the dearth of objective, scientific, quantitative indices of air traffic control safety, efficiency and performance, all conspire to keep the validity and reliability of the selection procedures low because the validity and reliability of the criteria against which these procedures are judged are themselves low. If the validity and reliability of the selection procedures themselves are in fact high, there is no means of recognising this in the absence of equivalent validity and reliability in the criterion measures.

Subjective evidence from controllers, although it may eventually be discredited, currently offers enough encouragement to suggest that there is scope for further progress in quantifying the attributes of a good controller, thereby improving the criteria for validating air traffic control selection procedures, a prerequisite for improving the procedures themselves in an intelligent rather than a random fashion. A great deal of effort could be expended in the improvement of selection procedures, to no avail as long as the criterion measures are suspect. Perhaps the balance should be redressed, with more resources devoted to criteria for validating selection procedures, and fewer to the actual procedures. Sooner or later, a better rationale for making changes in selection procedures will have to be found.

Evidence for the validity of selection procedures should be obtained more thoroughly in the form of statistical correlations. Some data are already in quantitative form, or can be so expressed with little effort. Examples are marks and assessments obtained during and at the end of training, assessments made at promotion boards, the timing of achieved promotions, the nature and dates of obtaining further professional qualifications, and the incidence and dates of attrition. Such measures can be correlated with the overall assessment at the end of selection, and with individual markings incorporated within that overall assessment. The resulting correlations will show the predictive value of selection as a whole and of its various components, for progress and attainment during training and during subsequent air traffic control career. The true prognostic value of the selection procedure can then be determined, and compared with the ideal prognosis. Action should follow, its nature depending on what is found and what is required. Assessments which are in the form of pass or fail have very limited value in determining the validity of the selection procedures and wherever possible more detailed quantitative measures should be used.

If the correlation between selection and training is poor, one or other, or perhaps both, need to be re-examined, depending on the correlations between selection and achievement as a controller and between training and achievement as a controller. All three should be in step. If they are not, selection or training, whichever has the lower correlation with achievement, needs careful reappraisal. If selection and training correlate highly with each other but not with achievement, both need to be looked at afresh. The whole point of selection, and of training for that matter, is that it should relate to ultimate achievement as a controller and the success of the selection procedure depends upon this. A series of correlations can show where the procedure is succeeding, where it has some limited success but needs improving, and where it fails because it lacks predictive value. If it has no predictive value at all, it should be scrapped.

## 11g ADAPTING SELECTION PROCEDURES TO CHANGING NEEDS

From time to time, changes in selection procedures for controllers become necessary. Air traffic control is not static. Its demands, equipment, procedures, facilities and organisation evolve, and selection procedures should evolve accordingly. New requirements, such as the ability to understand software, to utilise automated aids to higher mental functions efficiently, to relate effectively to machines, to work within a team structure which is smaller and less tightly defined, or to maintain interest during inactivity, may become desirable attributes in controllers, sought in selection procedures if means to test for them can be devised. Because of the lag between selection and becoming fully qualified as a controller, it is desirable, though rare, for selection procedures to consider not the current air traffic control requirements but those some time ahead, in so far as they can be predicted with confidence.

Continuous efforts have to be made to adapt selection to new requirements, to ensure that the evolving changes in the selection procedures are valid and reliable and can therefore be justified. The rationale for changes may have to rely on deductions of the required skills and attributes if the changes originate in technological innovations, since long term evidence on validity can accumulate only gradually after the changes have been introduced into operation. Most of the innovations have been the subject of tests and prototype evaluation before they have gone into service. Much more could be done during these initial evaluations to define the training procedures which the innovation is likely to entail, and to specify the skills and attributes required for its successful operation, which might therefore feature in appropriate selection procedures. By relating planning and evaluation more closely to selection, it should be possible to make significant progress in adapting selection to the changes taking place in air traffic control, and thereby to enhance the predictive value of the selection procedure itself. Air traffic control has changed so much that selection procedures which have not changed for many years must almost certainly be inadequate now in some respects in relation to new roles.

# CHAPTER 12

## THE TRAINING OF CONTROLLERS

### 12a TRAINING OBJECTIVES

Although the main objective of air traffic control training is self-evident, being to produce fully qualified, safe and efficient controllers by the most cost-effective training methods, there is little uniformity or standardisation in the practices followed in various countries to achieve this objective. Training is protracted because there is a great deal of information that the controller must be taught, but policies differ on the best training techniques, on the desirable degree of specialisation during training, and on the balance between academic learning, practical training in specialist training facilities, and on-the-job training. Training has to reflect some of the main differences between countries in their air traffic control, such as the extent to which civil and military control are integrated, the traffic demands, and the sophistication of the installed air traffic control equipment. Training also has to reconcile two requirements which are potentially incompatible: a set syllabus leading to an absolute standard of proficiency has to be followed, and this is easier to administer if it is adhered to rigidly; yet individuals differ in their rate of comprehension and retention of information, and some provision for flexibility in response to individual training needs is essential.

The expected pace and content of learning, and the choice and training of instructors, are further topics where practices are diverse. Some courses have a high academic content; some emphasise classroom teaching; some concentrate on practical exercises; some emphasise teamwork; some rely heavily on on-the-job training and experience. Instructor-pupil ratios vary substantially. Some courses aim to teach principles; others concentrate on practical examples. The need for instructors to be taught how to teach is now widely acknowledged. Their attitudes towards instructing vary greatly, because in some countries a spell as a training instructor is seen as a positive step towards career advancement, whereas in others it has the contrary reputation. An anomaly in training is that logically the training of controllers should include experience of all equipment they are likely to encounter at the places where they may subsequently be assigned. Training schools should therefore be among the first places where new equipment is installed: all too often they have been among the last.

Most air traffic control training schools accept pupils from many nations. Training costs per pupil are high, and many smaller nations have neither the resources nor a sufficient number of air traffic controllers to justify a training school of their own. Partly as a result of this, training in schools has to emphasise general rules, principles, procedures, and standards, rather than the particular air traffic control problems that arise in the country where the school is located. Sometimes training has to fulfil other requirements also. English being the international air traffic control language, some fluency in it, coupled with clear and unambiguous articulation of English over R/T or telephone, is such a fundamental requirement that every prospective controller must reach a reasonable standard in it, if necessary by special training in spoken English, before the air traffic control training begins. For some peoples, where the structure, phonetic properties, and articulative characteristics of their own native language are very different from those of English, their poor intelligibility when speaking in English over an R/T channel can become a problem not merely for a few individuals but for nearly everyone, and persistence is required to overcome it.

In some countries, further constraints may govern aspects of air traffic control training. An example is a national policy which requires the selection and training for air traffic control posts of designated proportions of candidates from various subgroups in the population, identifiable in terms of sex, ethnic origin, national origin, or physical disability for example. Such a policy can pose particular selection and training problems which must be overcome. These arise not so much in the publicised and sensitive area of any lack of equivalence across subgroups in their abilities, skills and innate potential (although such difficulties may not be wholly avoided), but more in motivation, associated in particular with willingness to see the need for, be sensible of, or subscribe wholeheartedly to, a professional ethic with its notions of commitment, dedication, norms, self-discipline, and closed ranks when challenged.

Such policies also mean that selection and training processes may be scrutinised hostilely for signs of bias. They must not only be fair and impartial, which is in any case always an objective of any scientifically validated selection and training procedure, but they must also be seen to be fair and impartial by people with no knowledge of scientific methodology, an objective that can be much more difficult to achieve, especially if some selection and training procedures that possess true validity lack comparable face validity. Hitherto, most evidence suggests that differences between the various relevant subgroups in the population are small enough to be overcome by training and allocation procedures. This is fortunate, because it is in the interests of everyone that national employment policies and the requirements of aviation safety do not clash.

The basic principle underlying selection and training procedures is that all users of air traffic control are entitled to receive a service at all times which meets the required standards of safety and efficiency that must never be compromised. With each individual, training must continue until he or she reaches those standards consistently, or until the efforts to train the individual to become a controller are abandoned. Although the air traffic control service which a particular pilot receives obviously will vary to some extent according to the experience and abilities of the individual controller who is providing it, nevertheless that service must never fall below the minimum standards, no matter who the controller is. It is a function of training to ensure that as far as possible it never does and never will.

A further objective to maximise training efficiency is to ensure that there are no gross sudden changes in the demand for training. Such changes must be fundamentally inefficient in certain respects: either training facilities are underused, or training is being conducted under unnecessary pressure, handling more pupils than the facilities were designed to deal with. The ideal is to keep supply and demand in balance Failing that, changes in demand should be relatively long-term so that adequate provision can be made for them by advance planning.

12b THE CONTENT OF TRAINING COURSES

Each air traffic control training school (academy, college, etc) has its own detailed syllabus, curricula and training manuals. These are the best sources for fuller details of what is taught during training. Training content frequently comes under close scrutiny, especially in terms of general policy, objectives, and costs. Occasionally, an appraisal of air traffic control training is conducted, to identify ways in which it might be improved[139]. Here, training content is discussed in general terms only.

Training can be done within the school, or outside it on-the-job. Most training courses include both these aspects. Training may aim to provide every controller with knowledge and some experience of nearly every type of air traffic control, or each controller may be assigned from the outset to one type of control (for example en route or terminal), and trained primarily for that. The air traffic control facility where the controller will be assigned on completion of his training may be known from its outset and he may be trained specifically for it or the decision on his allocation may be taken only on completion of his training so that the training itself must encompass a broad range. Such differences, plus varying policies on the extent of background knowledge that each controller should possess and on the desirable degree of intensive individual tuition during training, have the effect that the total time required for training varies considerably.

Training content may be classified under the following broad headings:

(1) Academic knowledge, theory, rules and background information.

This covers the principles of navigation and flight; basic understanding of equipment such as radar and computers and their functioning; knowledge of related subjects such as meteorology, aviation law, and air traffic control history.

(2) Classroom instruction on fundamental air traffic control principles.

This includes the structures and divisions of airspace and airports; the rules of the air; the responsibilities of air traffic control and the divisions of responsibility within it; ground-based and airborne facilities; the types, language and formats of air traffic control communications; basic air traffic control principles and procedures; handling characteristics, manoeuvrability and limitations of aircraft, and the equipment and facilities installed in them.

(3) Individual or group demonstrations and tuition.

This covers air traffic control teams and their interactions; correct and incorrect procedures; aspects of task sharing between individuals; the allocation of resources by each individual; the time scales within which tasks must be completed; the optimum timing and ordering of different tasks; the learning of principles and rules for specific tasks, such as conflict detection and resolution, stacking, approach sequencing, etc.

(4) Practical instruction and rehearsal using simulation.

This covers learning and practising procedures; the correct usage of the displayed information, communications, and controls associated with them; the effects of traffic demands on work and its scheduling; procedures for handling emergencies and compensating for system failures; the optimum allocation of priorities, effort and resources; the progressive acquisition of appropriate skills, fluency in speech and use of controls, and confidence.

(5) Practical experience in a real-life setting.

This covers controlling within the school environment real aircraft flown for the benefit of controllers under training; experience of and familiarisation with real air traffic control environments in a subordinate capacity, either by watching controllers, conducting [illegible] limited control under close supervision, or performing some or all of the tasks of an air traffic control assistant; experience of flight and of the flight deck; first-hand knowledge of the pilot's tasks, perhaps including obtaining a private pilot's licence; experience of the professional norms, standards, motivations, responsibilities, and ethos of air traffic control.

Training is classified according to the main types of air traffic control. The divisions between some types, especially between military and civil air traffic control, may be so complete that they have separate and totally independent training facilities. Other divisions, between airways and off-airways traffic, between en-route and terminal control, between radar and procedural control, are fundamental enough to be treated in separate training courses which are assessed separately and not conducted concurrently. This training structure often means that the individual controller can obtain further validations to extend the types of air traffic control for which he is qualified.

Some training is for a specific system or location. The former is becoming more common where the largest airports or the busiest regions of airspace are covered by specially installed air traffic control equipment, aids, procedures or instructions which controllers have to learn to use. The latter, training by location, is most common in the United States, where controllers may receive much of their training not at the academy but on-the-job at the air traffic control facility at which it is intended they will be employed. The fact that different countries have evolved different solutions to the problem of the most desirable balance between general air traffic control training and training for a specific location indicates that this is a topic on which there remains much scope for debate, even though each nation has perhaps adopted the solution best suited to its particular air traffic control needs. No single optimum solution for all needs may exist.

Air traffic control is essentially a team activity, and will remain so, although the trend is for man-machine relationships to replace man-man relationships, partly because there has been greater success in devising automated aids for individual tasks than for team functions. An implication behind team training is that distinctive team functions determine to some extent the efficiency of the team, and these go beyond the sum of the functions of the individual team members, so that proficiency in them cannot be acquired by training each individual team member in isolation. Although this implication is widely believed, much team training does not in fact teach collaborative team functions, but provides a setting within which each controller practises his own functions alongside other controllers who are doing the same. However, where functions are designed from the outset to be team functions, every team member must realise that what he can do depends vitally on what his colleagues are doing, so that his knowledge of some at least of his colleagues' activities must be detailed and kept up-to-date. The training of teams as teams rather than as collections of individuals working alongside each other deserves more attention in air traffic control, and elsewhere, than it has received. A general review of the current status of team training has recently appeared[140].

At this point, some clarification of a fundamental issue seems desirable lest the tenor of these strictures is misconstrued. Those who conduct air traffic control training are generally dedicated, competent, and well aware both of the deficiencies in many of the training methods they must employ and of the opportunities for improvements in training which current technological advances may offer if they could be used. These criticisms are therefore not directed at training instructors, but are intended to point out that their best efforts may be frustrated by years of inadequate research support for air traffic control training, inadequate validation of its content and technique, and reluctance to sanction the experimental introduction of innovative training methods and techniques to see whether they might help and to discover how they could best be adapted to the particular needs of air traffic control training. Not every air traffic control training facility has had to contend with inadequate resources and support, but many have.

Fundamental learning principles - overlearning, demonstration, the elucidation of principles, active rehearsal, extra entrenchment of material just learned, immediate detailed knowledge of results, adaptive training to fit individual needs, opportunities to develop and exercise skills, the need for frequent active recall, the breaking of undesirable habits, the optimisation of the transfer of training, the building of confidence and motivation, the learning not merely of procedures and actions but of the reasons for them, the switching of attention to facilitate task sharing, etc - these are at the heart of successful training. Their realisation implies well-defined training goals, clear intermediate achievements on the way towards attaining these goals, the training of instructors in teaching methods, known validity and reliability of training content and techniques, knowledge and evaluation for air traffic control training of advances in training techniques and especially in those using micro-computers, greater research expenditure on training, and willingness to implement authenticated research findings. Currently there are some encouraging reappraisals of air traffic control training. If the opportunities which they present are seized and acted upon, substantial benefits for air traffic control training may accrue.

## 12c THE ROLE OF SIMULATION IN TRAINING

Attitudes towards simulation in air traffic control training have been, and in some respects still are, somewhat ambivalent. On the one hand, there has been much emphasis on the necessity for simulation as an indispensible training tool[141]; on the other hand, there has often been a marked reluctance to provide the funding and resources for simulators for air traffic control training, especially for simulated radars. The benefits of simulation have on occasion been so extolled by its advocates as to suggest that it is a panacea for training problems, and that other training methods are superfluous, a point of view which has certain affinities with the equally erroneous contention that the more sophisticated and realistic the simulation is, the better it must be for training. Some air traffic control training contexts have lacked even simple simulation facilities, although these are almost invariably beneficial; others employ or propose to employ very elaborate simulation facilities in the quest for realism, and the use of innovative technology seems to overtake the fidelity requirements for training purposes[123]. In some contexts, notably air traffic control evaluation, simulation has been judged to be both indispensible and overused[112]. The comparable judgment on simulation in air traffic control training would probably be that in some contexts it has been insufficient and in others over-sophisticated. Although it is widely presumed, almost certainly correctly, that simulation is beneficial for air traffic control training, scientific proof of this presumption is conspicuous by its absence.

In relation to training real-time rather than fast-time simulation is normally meant. Fast-time simulation may have a role in revealing the circumstances under which certain variables become critical, and the kinds of material that should therefore be chosen to demonstrate their importance. In training as elsewhere in air traffic control, there has been insufficient integration of fast-time and real-time simulation techniques and findings.

The basis for employing simulation to train controllers is the notion of transfer of training. Learning in the simulator transfers to real-life. It would be expected that the degree of transfer would depend on the faithfulness with which the simulation replicates real-life, but this does not always seem to be so. Where procedures are being taught, a rudimentary, even non-dynamic, simulation may suffice to teach the procedures. A series of photographs may illustrate successive stages in the use of a touch-input device as effectively as the equipment on-line. In the case of dynamic simulations that include some form of man-machine interaction, their most important requirement for training is feedback in the form of knowledge of results, so that the man can learn by his mistakes, recognise his successes, and make other finer distinctions between the two.

If the aim of training is to acquire skills, then the relevant physical components of the system - the type, sensitivity, feel, location and operation of controls - have to be replicated closely, preferably with the same equipment in the simulation as in the real-life tasks. But the system context can be quite primitive. Fluency and skill in operating a keyboard can be acquired using only the keyboard and its associated sensory inputs, though the learning process can then be tedious and it may be difficult to sustain motivation. Nevertheless, it is wasteful to have a large and unnecessary system on line just to train a man to use a keyboard.

To simulate a work position for training purposes, the most important requirement is probably completeness, rather than realism or fidelity. If some fundamental attribute of the workspace has been omitted, enhanced realism in the aspects that are present cannot compensate for its absence, or restore realism to the simulation as a whole. The more complex the task, the information, the knowledge, and the skills become, the more difficult it is to use simulation for training in the expectation that the whole of the training will transfer. This is because it becomes more probable that the simulation will in some fundamental respect be incomplete, or that some fundamental attribute of the system will be simulated incorrectly so that the learning in relation to it is inapplicable to real life.

Given this context, in some respects air traffic control simulation must, a priori, be inadequate for training just because it is simulation and thereby incomplete. If it were complete it would not be called a simulation. The aircraft to be controlled are not real aircraft, or at least not real passenger-carrying aircraft, and the controller is not responsible for the safety and lives of the crew and passengers. Serious infringements of separation standards may be criticised as major errors which would be dangerous, but in the simulation the pilot does not file a near miss report leading to an official enquiry. The simulation is incomplete in its emotional climate, even if every physical aspect of it can be replicated faithfully at enormous cost. If the man has all the requisite skills and knowledge but cannot face the responsibility of controlling real aircraft unaided, this may never become apparent as long as training is confined to simulation. Simulation as a technique therefore has some limitations which cannot be circumvented.

Simulation may encourage learning in the form of a series of specific problems to be solved correctly, but it may be less suitable for the demonstration and elucidation of principles. In later stages of training, simulation may be most effective if used flexibly: this should include the freezing of the system while instruction, explanation and correction are given, and the replay of previous exercises to show the origins of mistakes, the factors taken into account in deriving the optimum solution, and the timing of the correct solution. It can often be enlightening for the instructor to demonstrate the solution of an air traffic control problem and then to present it to the pupil who does not find it as easy as he thought to implement the same solution. Simulation can also aid in the categorisation of problems, in the systematic identification of all the variables in each, and in the detection of circumstances when the correct decision is to do nothing. A further advantage of simulation is that the complexity of problems can be increased gradually during training, in step with improvements in the student's understanding, knowledge and skill, and the difficulty of the problems can be adapted to the needs of the pupil.

A common fault, a corollary of this progressive increase in difficulty, is to stop training on a particular type of problem just after the most difficult examples have been solved successfully. This does not represent sound learning. There has been least familiarity and practice with the problems that are most difficult, and greatest familiarity with the easiest ones. Further experience of the most difficult problems should be given until all the ways in which they can be tackled and solved have been thoroughly learned and mastered. Some overlearning, that is continued learning of something that has apparently just been learned, can be strongly recommended, especially for difficult problems during air traffic control training, because it will result in the long-term maintenance of performance without much subsequent rehearsal, in higher standards, and in increased confidence.

In using simulation, a balance has to be struck to satisfy two distinct requirements. One is to provide continuity, so that training can be improved from year to year by retaining what is successful and modifying what is not. If there is continuity across training courses, it is easier to tell whether training standards are being maintained or improved, or are falling. Such factors encourage consistency in the simulation exercises used for training and in the traffic samples they employ. However, air traffic control itself changes, and the training has to be changed to keep in step with new requirements. Samples may need to be changed because new points have to be made during training. It is improbable that the samples of traffic used in air traffic control simulation for training a few years ago can be employed now to place greater emphasis on the effects of alternative air traffic control strategies and tactics on fuel consumption and conservation. These were not such important considerations when those samples were originally devised. Special samples may have to be written in order to make training reflect the greater concern for the factor of fuel conservation, and to teach controllers more about the consequences of their actions for fuel conservation. From time to time, additional factors, such as the recent one of fuel conservation, are accorded greater importance. The best way to ensure that they receive it, is to teach the necessary additional knowledge as part of training.

The ultimate simulation is to use the real-life system as a simulated one. Where this is possible, it can be a very effective final stage in training. It can provide an intermediate link to facilitate the full transfer to the real system of all that has been learned during training. It has been employed more in cockpits than in ground control systems, but current evidence suggests that it would be effective in air traffic control. Its benefits would be to reinforce training, and to maintain learning and knowledge among experienced controllers, particularly in relation to procedures and problems which seldom occur in real life and which they therefore do not have the opportunity to remain familiar with. To use a real life system as a simulated one can also help retraining, by familiarising controllers who are experienced on one air traffic control system with another system which is in some respects different but which is known to be complete.

## 12d ASSESSMENTS OF PROGRESS DURING TRAINING

The purposes of assessment during training include the following:

(1) To measure the level of knowledge and skill currently attained, and to verify that what has been learned has been correctly understood and can be put to practical use.

(2) To qualify a controller in a particular option, course, or part of a course.

(3) To ascertain that the controller has reached a criterion level of performance, as a condition for proceeding with further training.

(4) To provide evidence of progress in a standard quantified form, to permit absolute or relative judgments of that progress.

(5) To pick out those who need some re-training, more intensive tuition, or further practice, and to specify the desirable content of additional training.

(6) To identify those whose progress and prospects are so unsatisfactory that their training should be discontinued.

(7) To measure the efficacy of training, with particular reference to any changes that have been introduced in content, materials, techniques, or equipment.

(8) To standardise the content and efficiency of training at various facilities and locations.

(9) To verify the continued relevance of training to operational requirements.

(10) To give guidance on suitable assignments for controllers on completion of their training.

Assessments during training can be classified as objective or subjective. The former relate to measures on quantitative dimensions, such as delays to aircraft, or number and duration of infringements of separation minima between aircraft. These measures make most sense if they form part of a standard battery of tests, always presented under the same conditions at the same stage of training, so that norms of performance are built up, and the scores of each individual can be interpreted not merely as indices of his own rate of progress, but also in comparison with his peers. The scores themselves should be impartial, and not in any way dependent on the person who does the scoring.

This latter source of bias is endemic in subjective assessments. These are generally supervisor's ratings. Whether they are formalised by defined topics on each of which a rating is required, or remain informal in that the supervisor chooses his own words, they are notorious for poor reliability[139], which is not improved greatly by altering the time scale over which the ratings are made. Some improvements are possible by thorough training of the assessors, but not to the extent of curing the problem of unreliability. Different supervisors or controllers are still liable to give substantially different ratings of the same individual doing the same tasks. Correlations between those making ratings in this way are generally so low as to leave most of the variance unexplained. This is not because of any lack of integrity, impartiality or effort on the part of those making the ratings but a reflection of the inherent subjectivity of the dimensions on which the ratings are made. It also relates to the difficulty in defining a good controller and in specifying the attributes that are sought, and their relative importance.

A requirement for both subjective and objective measures is that the assessments should provide quantitative evidence or scaled ratings, and not be expressed simply as a pass or a failure. To take no account of the degree of success or failure in assessments is to evolve a very blunt instrument which does not lend itself to much sharpening. Every measure should aim not merely to separate success from failure but to differentiate among those who succeed and among those who fail.

There is a further possible form of bias in assessments during training. Ratings can become self-fulfilling prophecies. Instructors form views about the individuals they train, and this is inevitable and in many respects helpful because the instructor's views are formed on the basis of much relevant knowledge and experience. However, it is often striking how early during training the instructor's views on individuals have apparently become entrenched. Once set, their views are susceptible to the inherent human characteristic to notice and emphasise evidence which apparently reinforces attitudes already held, and its counterpart to discard, fail to notice, or misinterpret any contrary evidence. This is not a matter of wilful bias, and cannot be wholly countered by exhortations against it or by training to prevent it. The practical point is that in a context where early impressions of unknown predictive value can be so readily formed and acted upon, subjective assessments which could be biased by such impressions should be eschewed wherever possible, in favour of objective assessments free from that source of bias. The need to validate these subjective judgments from the point of view of their predictive value for the selection of controllers has already been discussed. Although it is easier to make subjective than objective assessments, and although a full range of suitable objective assessments may not be immediately to hand, there is ample evidence[134,142], that appropriate measures can be devised, and, subject to validation, much more extensive use should be made of them in assessments during training.

Although the use of objective measures can be extended, they cannot cover adequately every aspect of training assessment. Some attributes, such as a propensity to panic in crisis or acceptability to colleagues, may remain subjective. Independent assessments by several instructors, or assessments by others who make no direct contribution to teaching, may help to increase reliability, and even if they do not they increase the apparent fairness of the assessments if they are scrutinised critically. Continuous frequent assessments during training are likely to give a more representative view than rare brief assessments, though the latter may have value by showing the individual's reliability when subject to strain. Whenever real aircraft are flown for air traffic control training purposes the opportunity should be taken to make assessments of emotional state and relevant aspects of personality since a controller's subsequent difficulties in shouldering the full responsibility for the control of real aircraft may first be hinted at with real aircraft during training. More detailed records of the kinds of mistakes made during training, their frequency, and the amount of learning needed before they could be overcome, might provide further useful indices of training progress, to be incorporated into assessments. The ability of the controller to do a task which the instructor has just demonstrated and explained might provide a further basis for assessment. Whatever approach is followed, some standardisation is essential in the tasks on which individuals are assessed, in the conditions under which the tasks are done, and in their scoring.

To standardise assessments, it seems necessary to have some means of ensuring that training conducted at different facilities is comparable in quality and content, so that the controller is neither advantaged nor penalised by the facility at which he happened to be trained. This aspect of standardisation points to some form of centralised, universal, independent testing and assessment authority.

## 12e THE RELIABILITY AND VALIDITY OF TRAINING PROCEDURES

A few years ago, one verdict[139] about training for en route and terminal controllers in the United States was that "there is evidence that training is not standardised at the facilities, that training times given to various topics differ between facilities, that some procedures specified by the curriculum are inconsistent with others in the curriculum, that qualification standards are interpreted differently at various facilities, and that some teaching materials do not conform to current operational practices". This report goes on to note that there are deep-rooted longstanding disagreements about the value of, and desirable emphasis on, various forms of training, and that objective and impartial evidence is needed to resolve these disagreements. Nevertheless there was clearly the general view that training on the whole is appropriate and does fit the controller for his task.

Many of the misgivings about the suspect reliability and validity of selection procedures apply with equal force to training. Perhaps of overriding importance is the purpose of training - to produce controllers who will prove to be safe and efficient in the long term. The purpose of training is not simply to complete training successfully. It is tempting to treat the completion of training as an end in itself, and to judge the value of assessments taken during training solely in terms of their ability to predict who will complete their training successfully and who will not. While this should not be ignored, assessments during and at the end of training should be correlated with subsequent progress, including supervisors' and peers' ratings of competence, promotions, attrition, and other quantifiable data of relevance, to establish their long-term predictive value. All the quantifiable assessments during training should be examined to establish their predictive value as a conglomerate and individually, with particular reference to those which are used to influence the decisions on the kind of air traffic control job for which each individual seems most fitted.

Training procedures may be unreliable simply because they are inconsistent and differ a great deal between one facility and another. They may also become unreliable if they have to be changed drastically to cope with gross sudden imbalances between supply and demand, from whatever cause. Training procedures may be invalid for any of the following reasons: they do not teach what is necessary; they are at the wrong level of detail; they emphasise rote learning and a series of disconnected examples, rather than insight, understanding and the practical application of principles; they teach subjects in the wrong order or with the wrong relative importance and priorities; they teach procedures that are obsolete on equipment that is out of date; they teach in an environment so different from real air traffic control that the ability to perform a task in training does not guarantee an equivalent ability in real life. Most of these sources of training inadequacy are familiar to instructors, who may be powerless to do much to circumvent them in the absence of direct knowledge of the validity of the training being given. Just because a particular training schedule produces controllers, it does not follow that improved training could not produce better controllers: indeed it almost certainly would. But as long as we have no objective means for recognising better controllers, and especially for quantifying how much better they are and for explaining exactly why they are better even if we manage to produce them, so we have no means of recognising valid training improvements, of quantifying them, or of explaining them. It is not known how much the validity of the training of air traffic controllers could be improved. It is not even possible to cite a quantitative figure to state what the validity of the current training procedures is.

There appear to be some tacit assumptions about the relationships between the various possible measures of validity in training. If changes in training are introduced and they lead to a reduction in attrition rates, it does not follow that the quality of the accepted controllers is better, or that the controllers who are still being rejected are the ones who, in the long term interests of air traffic control, should be rejected. Supporting evidence is needed for such conclusions. If those who obtain the highest assessments at the end of their training do not, during their subsequent careers, prove to be better controllers on average than those who were borderline passes at the end of training, perhaps some of the controllers who failed would have been as good as many of those who passed. Work to quantify the reliability and validity of air traffic control training, and to settle such issues, is urgently needed.

## 12f TRAINING FOR NEW TASKS

Because air traffic control demands, equipment, system design, responsibilities, and even objectives change from time to time, new tasks, or major changes in existing tasks, must occur, for which appropriate training has to be devised and implemented. If the whole concept of the air traffic control system is revised drastically, or important new forms of automated assistance are provided, then the envisaged roles for the man may become very different as a consequence, particularly if the man is expected to adapt his roles to the demands of the revised system[38]. Training for new tasks should be introduced as the new tasks arise. Evaluations of new functions should include the testing and optimisation of training for them. Some guidance would then be available on appropriate training, content and techniques when the training schedule for the tasks was being set up.

In practice, these commonsense ideals are seldom realised. Training lags behind operational needs. Logically, training facilities should be the second to receive new equipment required for new tasks. Since training should precede operational use, training facilities need the new equipment ahead of the operational environments. Only evaluation facilities, where the viability and practicality of the new tasks and new equipment are established, need to receive new equipment before training facilities do, since if the equipment and tasks are rejected for operational use as the result of an evaluation the need to install them in training units does not arise. If it does arise, training comes next.

The links between evaluation and training could often be strengthened, with benefits to both. The derivation and proving of adequate training procedures for new equipment and new tasks should be a regular part of their evaluation, to which those professionally concerned with training should contribute. Training for new tasks must be compatible with the broad training schedule, and not devised and tested without regard to it. The emphasis in an evaluation of new equipment or a new task may be to prove its feasibility or to quantify performance attained with it: in either case, the answer may depend on the kind of training devised for the evaluation and on the efficacy with which it has been carried out. The evaluation itself may point the way to training difficulties which would have to be resolved. Its design should seek to reveal such difficulties and to explore solutions to them, just as it seeks to discover inadequacies in equipment or in task performance and explores means to circumvent them.

Currently the usual emphasis in evaluations is to devise training and familiarisation wholly specific to the evaluations themselves as distinct from subsequent operational conditions. The training adopted may be based largely on grounds of expediency, to minimise the time when the system is on line for training but not providing useful evidence for evaluation purposes. Alternative training techniques are not explored routinely. It is difficult to gauge if the findings of the evaluation might have been different had the training for it been altered. Sometimes there is retrospective evidence that some participants in evaluations have never understood correctly the intended functions of some facilities or the full implications of some tasks. Better integration of evaluation and training might help to ensure that this could not happen.

It has not yet proved possible in the training for many new air traffic control tasks to take full advantage of the multiplicity of training techniques now available, nor to relate their efficacy to the known principles for the learning and retention of new information. Training should normally continue for somewhat longer that it does, especially on the final phase using the most difficult material which normally requires the greatest practice before it has been mastered. The value of demonstrations aimed at insight into the relevant variables often seems to be underestimated. In the past the main reason was often that simple dynamic demonstrations were not technically feasible, but the advent of microcomputers offers enhanced opportunities for demonstrations, and also for training for new tasks within a realistic dynamic air traffic control environment rather than in isolation. Human factors advice on training for new tasks covers the following broad topics:

(1) The specification and validation of the most appropriate training techniques.

(2) The optimum use of evaluations for deriving guidelines for training.

(3) The possible contributions of training to evaluations.

(4) The level of proficiency to be attained, and suitable tests for measuring the proficiency actually achieved.

(5) The most effective criteria for establishing that training is complete.

(6) The content, pace, and duration of training.

(7) The material appropriate for training, its order and presentation, and its range of difficulty.

(8) The sources of errors, delays, confusions and misunderstandings which will arise during training, and the success of various methods for allowing for or circumventing their consequences.

(9) The probable learning curve and the expected range of individual differences in performance.

(10) The need for, and probable effectiveness of, extra training to counter inadequacies in individuals, and the most efficacious extra training techniques.

(11) The extent to which training in a new task can be done successfully in isolation, the need for training in an air traffic control setting, and the complexity of the setting required to achieve the training objectives.

(12) The successful integration of training for new tasks with training for existing ones, and the influence of new tasks or procedures on the reliability and validity of training as a whole.

(13) The principles and practicality of automated aids to training in new tasks, and the types of aid most likely to be effective.

(14) The relevant underlying psychological abilities and attributes on which the new tasks depend, and the feasibility of using tests of those to select those suitable for training in the new tasks.

12g RE-TRAINING

Re-training can become necessary:

(1) If a major aspect of the system itself or the equipment or tasks within it is changed.

(2) If a controller moves to another air traffic control job.

(3) If the performance of an individual controller is waning or could be improved.

Many of the main guiding principles for re-training have been discussed in relation to the content of training courses, assessments of training, and training for new tasks. Obviously the controller who is already experienced uses his experience as the basis for new learning during re-training. The extent of re-training required therefore depends on how closely the tasks resemble those he has done before, on how long it is since he has done them, on the extent to which they have changed in the meantime, and on the extent to which he himself has changed. However, re-training poses one class of problem not encountered in initial training, namely the need to forget or not follow certain familiar functions, as well as the need to learn new ones. This is the source of some of the difficulties which older, more experienced controllers may encounter during re-training, if many of their overlearned and very familiar actions and skills have to be discarded because they are no longer appropriate. This is one context where practical knowledge about the most effective means for training to forget would be a real help if it existed.

As far as possible, re-training should seek to develop skills which are either essentially the same as previous ones or are quite new. Tasks that are a complex amalgam of familiar and novel activities may encourage the extension of existing practices beyond the point where they are still apposite, because the transition between old and new is too smooth and unobtrusive and too easily made out of habit. This transition may lead to a reversion to familiar but inappropriate actions, especially under high workload or stress when their immediate consequences may be most dire. There is much to be said for the perpetuation of existing skills whenever possible in revised systems, because re-training problems are minimised and the acceptability of the revisions is enhanced. Where this perpetuation of skills is not possible, the occasions when new actions could gradually or imperceptibly revert to old habits should be clearly defined and severely discouraged, preferably by altering the system design to make the reversion impossible or highly obtrusive. It is vital that the controller cannot do anything dangerous out of sheer absentmindedness, forgetting for the moment that he is in the new system and not in the old one. Re-training must address this problem.

A return to the fundamentals of task analyses can facilitate re-training, especially if a controller is changing his job. Differences and similarities between jobs, or between the same jobs in different places, can be revealed by task analyses, and used to specify where existing skills and knowledge will remain relevant and where new learning must take place. The degree and locus of similarity between the old and the new become apparent when the respective task analyses are compared. Sources of potential confusion between them can be identified where the similarities are partial but incomplete. Re-training can then be directed to achieve the correct balance between the entrenchment of existing skills and knowledge which remain relevant, the acquisition of new skills and knowledge where needed, the extinction of old ways and habits which no longer have any place in the revised system, and the clear separation of new and old where the interactions between them are confused or vague.

Re-training occurs extensively wherever the controller's new job is very different from his old one, especially if he no longer is an active controller but occupies a managerial position or is concerned with hardware or software. Here the approach to re-training may be exactly the same but should not be. Granted that it is essential for the man to learn during re-training the skills and knowledge that his new position requires, it is not desirable that he should forget his former skills, since it is partly on the basis of them that he has been appointed to his new role. They remain relevant there, and complement rather than clash with his new responsibilities. Therefore some re-training of managers and others to keep their skills as controllers alive should be seriously considered at intervals. Reminders of their attitudes when they were controllers would not be untoward and would help to reassure controllers that their needs were understood.

12h AUTOMATION IN TRAINING

The impact of automation on air traffic control training has increased for two distinct reasons. Training techniques rely more on various forms of automation as aids to learning. Many of the functions for which the man is trained are themselves substantially automated.

Some automation, albeit primitive, is an essential ingredient of much air traffic control training, once it has progressed beyond strictly procedural control methods based on flight strips. The needs to generate radar displays, tabular information displays, traffic samples, communications, and representations of pilots, and the requirement to provide knowledge of results, all lead towards automated assistance. Efforts to standardise training and to assess training progress objectively likewise point towards the automatic generation, presentation, and scoring of standardised air traffic control tasks and problems.

The advent of the microcomputer, with its associated displays and facilities to generate tasks and to relate adaptively to the man while he is learning, has opened new vistas of air traffic control training where the man sits at a terminal, interacts with a computer, and gains in knowledge and experience using programmes of air traffic control instruction which adapt to suit his individual needs as he goes along. Large computer systems, with remote terminals, may fulfil a similar purpose. Students do not always use automated aids in the ways intended. A potential advantage of the individual instruction offered to a student at a terminal is that weaker students can supplement the standard classroom laboratory simulation and group tuition with extra individual study and practice at the terminal, directed specifically towards the tasks, procedures and instructions which present them with difficulties and employing computer dialogues matched flexibly to their knowledge and needs. Unfortunately it can be difficult to prevail on the weaker students who need this experience most to use the terminals in their own time independently in this way. In practice it is often the most able students who need extra training least who make most use of such individual training aids. To some, even friendly computers seem daunting.

When automated aids are used in this way, the air traffic control problems presented are usually variants on a theme, progressing in complexity in stages subject to the successful solution of the problems at each stage. The problems are already flexible in response to the man's requirements. A further feasible stage using microcomputers is to allow the man to formulate his own problems as well as work out solutions to problems presented to him. It can be a salutary experience, and a well-remembered lesson, to formulate a problem and then be unable to solve it. An advantage of tuition at individual terminals is that immediate knowledge of the consequences of each decision can be provided to the controller as the outcome of his actions unfolds before him.

Automated aids to training can extend the ways in which learning is reinforced by insight into the effects of actions. It is possible for an instructor to demonstrate the solution to an air traffic control problem and then for the student to demonstrate that he too can solve the same problem. A problem can be developed dynamically and then stopped by freezing it on the display while discussions are held on how it has arisen, how it could have been prevented, and how it must now be solved. Various solutions may be advanced, and each tried in turn to show its effectiveness and to demonstrate the further problems that it may lead to. The student's own performance can be recorded and replayed to him, and stopped while the instructor points out his successes and failures. The reason for the latter can also be clarified. The instructor's solution to a problem at which the pupil has failed can then be given and also replayed with explanations. To make different points, a problem can be replayed as often as necessary. Such automated aids offer great flexibility, build on each individual's strengths while revealing his weaknesses, give insight into the implications of decisions, and bolster the individual's confidence by adapting the pace of progress to his abilities.

It is also possible to look at the same problem from different points of view. A conflict resolution, for example, may be treated from the different points of view of the various aircraft in potential conflict. The crucial importance of quite minor aspects of a problem to the correct solution to it can be demonstrated by taking similar problems which differ only in that minor aspect, and showing that the correct solutions differ. For example, in conflict resolution a point may be reached where an aircraft can no longer be turned safely behind another to resolve a potential conflict. The small difference between the circumstances when a turn is or is not a practical solution can be perceived, and training in the necessary judgments can be achieved, by the use of automated training aids which permit problems to be generated and presented to order, and small variants in them to be specified.

In training, and in man-computer dialogues, the computer is generally friendly. This means that it does not stop for no apparent reason, and does not give a peremptory indication that its operator has made an error, without also providing some help by describing the nature of the error in some detail and preferably by suggesting a remedy. It is also kindly, courteous and infinitely patient in its dealings. If sorely tried it does not become upset, and at the very worst merely becomes sharply humorous. While this commendable idealised computer personality may be helpful to facilitate training and to encourage the operator's ability and confidence to embark on constructive man-computer dialogues, it means that some aspects of training must remain incomplete, and others may not transfer well to real life. Perhaps this principle can be carried too far. In the later stages of training there may be a place for the cantakerous computer, which has only a limited tolerance of errors and naive mistakes, which complains about complex solutions to problems when simpler ones are available, which questions manoeuvres that are apparently unnecessary, and which sometimes takes much longer than usual to respond to instructions. Such a device in the later stages of training might inject a note of realism, and help to prepare the budding controller for real-life problems that lie ahead.

Some controllers have to be trained to work in highly automated air traffic control environments, where the man-machine interface used for training is similar in complexity and equipment to its real-life counterpart. These controllers may also have to be trained to cope with very high traffic demands, since some of the difficulties they will encounter only occur under such conditions. Factors such as team structure, co-ordination and liaison may change when everyone becomes very busy. Each controller may become much more autonomous, with little time to keep himself informed about his colleagues' activities. The content and format of air traffic control messages may also be different under pressure. The controller must become familiar with such effects so that he does not meet them for the first time under real-life severe pressure and under operational circumstances. Team training should be able to help to prepare the controller for these changes as demands increase. The more automated real-life air traffic control systems become, the more air traffic control training must employ simulated systems capable of an equivalent degree of automation.

A further impact of automation on training is in the recording and scoring of each controller's progress throughout training. In the future much of this could become automated. Automation offers more impartial means of assessment, but it also permits much more frequent assessments, and more detailed records of progress. It may also be used to record the incidence and correction of specific faults during training. In most training contexts, there is still heavy reliance on subjective assessments by instructors, and these may never be replaced entirely because certain attributes of the controller would be very difficult to assess in any other way, but automated training techniques do offer far more objective evidence of progress as well as ready comparisons between individuals, between facilities, between courses, and between training years. They may also offer anonymity of assessments which may prove to be a boon, both to render any legalistic accusations of bias demonstrably false, and to ensure that assessments cannot be influenced excessively by early impressions which lead to favourable or unfavourable attitudes by instructors towards individuals, with self-fulfilling prophecies of success or failure. Suspicions of bias may be unfounded, but it would still be advantageous to have a sure way of demonstrating that they are. Greater automation of assessments may well offer this advantage.

# CHAPTER 13

## HUMAN FACTORS IMPLICATIONS OF CONDITIONS OF EMPLOYMENT

### 13a THE MANAGEMENT OF CONTROLLERS

Air traffic controllers have acquired a reputation for being difficult to manage. Whether this reputation can be substantiated depends largely on the point of view adopted. If controllers are employed by national governments, then they may be less amenable to active managerial direction than many of their fellow government employees, especially if such direction can be construed as interference. If controllers are viewed as part of the aviation community and related to other groups within that community such as pilots, then their reputation for being difficult to manage may appear much less deserved.

Styles of management vary, according to national air traffic control policies, norms for acceptable management practices in different countries, conditions of air traffic control (especially military or civil), and local and individual interpretations of managerial functions. The quality of management of air traffic control appears no more uniform throughout the world than the quality of management of most other international professions, and there is little reason to expect it to be. However, two additional factors can be identified in relation to air traffic control and its management, which, if not unique to air traffic control (they may well apply also to pilots for example), may nevertheless help to explain some of the problems that seem to occur: one concerns the selection and training of controllers; the other stems from air traffic control as a profession.

In so far as the selection and training of controllers have validity, they encourage the formation and development of certain attributes in controllers. These include the ability to act decisively, to be self-reliant, persistent, and self-confident, and to be firm rather than vascillating. They also include the abilities to seek the justification of actions in terms of reasons rather than to take things for granted, to require confirmation and verification and not to act on assumptions, to sift essentials from inessentials, and to evolve tactics and strategies independently. Further characteristics include the ability to solve problems oneself rather than to accept imposed solutions, to value most the aspects of work that use professional knowledge and give opportunities to exercise skills, and to believe in the vital importance of the work and in the uniqueness of the skills that it requires. Controllers may also learn to value most highly the professional opinions of their immediate colleagues whom they see as best placed to make informed judgments about the competence of air traffic control provided, and they may learn to identify most closely with those who belong to the same team, by being at the same suite, on the same watch, or in the same air traffic control facility. It should come as no surprise that people selected and trained to possess such attributes might not be the most amenable to managerial directives. They can be expected to question decisions that mystify them and demand to know the reasons for them. They may also tend to discount as frivolous reasons which seem to them to be only obliquely relevant to their functions as controllers, but which may nevertheless be central to management who must take account of other things. Controllers may be reluctant to concede that those who, in their eyes, lack up-to-date practical experience of air traffic control or practical skill in it, could possibly be knowledgeable enough to take managerial decisions about it, particularly those which have a direct bearing on the controller's work. They may lament managerial failure to understand their needs, to accede to their requests, or to keep them as fully informed of future developments as they would like to be. They may feel that the equipment with which they must work, and their conditions of employment, fall far short of what they need and deserve, because of the importance of their work and the skills needed for it. In short, the kind of attributes sought and developed in the successful controller seem to be those characteristic of people who would be difficult to manage.

One method for examining the relative status of air traffic control as a job in each nation is to note the minimum entry qualifications for a controller there, the typical pay of a controller in mid career, and a few further conditions of employment, and then compile a list of other jobs which in these chosen respects are roughly equivalent to air traffic control. When this is done, it is striking how much the lists for different countries disagree. The status of air traffic control as a job is far from uniform throughout the world. On the whole, the higher the status of controllers in a nation, the more air traffic control in that nation assumes the hallmarks of a profession, as distinct from a trade or job, although there are inevitably some exceptions to such a glib generalisation.

In a profession, the norms and standards of acceptable performance, and a professional ethic, tend to arise from within the profession itself and be maintained by it. They are resistant to change by exhortation or direction from outside the profession, which is interpreted as interference and often resented or dismissed as a sign of ignorance. Members of a profession close ranks when challenged, to defend the integrity of professional standards and practices and their professional pride wherever these appear to be questioned or slighted. The attitudes of each individual to his conditions of employment are strongly influenced by his professional colleagues, but he gains satisfaction from the work itself, to the extent that many members of the profession would be unwilling to do any other job. In the case of air traffic control, all members of the profession are expected by their colleagues to subscribe to the need to maintain a good air traffic control service wherever possible and to be competent to do so, even when they consider that their conditions of employment and air traffic control equipment are disgraceful.

The level of performance actually achieved is therefore dependent to a considerable extent on professional norms rather than on the equipment or on management decisions. This can be both a strength and a weakness. With a strong sense of responsibility to, and identification with, the profession and the job, a controller may make a very great effort to provide a safe, efficient and satisfactory air traffic control service, even when the equipment is inadequate and the conditions of employment are poor. But if for any reason controllers no longer identify closely with air traffic control as their profession, no longer care about air traffic control and take pride in it, and no longer feel that they owe any allegiance to it, then their achieved performance may deteriorate without any change in the air traffic control system itself, if that performance has been propped up by adherence to professional norms and standards that have gone. Everyone would be the loser if such a situation were allowed to develop.

These attributes of air traffic control, which are not peculiar to it but can be found in other professions, are the source of some management problems. Because management and controllers look at air traffic control somewhat differently, differences and misunderstandings are almost bound to arise between them from time to time concerning what should be achieved and what is of fundamental importance. When such disputes arise, it does not follow that one side or another must be wrong. Usually both sides are right, given their different perspectives, interests, and terms of reference. The differences between them must therefore be reconciled by full knowledge on the part of both sides about all the interests that have to be considered by building on common interests, and by agreeing on the long-term objectives of the furtherance of air traffic control which all share.

An important aspect of professional norms and standards is that their origins may be apparent only to those within the profession, and sometimes not clear even to them. Consequently a well-meant management proposal can inadvertently touch on sensitive issues for the controller, and receive an unexpectedly sharp rebuff. The motives for such a proposal can all too readily be misconstrued by controllers in their turn, as a failure to understand their needs and give them the equipment they should have, or as an attempt to curtail their responsibilities. In such circumstances where misunderstandings can arise, relations between controllers and management can become prickly, controllers can acquire the reputation of being difficult to manage and unresponsive to management suggestions, and management can be seen by controllers as out-of-touch with real air traffic control. When in the face of increasing demands, air traffic control must evolve to maintain a satisfactory air traffic control service using various kinds of new aids, many occasions for argument at cross-purposes are potentially present.

Goodwill on both sides, and a better insight into the origins of misunderstandings, may offer prospects for progress. Management-controller relations are good in some countries. The collaborative techniques which have been successfully developed to achieve this could be examined to see if they would be applicable where relations are poor.

13b CONSULTATION WITH CONTROLLERS

The extent to which controllers should participate, and are able to participate, in management decisions, and particularly in the specification of future systems and tasks, is a contentious subject. National policies differ. It is clear from these policy differences, which have led to many kinds of controller participation being tried on an experimental basis, that there is no simple solution to this issue, or at least none that has yet been found. To suggest that managers, programmers, and the technical staff in air traffic control should be drawn, partly or exclusively, from the ranks of controllers, seems to have some logic, although it has been noted in relation to selection that these different jobs may call for different skills and attributes. The contention that managers, programmers and technical staff must be former controllers cannot be supported by existing evidence; nor can it be refuted. The limited relevant evidence can be interpreted in more than one way: if there is a conclusion, it is that the issue is not in fact as important as it is often claimed to be.

In some countries procedures for consultation between management and controllers have been formalised. This is in general successful, but there are two main kinds of difficulty. One is that the terms of reference may seem unduly constrained, particularly from the point of view of the controllers' representatives. The other, a difficulty mainly for management, is that many issues that controllers wish to discuss may not in fact lie within the powers or jurisdiction of management, although it may seem to controllers that they do.

The type of consultation most likely to be productive concerns factual and readily quantified questions, such as conditions of service, remuneration, aspects of the physical working environment, and the implementation of national regulations about workplaces. Another productive form of consultation can be the formation of a team or working party with management and controller representatives, and with other representation such as technical staffs also where they are relevant, tasked with a specific function for a known timescale. This approach can work well as one stage in the conversion of a broad plan for a new air traffic control facility into a detailed specification. Everyone who participates can learn a great deal from such an experience, including increased tolerance. However, it involves much painstaking effort, a willingness to compromise, and the ability to put before any sectional interest the common objective of a good and efficient air traffic control system as a whole. The members of such a collaborative team have to be chosen with care and may need some special training since not everyone is able to understand and follow the processes by which a system is specified. This kind of function has the advantage of a clear end product which must be agreed and understood by all team members who may be asked to justify and defend it to others. The team is strengthened by this collective responsibility and by evidence of tangible progress in the form of partial or tentative draft specifications.

Effective consultation between management and controllers seems most difficult to achieve when the end product is more vague, and recourse has to be made to opinion rather than fact. In topics such as morale, job satisfaction and attitudes to computer assistance, it is difficult to recognise when all that can be achieved by consultation has in fact been achieved, often because it seems so little. Hopes of major benefits can be raised, only to be dashed. Tangible findings and actions as a result of consultation may be elusive. Lack of progress can be attributed over-readily to wilfulness. Consultation on such topics, which should in theory be highly productive, runs the risk of entrenching misunderstandings, and the participants should be forewarned not to expect too much. Most attempts to employ consultation to examine attitudes, job satisfaction and allied notions in air traffic control have not been as successful as expected; although it is probably worth persisting with them, consultation may not be the most fruitful approach. It may be better to tackle such problems on a research or a consultancy basis using specialists who can be seen by both sides to be independent.

In principle, the more consultation the better between management and controllers. It is however, essential that such consultation is based on a realistic appraisal of what is both possible and practical, and does not presume that anything and everything is negotiable and can be changed. Factors such as cost, equipment reliability and availability, and timescales mean that the ideal, even it can be specified and agreed, is often unattainable, and consultation should not be used by either side as a delaying tactic. Where regular consultation does not already exist, it is advisable to start with quantifiable straightforward issues where useful unambiguous agreements can be reached and implemented. The basis of goodwill and trust established in this way can be a real asset when consultation is extended to more difficult issues. The extent of this basis of mutual regard should guide the pace at which the process of consultation is expanded.

## 13c THE NEEDS OF MAN AT WORK

The cornucopian studies, theories and prognostications about the needs of man at work have produced abundant blossoms, all shallow rooted and apt to spread uncontrollably until hedged about. The very concept of "needs" has acquired diverse connotations because it features prominently in some theories and not at all in others. Many a notion has been propounded in such detail that a whole textbook has been devoted to its ramifications. Every theory has been based on selected evidence, and none has yet gained universal acceptance or seems about to do so. Each theory has some supporting evidence and also some refuting evidence which even its most ardent advocates find difficult to reconcile with it if they make the attempt. Findings about the needs of man at work have been generalised too often and too far. The underlying assumption, that all those at work share common needs which the work must fulfil, looks facile. Some needs appear to depend more on characteristics of the individual person or group, or on the nature and conditions of the work itself, than on any universal want, and others could be satisfied outside the work environment as well as within it. Unfortunately, many postulated needs, taught as dogma, have led to practical attempts to satisfy them in contexts where they do not apply. The results have therefore been disappointing.

Studies of human needs at work have seldom addressed air traffic control specifically. This conveys an advantage because their findings can be looked at afresh from the point of view of the characteristics of controllers, of their tasks, of their work environment, and of their conditions of employment. When these needs are examined from the point of view of air traffic control, a list can be compiled of the identifiable human needs at work that seem most relevant to air traffic control and most probably applicable to it. This list is given below, untrammelled by theoretical constraints:

(1) There should be work to do, preferably in a maintained flow and especially without long periods of enforced idleness.

(2) The work should require some skills, particularly higher order skills which can continue to develop and be refined and improved for a very long time.

(3) The work may involve considerable routine, but should not be exclusively routine, and at least a substantial minority of the work should require skills, some of which should be cognitive skills.

(4) The work should be designed so that it is possible to learn it, to recognise when it has been learned successfully, and to have some insight into the learning process while it is taking place.

(5) The work must offer opportunities to exercise the skills that have been learned, and occasions when those skills can be rehearsed to demonstrate that they have been maintained.

(6) The exercise of skills should not merely be to confirm to the individual that he still possesses them, but the work should be organised so that there are opportunities for the individual during the natural course of his work to make his skills apparent to others, and especially to his immediate colleagues.

(7) Skills should be quite complex, and improve task performance discernably whenever they are exercised, to the extent that the general proficiency of an individual at his job can be gauged from his skilled performance.

(8) Some aspects of the job, or some tasks, not necessarily those which occur very frequently, should represent a challenge to the individual, even when he is fully skilled, but this should be a challenge which he can meet successfully by the application of his specialised skills and knowledge in extended and non-routine ways.

(9) To respond to challenges and to perform tasks efficiently at all times, it should be necessary for the individual, even when employing skills, to have to make a considerable effort from time to time and to give his whole attention to the work, so that he cannot learn to do every facet of his work satisfactorily without trying hard.

(10) The work should be of intrinsic interest to the individual doing it, so that to some extent he is an enthusiast for it and takes pride in it.

(11) As far as possible, the work should be designed so that the man is highly motivated to do it, looks forward to work rather than dreads it, and is willing to try to do it well at all times.

(12) Although some tasks may inevitably become repetitive, routine and tedious, their level of difficulty, the challenge they present, the effort they require, and the consequent typical levels of activity of the individual while performing them should be sufficient to ensure that boredom, if it occurs, is transient and never a permanent feature of the work.

(13) The task demands should ideally keep the man busy but not over stretched, with some control over his own workload, and without exceeding his capabilities when he is working as hard as he can and using his skills to the full, and the peak use of his capabilities, though it should occur occasionally, should not become a regular, unavoidable, and sustained feature of his work.

(14) Task demands should never be so excessive as to make the man desperate or panicky, and should not induce any prolonged or semi-permanent anxiety, though some transient and mild anxiety may not be harmful or unsafe as long as its cause can be overcome by the exercise of appropriate skills.

(15) Sources of undue stress should be avoided wherever possible, especially ambiguous situations in which it is not clear what the correct action is or what options are available, and observed symptoms of stress should occur only rarely under exceptional circumstances where they are a normal rather than an abnormal reaction to the task.

(16) The man needs to know from the work itself that he is doing it well, and therefore it should be designed to show the implementation of his instructions, the effects of his actions, and his positive achievements.

(17) The man needs to believe that his job has value and is worth doing, and he therefore should have some indication of the place of his job within the whole system, the ways in which his roles and actions interact with those of others, and the circumstances where his own successful contribution had a crucial significance.

(18) The man's knowledge of the outcome of his actions, whether it comes from the system, from his own task performance and its own effects, or from other people, should be clear and unambiguous, either in the form of praise or blame, and should refer specifically to events and actions and not take the form of any general or apparently arbitrary praise or condemnation.

(19) Some work, or its products, should be sufficiently public to afford the man an incidental opportunity to assess the competence of his colleagues and to allow them to assess his competence.

(20) There should be sufficient direct evidence to the man about his level of achievement during and after the performance of his tasks for him to develop self-esteem in the knowledge that the job is within his capabilities and is important.

(21) When the man works not in isolation but as a member of a team, the tasks should be designed so that each team member has a distinct and worthwhile contribution, though not necessarily an independent contribution, to make; each individual assigned to the team should be capable of functioning effectively as a team member, and the criteria that must be met in order to be accepted as a full member of the team should be clear.

(22) A functioning team develops its own norms and standards of performance, expectations, group attitudes, and group solidarity, and team tasks should encourage, by their allocation of roles and responsibilities, the full participation of every team member in these group activities which consolidate his acceptance and acceptability as a member of the team and help him to identify with it.

(23) If possible there should be some flexibility in the amount of social contact which the work entails, so that individuals with strong needs for independence or with strong needs for group membership and conformity can still be accommodated successfully within a functioning team.

(24) Jobs should not be designed so that any individual can become wholly isolated.

(25) It should be easy for supervisors and management to notice and praise individuals or teams, and to point out clearly why they have been singled out for favourable comment: it should be equally easy, if the need for unfavourable comment arises, to make it clear whom such comment is directed at, so that it is not inadvertently extended to those to whom it does not apply.

(26) Tasks should be sufficiently open to others and particularly to colleagues who are knowledgeable about them, to facilitate rather than impede the development of professional norms and standards, to allow everyone to form a view of the standards of performance that are a tolerable minimum, those that represent the normal, and those to which they should aspire as being high but attainable: the individual needs to be able to place his own performance in this context from time to time.

(27) The man needs to believe that he can have some influence over decisions which affect his work directly, particularly those concerned with new aids, new roles, new tasks, and changes in status and responsibilities: he therefore tends to resent any changes made without consulting him, no matter what their other merits, and to welcome any opportunities to put forward his own point of view, on the understanding that it will be taken seriously and if practicable have some influence.

(28) The man needs to have some evidence from his job, its performance, his working conditions and his management about his prospects and career, particularly to help him to form realistic aspirations.

(29) The man needs reassurance, and if possible evidence, that no aspect of his work environment, the equipment in it, his activities, or his tasks can be harmful to him or impair his health or well-being in any way.

The above identifiable needs are not of equal importance. From the point of view of most controllers, none is trivial. From the point of view of the safety and efficiency of the air traffic control system, none is of over-riding significance. These needs are intended to indicate desirable attributes of the tasks and working conditions of controllers which can be influenced directly or indirectly by decisions on the planning, design and implementation of systems, tasks or conditions of employment. The list of needs may also help to furnish explanations of puzzling difficulties, and may point to possible ways of resolving them. The importance accorded to the needs of man at work is partly a matter of policy and judgment, partly an outcome of the style of management and the extent to which needs have already been recognised and allowed for, and partly the result of factors outside air traffic control such as the effects of levels of unemployment on the propensity of controllers to resign. Perhaps in air traffic control as a whole, the importance of trying to satisfy human needs in the work environment has been underestimated, but this does not mean that air traffic control should emulate other contexts where the importance of satisfying human needs and aspirations has been overstated.

## 13d CAREER STRUCTURE

If there is a policy to fill management posts from the ranks of controllers or to retrain controllers for technical jobs or as computer programmers, then the controller may have more than one career outlet and his career structure may depend partly on special skills and abilities. Otherwise the career of the air traffic controller is characterised by quite rapid progress, by training, experience and courses, to a career grade, beyond which relatively few controllers can expect to progress because higher posts are so few that opportunities for promotion are rare. Even if controllers can fill managerial, technical or programming jobs, their career prospects may still be restricted because these posts are not numerous compared with the number of controllers eligible for them. Progress in the form of higher seniority on moving to a larger air traffic control unit may be an integral part of the controllers' career structure which is unattractive to them if they believe that the rewards are not commensurate with the upheaval.

A problem can arise if the predictive value of selection and training assessments for subsequent career advancement is low. Although this lack of predictive value may be well known to management, it may not be to individual controllers. Those placed near the top of their course on completion of training may therefore form career aspirations then that are unrealistic. Eventually the mismatch between these aspirations and subsequent achievements may lead to disillusionment and bitterness. It is important for controllers to be reconciled to their actual career opportunities, in much the same way as they must accept shift work and, in some countries, regular movements to different air traffic control facilities, as aspects of their job. This is a more productive attitude than constant battling against conditions that cannot be changed much. It is not quite true that the ambitious man should not become an air traffic controller, but it is not advisable to become an air traffic controller in order to realise ambitions for career advancement. The limited opportunities for career advancement make it all the more important to try and satisfy the needs of man, particularly for self-esteem, motivation and aspirations, by the air traffic control job itself and the conditions under which it is done, since these needs are unlikely to be satisfied by the career structure. This limited career structure is very common in air traffic control throughout the world, and the prospects for offering enhanced promotion prospects or career development are not encouraging. The situation may however be markedly different in military air traffic control, where career prospects are better, and the career structure is more apparent. Advancement there however may depend primarily on individual attributes, "officer qualities", and be little related to ability as an air traffic controller.

If most controllers find air traffic control itself so satisfying that they do not wish to leave it, even for an administrative job within air traffic control, this can simplify the problems of building a realistic career structure for the remainder whose ambitions lie elsewhere. Perhaps better guidance could be given on the attributes sought in career advancement, other than experience and seniority. The predictive value of success as a controller for subsequent success as an administrator should be established, as it could be helpful as a guide to suggest how closely careers in air traffic control or in its administration and management should be integrated.

## 13e WORK-REST CYCLES

Working hours are studied in air traffic control because of their actual or potential effects on safety or efficiency or on the well-being of controllers. Many studies, originally conducted in an impartial spirit of scientific enquiry, have been re-interpreted to bolster arguments for or against existing or proposed rosters, watches, duty hours, rest intervals, sleep patterns, or payments for overtime or work at unsocial hours. Evidence about working hours can readily be distorted if it is not considered as a whole but the convenient bits of it are singled out while the inconvenient remainder is ignored.

Work-rest cycles and rosters are an emotive topic in air traffic control. The human factors specialist is not often asked for an impartial assessment of all the relevant evidence, but for any available carefully selected findings that could possibly support a stance that is proving difficult to defend. Although he may look askance at such requests from any source, since they are difficult to reconcile with his impartiality, even-handedness, and scientific integrity that must be preserved at all costs if his own role is not to be jeopardised, nevertheless in practice such requests are not as embarrassing as they could be. The reason is simple. Despite many laboratory findings on the potentially adverse effects of major disruptions of circadian rhythms, of long hours of continuous work, or of inadequate sleep, in real life tasks these effects are generally noticeable by their absence. The evidence is overwhelming that working hours, unless they are in some respects extreme, do not have major effects on air traffic control or on controllers.

Many factors may be highly relevant in determining what the working hours ought to be, but efficiency, safety, and well-being are not among the most important. At first sight this seems odd, even perverse. There are three fundamental straightforward reasons to explain it. One is human adaptability, impressive in many circumstances but especially so in relation to work-rest cycles where they are a normal and familiar aspect of a demanding job that is liked. A second reason is that air traffic control, consisting mainly of cognitive tasks with a high storage load, epitomises the type of job most resistant to disturbance by erratic work-rest cycles. The third reason is that if work-rest cycles do become so extreme as to begin to affect performance it is peripheral and incidental unmeasured aspects of it that are most likely to be influenced, rather than the more readily measurable essential core of the work. A further explanation, a matter of expediency rather than principle, is that the longest periods of continuous work in air traffic control are generally associated with the times of lightest traffic demand.

When proposals to alter working hours, shifts or rosters are discussed, human factors evidence cannot normally be used conclusively, either to support the proposals, or to defend existing arrangements. It is usually neutral. Unless a very major change is contemplated, controllers will almost certainly be able to adapt to the new hours and rosters as well as they did to the old. Consequently, changes in efficiency, safety or well-being, either for good or ill, are equally improbable as a result of changes in work-rest cycles unless these become extreme. Of course, acceptability is another matter. Salient considerations in determining acceptability are the number of whole days off work that a revised rostering would provide as compared with the existing number, the extent to which controllers can plan ahead knowing when they will or will not be at work, and changed differentials between the hours of work or work-rest cycles of controllers and those of other groups with whom controllers have traditionally enjoyed parity or a clearly defined fixed comparative relationship. Changes in rostering which convey advantages in any of these terms may be favoured as strongly as other changes which convey disadvantages in these terms would be resisted.

Reviews of air traffic control practices in regard to working hours and work-rest cycles[27] describe conditions in various countries, and usually claim that total hours or maximum periods of continuous work should both be reduced. They generally fail to append data in direct support of these claims. It is not usually possible to separate work-rest cycles from other variables such as traffic demands, in order to assess their respective effects on the controller and on his proficiency. In some countries, not within NATO, controllers can be required to work for very long hours without a break in conditions that seem harsh. Very diverse air traffic control working hours and work-rest cycles prevail in different parts of the world, ostensibly without serious consequences for the controllers themselves or for the efficiency and safety of air traffic control. In general, scientific evidence on this point is not strong enough to draw sound conclusions.

Within the NATO countries, the typical working week for controllers is about 40 hours or less and the maximum shift length, which usually falls during the night, is typically of the order of 10 h[illegible], a figure to be interpreted with caution since it may refer to time at the workplace and resting b[illegible] available for duty, rather than time actually on duty. Also within these countries, the maximum time on duty controlling heavy traffic without any short rest break is often about two hours, although this time may be extended when traffic is light. Considerable departures from these typical figures of 40 hours, 10 hours and 2 hours, can and do take place without incurring measurable effects on performance, safety or well-being, either in the form of improvements or decrements. The duration of a short rest break is often a statutory matter, although in human factors terms it would be better to settle it empirically. It should allow adequate time to visit a toilet, obtain a hot drink and spend a few minutes in relaxed surroundings other than the workspace. The time allowed should logically depend partly therefore, on how long it takes to walk from the workspace to the rest facilities and back.

National practices vary in regard to the maximum duration of continuous shifts. Evidence of performance decrements associated with longer continuous shifts does not exist in a form which could give useful, general, practical guidelines on the optimum timing of rest intervals. Perhaps there are no performance decrements to be discovered; perhaps no existing measures are sensitive enough to show those present; perhaps potential decrements are counteracted by other factors such as light traffic. Some findings, which purported to show decrements after shifts of about seven hours or more, have not been consistently supported. Any decrements must be subtle, and relatively unimportant or localised, or they would have become apparent by now by appearing consistently. This conclusion is supported by other evidence, for example on safety. Reports of incidents and accidents are not closely related to work-rest cycles, duration of watches, rostering or total hours worked. Obviously the mathematical probability of an incident or accident rises with the number of airborne aircraft and with the density of the aircraft traffic, but light traffic loading does not bring immunity from air traffic control safety hazards. The only slight relevant tendency which may be discerned in this context – and it is slight – is that rather more incidents may occur soon after a watch change, but the remedy for this, if there is one, does not lie in tinkering with shifts and work-rest cycles but with methods and timing of the handover of air traffic control responsibilities, with full briefing of incoming controllers and with the use by the incoming controller of the most efficient means for building his picture of the traffic as quickly as possible.

For a long time, the emphasis on circadian rhythms, and the laboratory experiments on the effects of disrupting them, suggested that the most important consequences of this disruption were on sleep. This finding was verified in industry where it was established that for simple routine repetitive tasks the kind of work-rest cycles typified by air traffic control were indeed more disruptive than a regular daily pattern, and the typical recommendation for industry was therefore to work several nights in succession. Only relatively recently have properly controlled experiments been conducted to check that this finding, on which recommendations were at one time made, was valid for cognitive higher level tasks with strong reliance on memory, the category to which air traffic control tasks belong. When tested the finding did not remain valid for these higher level tasks. Those who perform such tasks adjusted most quickly to shift changes: their performance is relatively unaffected by shift changes and by sleep patterns; and the kind of rapidly rotating shifts and associated sleep patterns typical of air traffic control is probably the most safe, the most efficient, and the most healthy[143].

Limited confirmation of these tentative findings, and of the relative unimportance for air traffic control of work-rest cycles and the resultant sleep patterns, came from the study of the effects of two shift rotation patterns on reported sleep among controllers. Although the differences between the work-rest cycles in the two patterns were gross, the effects on sleep, or on anything else, were negligible[144], even allowing for the notorious fallibility of subjective reports of amounts of sleep. A study of stress also found that work-rest cycles did not appear to have any significant effects on stress in air traffic control either[142].

A few further tentative indications seem worth mentioning. Individuals who are accustomed to shift work and to irregular work-rest cycles develop very successful long term adaptation to these conditions and seem none the worse for them, although there remain large differences between individuals in their ability to counteract drowsiness or to sleep in unusual places at unusual times. The temporary loss of sleep entailed by certain work-rest cycles does not seem to impair proficiency in the performance of tasks such as air traffic control. More likely to be affected are certain peripheral aspects of the work. The individual may tend to become more absentminded, more careless, more clumsy and more irritable after serious sleep deprivation. Whereas his ability to perform his tasks is not impaired, his motivation to do so is gradually reduced. Job rotation may help to sustain motivation in this context.

A main factor in determining work-rest cycles is their acceptability. A main determinant of acceptability is the number and grouping of complete days off work. Controllers may tolerate, and even welcome, quite arduous work-rest cycles which increase the number of whole days off. Their competence and state of alertness are influenced more by their tasks, traffic demands, the presence and proximity of colleagues, and involvement in teamwork, than by work-rest cycles.

Motivation, morale, traditional practices, professional norms and standards, agreements with colleagues, and constraints on family life, are further determinants of the acceptability of work-rest cycles. The curtailment of unsocial hours, though apparently beneficial, may be viewed ambivalently or encounter resistance if it entails financial loss, particularly if there is a substantial discrepancy between nominal and actual hours that have to be worked during the night. With regard to work-rest cycles, total hours worked, and time off, there may not only be incompatibilities between the ideal roster from the management point of view and the ideal from the point of view of the controllers' official representatives in negotiations, but also incompatibilities between the latter and the true wishes of individual controllers, who may not fully agree among themselves what the best work-rest cycles for them would be.

## 13f OCCUPATIONAL HEALTH

The individual members of any profession may be expected to incur their normal share of illnesses and ailments, unless special factors intervene. Some symptoms may be caused or aggravated by the nature of the work or the conditions under which it has to be done. Some may be rare in a particular profession where individuals have to pass a medical examination to gain entry to it, and certain medical conditions preclude acceptance. Some may be rare because an early diagnosis during annual medical examinations brings early treatment, or because some form of preventative medicine is introduced as a condition of employment.

Because some would-be controllers are rejected on medical grounds during the initial selection procedure, it might be expected that controllers as a whole would be slightly more healthy than the general population from which they are drawn. Because a few conditions, such as alcoholism and obesity, are actively discouraged in controllers, to the extent that a persistently alcoholic or obese controller may lose his licence, controllers might be expected to remain slightly ahead of the population as a whole in their average general health.

Other factors may counteract this tendency. To the extent that controllers have to work erratic hours, this might be expected to impair health slightly on average if there is any evidence that shift work does so. Controllers have a sedentary occupation, and may therefore have to be exhorted to take sufficient exercise. They may have unusual meal times, and these, coupled with sources of stress at work, may lead to stomach upsets or more permanent symptoms such as gastric ulcers. The stress may be associated with hypertension. A strong impression of air traffic control as a stressful occupation has gained ground, and been the subject of conferences and research in several countries. Controllers may feel anxious and worry about their responsibilities and the task demands: these worries may persist when they are off duty, perhaps to be alleviated by a stiff drink or a mild sedative. The controller adapts to these palliatives, and the drink has to be stiffer and the sedative less mild to maintain its apparently beneficial effects. Eventually a mild stimulant may be needed to counter the sedative before the controller goes on watch. He is then caught in a cycle that it is difficult to break out of. He is aware of this and his worries about it are added to his original anxieties and aggravate the problem. These, or the original worries, may trigger further psychiatric or psychosomatic symptoms. He may work in conditions where the physical environment - especially temperature, humidity, and air flow - is designed to suit equipment as well as be tolerable to him. He may find that he has a dry sore throat, headaches, aching eyes, and general malaise. Some of the information on his displays may seem difficult to see. He may need a specially prescribed visual correction tailored to his workspace. He may attribute the need for spectacles or lenses to deficiencies in the design of his displays or workspace, to excessive demands that his tasks make on him, or to unfavourable physical environmental characteristics, rather than to other more probable causes such as his age.

There are therefore many factors related to the controller's work and working conditions which could influence his health: a few of them are apparently in his favour but most of them seem not to be. Many of these factors are associated with modern ways of life rather than specifically with air traffic control. If they present problems, the solutions may not therefore be within the province of air traffic control. Some problems may resolve themselves. For example those who would suffer most from stress or anxiety might find the responsibilities of air traffic control intolerable as a permanent feature of their work and leave soon after completion of their training if not before.

In reality, two facts stand out regarding the health of air traffic controllers. One is that in some countries they do seem to have some particular health problems but in many countries they are about as healthy as the general population. The other is that if air traffic controllers as a group do have particular health problems these are not the same in all countries, suggesting that it may not simply be air traffic control itself which causes occupational health problems among controllers, but other factors such as the physical work conditions, selection and training methods and procedures, equipment and aids provided to controllers, or management styles.

Some incipient occupational health problems can be traced to the workspace design, and remedies for them must be sought in redesigned workspaces. These problems recede as technological advances remove some of the constraints which caused them, and allow greater flexibility in future designs. Examples of them are many postural and visual problems. The former often originated from the requirements for the controller to sit awkwardly alongside a horizontal display and to lean sideways over it or twist round it to see other displays or to annotate flight strips on a large flight strip board. The latter problems could arise from frequent cross referencing between a vertical or horizontal individual or team display and a general wall-mounted display, particularly if there were gross differences in luminous flux so that each change of view was accompanied by a different focal distance and a different pupil size.

Remedies for postural and visual problems cannot always be found in the work environment. Many postural and visual problems can be aggravated by another factor that cannot be controlled. A radar controller in particular can spend his working hours gazing at a cathode ray tube display and then go home and spend his leisure hours gazing at another cathode ray tube display. At work, an attempt, generally successful, can be made to optimise his visual and postural environment according to human factors evidence, but no such attempt can be made with his home environment. The extent to which the two can interact is not known but there must certainly be some interaction. If a controller brings into his work environment his visual and postural problems which have originated at his home, no solution to them can be obtained by changing his work environment, no matter how far it can be optimised. As long as the possible extent of such an interaction remains unknown, a great deal of effort could be expended to no purpose in trying to solve a wrongly identified problem.

A major study in the United States on health changes among controllers[137] concluded that hypertension was the commonest chronic illness among controllers, with an incidence much above that in a matched population. This finding confirmed previous United States studies, but is not typical of controllers in other countries. Nor are the other findings of a relatively high incidence of respiratory infections, viral disorders and gastrointestinal syndromes universal among controllers. Psychiatric problems, though not particularly prevalent, did tend to be associated with subsequent medical disqualification. One conclusion was that the probability of health change was influenced much more by the controller's attitudes to his work and by the context in which the work was done, than by the work itself. The development of more favourable attitudes by controllers to air traffic control as a whole and to their tasks, workspace and equipment, might lead to improved health rather than to improved performance[146].

13g RETIREMENT

There is no standard retirement age for all air traffic controllers. National policies vary. Where controllers are considered to be government employees, they normally have the same retirement age as other government employees. Some countries do not have a fixed age of retirement but it varies either according to a fixed number of years' service as a controller, or by fixing only a minimum or a maximum age for retirement and allowing some flexibility above or below this fixed age. It is essential everywhere to allow for earlier retirement of individuals on medical grounds including "burn out", which can have a relatively sudden onset, can occur considerably before normal retirement, and be difficult or impossible to predict in individuals far in advance[137].

Retirement can be a traumatic event for many people, both longed for and dreaded. Expectations about it may become unrealistic, with a sharp division between the true and expressed wishes and intentions of the individual as his retirement date looms. For controllers, two extra considerations can render it particularly traumatic. One is that if a controller has identified himself wholly and exclusively with his profession, he may find it difficult or impossible to make a clean break from it or to accept that his days as a controller have gone for ever. Members of other professions have to face this problem too, but for many of them, for example in the medical profession, there is the consolation of some possible further part-time or occasional professional work after retirement, a prospect which few controllers can realistically expect. The other additional factor which affects controllers originates partly in their shift work: controllers often base their social life as well as their working life upon their fellow controllers who are the people off duty when they are. Upon retirement, a controller may therefore lose not only his working life but much of his social life at the same time. If his social life is maintained, it may emphasis the loneliness of retirement since the conversations of his colleagues who are still active controllers dwell on current events in air traffic control of which he is no longer a part. Such circumstances prolong a difficult adjustment which must be faced eventually, and make its inevitability more painful.

Where early retirement, between the ages of between 50 and 55, has been achieved, as it has in some countries, this is not always a boon to the individual who feels far too young and fit to retire, and who cannot believe that there is no further useful work that he can do. The hard-won early retirement that his representatives have argued so hard to achieve can turn bitter when it comes, particularly if on retirement the man is determined to find another job but learns that at times of high unemployment there are no suitable jobs for a fit person who has retired in his 50s but whose skills as a controller do not transfer to or fit him for other skilled jobs. Retirement plans laid on the assumption that further work will be offered can be unrealistic now, even where they might have been much more reasonable a few years ago.

Evidence cannot be deduced from the efficiency and safety of air traffic control task performance to suggest an optimum retirement age for controllers. Such evidence would merely indicate that the retirement age should not be the same for all. The strongest arguments to support early compulsory retirement for controllers are probably those from social policies for the maintenance of high employment levels by providing jobs. The arguments that older controllers are less safe or less efficient are much weaker: in certain circumstances however, they may have some force. An older controller may find greater difficulty than a younger one in readjusting to shift work if he has been away from it for some time. The older controller may also experience greater difficulties in adapting successfully to major changes in equipment or procedures. The older controller may need a less demanding job because he lacks the stamina and ability to maintain the concentration that he once took for granted. None of these generalisations applies in every case: they are arguments, but not compelling arguments, in favour of early retirement for everyone.

It is more on humanitarian grounds than for the direct benefit of air traffic control as such that more positive steps may need to be taken to prepare controllers for their retirement. If their final posting can be to a region in which they wish to retire, this can facilitate the transition for some, but the practical opportunities for exercising this option are limited now and must remain so. If a controller's only real interest is air traffic control, he must be weaned from it before he retires and encouraged to develop other interests. If his social life is built exclusively on air traffic control, he should be encouraged to broaden that too, in the interests of his own future welfare and health. He must develop realistic expectations about the benefits and problems that retirement will bring. He must be prepared for the transition, discouraged from trying to extend it when his hopes of doing so are unlikely to be fulfilled, and deterred from making future financial commitments based on unrealistic expectations of further employment. Many former controllers now look on their retirement almost in terms of a golden age: more could do so with appropriate practical guidance.

# CHAPTER 14

## INFLUENCES ON THE INDIVIDUAL CONTROLLER

### 14a EXPERIENCE

Experience is related in two distinct ways to the performance of air traffic control tasks. One concerns selection, and has already been mentioned. Evidence has steadily accumulated, notably from a series of studies by Cobb and his colleagues summarised in a recent historical review[135], that previous aviation experience which would be expected to be advantageous for a controller in fact is not, and therefore should not be a feature of selection procedures for controllers. The single exception is direct previous practical experience as an air traffic controller. In this context, experience is inevitably confounded with age, but the irrelevance of previous aviation experience in the selection of air traffic controllers still holds true when age differences have been allowed for. Therefore, in controller selection, experience is not as important a factor as it might seem.

The other relationship of experience to air traffic control task performance concerns its effects throughout the controller's career. Once again, the factors of experience and age are closely related, and care must be exercised lest any findings caused by one are wrongly attributed to the other. Usually, performance would be expected to improve with experience and to deteriorate with age. One question concerns the extent to which these two effects cancel because one compensates for the other. The work that has addressed this issue has not really resolved it, partly because it did not include the extremes of age and experience where effects, if they occur, would be expected to be most significant. The most thorough discussion and study of the relationship between age and experience in air traffic control is still work done some years ago[134].

Differences between controllers are generally much larger than the changes within a single controller associated with his age or experience. A controller's experience has some discernible effects on his task performance, and perhaps, on average, it does not quite compensate for the effects of ageing beyond the age of about 40, but the effects of experience on competence are generally less on the average (though not necessarily in the case of every individual controller) than is often supposed. This is an issue on which many controllers hold strong beliefs. The most experienced controllers may be disparaged as "past it" or "over the hill" by the new generation of controllers. However, the differences that do occur in the performance of older controllers and that are ascribed to a reduction in their professional competence may sometimes at least be the result rather of greater caution, itself a product of their experience, as well as of gradual personality changes and changes in cognitive abilities. Most of the research on experience as a factor in air traffic control performance has been conducted in the United States. The findings obtained might not hold true elsewhere, and should not be treated as if they do unless there is some evidence of independent verification.

The experienced controller bemoans the brashness, lack of experience, and absence of insight of the less experienced controller. Those originally trained and practised in procedural control, without modern aids in the form of radar and computer assistance, were made more conscious of what they were actually doing, and have often retained an understanding of air traffic control in a frame of reference which dates from their procedural experience. Controllers who have known nothing but radar-based air traffic control systems, or even those with sophisticated automated aids, may need to know less about basic principles of air traffic control, may have poorer ability to revert to manual control in the event of system failure, but may nevertheless be better placed to accept and make use of technological advances.

The human factors specialist is familiar enough with the fallibility and selectivity of human memory to realise that the good old days of air traffic control were never quite as good as they now seem in retrospect. Camaraderie among controllers cannot be sustained in the same forms in the midst of highly sophisticated technical aids and complex man-machine relationships, but this means that it has changed rather than vanished. Inevitably the experienced man, who sees that some of his less experienced colleagues do not possess some of the skills that he has but fails to accept that they are not needed any more, can view some of these colleagues' actions with a jaundiced eye; and the converse can be true when the very experienced man clings to outmoded habits. The factor of experience can thus engender misunderstandings among controllers.

Some highly experienced controllers believe that less experienced ones are given responsibilities before they are fully fitted for them. Some controllers believe that those with most experience are nevertheless no longer fully competent for air traffic control duties and should retire. While in some individual cases there is substance in these contentions, particularly in the latter one, more detached evidence suggests that the importance of neither issue is sufficient to justify the emotions it generates, because on the whole the factor of experience in air traffic control has only minor relevance to air traffic control safety and efficiency. Where its effects are strong they are likely to be confined to relatively few people, and are therefore best resolved on an individual rather than a general basis.

Experience may be an advantage only as long as there are no major system changes. If major changes are introduced, and they are sufficient to discount experience because they render familiar tasks and procedures unnecessary, inappropriate or impossible, the experienced controller may be at a disadvantage since he must not only learn new ways, a process that itself is made more difficult when his experience runs contrary to them, but must also break familiar habits and try to forget what has become so familiar that it is liable to be done without thinking but must now not be done at all. Herein lies part of the importance, when tasks are redesigned, of making the old and new tasks as compatible as possible in terms of the skills and experience needed for them.

### 14b AGE

The findings on the relevance of age to air traffic control selection are markedly different from those on the relevance of experience. As evidence has accumulated that experience should not be an important factor in air traffic control selection, so evidence has accrued on the importance of age. The age criteria for selection have become more stringent and not less so. The older a man is when selected, the less likely he is to complete his training or to have a satisfactory subsequent career as a controller. The performance of the older man at air traffic control tasks will probably be poorer and he will be more likely to leave. In these cost conscious times, the older recruit offers poorer prospects for training than a younger man who is equal in other respects.

By contrast, the effects of age on the controller's performance throughout his career are equivalent in some respects to the effects of experience. The relationship between age and performance, like that between experience and performance, is small though not totally absent, according to a study which did not include the extremes of age or experience[134]. Some individuals could continue to perform their tasks efficiently and safely with no lapse of standards right up to their retirement age and beyond. Others evince quite marked and irreversible deterioration, either in a very gradual but progressive form over many years or in a more sudden and noticeable form over a shorter period - the phenomenon known as burnout. Most controllers are between these groups, and show a deterioration which is relatively slight with age, and can be countered by greater effort (leading to increased tiredness), by transfer to an air traffic control facility with lower traffic demands, or by restructuring of team responsibilities so that the man never has more to do than he is known to be able to cope with. A consequence of the combination of these trends, with some controllers showing no decline and others a marked decline with age, is that the spread of individual differences in proficiency among controllers is likely to increase with their age.

Burnout, a concept for which there is no accepted definition in air traffic control[135], refers to an individual who is no longer able to perform difficult air traffic control tasks that he once did with ease. It is particularly noticeable because it occurs most often in individuals who have seemed especially able, free from health problems, and marked out for promotion[135]. Individuals affected by burnout are aware of it in themselves and of their lack of resilience.

Explanations for the gradual decrement in the controller's ability to perform air traffic control tasks as he gets older can be found in the psychological literature on ageing, and particularly in the cumulative evidence on the effects of ageing on cognitive abilities. Characteristic effects of ageing include the following:

(1) Signals to denote that another event is pending tend to become distracting rather than alerting, and the ability to ignore irrelevant information deteriorates.

(2) The capacity to acquire new verbal information is not sustained.

(3) The ability to recall information immediately appears to be impaired, perhaps because of poorer storage capabilities.

(4) The rate at which information can be processed tends to decrease with advancing age.

(5) The ability to direct attention and to share time efficiently between tasks may become slightly impaired.

(6) The ability to adjust to, and compensate for, one's own limitations may be degraded.

(7) The ability to attend continuously to a complex monitoring task declines with age[147].

## 14c STRESS

Two decades of work on stress in air traffic control, and many papers about it (a recent review[50] cites 64 references), have produced remarkably little factual evidence, and in retrospect have accorded to stress an unwarranted significance in air traffic control. Many fundamental issues remain unresolved: among them are how to define stress, how to measure it, whether it is a cause or an effect, and whether it is a serious problem in air traffic control or not. With regard to this last question, the common presumption, made largely on intuitive and subjective grounds five to ten years ago, that air traffic control is manifestly a particularly stressful occupation, has gradually yielded under protest to the mounting objective more scientific evidence to the contrary[97]. The importance of stress as a problem in air traffic control has been exaggerated. If this text were to reflect faithfully the amount of work done on each topic by the space devoted to it, this section on stress would be among the longest in the whole volume. Since the intention is to make the length of coverage more commensurate with the importance of the subject matter, this section on stress should be quite short! The definition and study of stress is a live issue far beyond the bounds of air traffic control[148].

The manifestations of stress may be expressed in terms of performance or behaviour, physiological or biochemical changes, individual attributes such as personality, or subjective feelings or impressions. Stress can be affected by the nature of the tasks, their relationships to individual capabilities and limitations, conditions of employment and social climate. Stress in air traffic control may be attributed to workload, but this scarcely represents progress since there is little to choose between the concepts of stress and workload as sources of muddle and confusion. Stress may also originate outside work and interact with the job in complex ways. A controller with serious marital or financial difficulties may bring them to work where they interfere with his efficiency and thereby add the problem of poor task performance to the difficulties he already has; or he may visibly relax at work in the knowledge that he can put aside his other worries at least until the end of the shift. Stress as an external cause or origin (for example traffic demands, equipment failures, learning to use new aids, noise, ostracism, bereavement) has effects on the individual. The effects may also be described as stress, or alternatively as strain, distress, or similar concepts.

The broadness of the concept of stress in air traffic control is illustrated by Crump's[50] classification of relevant studies under the main headings of physiological and biochemical measurements, long term effects on health, task performance and subjective ratings as stress indices, and psychological measurements of stress. Findings from such a range of measures perhaps inevitably generate ambiguities and unresolved anomalies. An attempt to develop a stress index based on biochemical measures offered encouraging results in methodological terms, but discouraging results in terms of findings and interpretations. Some of the findings may not relate to stress as such but may reflect traffic demands, expressed either in terms of greater numbers of aircraft or in terms of each aircraft making more demands because of poor on-board equipment or a less experienced pilot. Many findings simply illustrate that air traffic control work is not particularly associated with symptoms of stress. Psychological studies, including self-ratings on such factors as mood and anxiety, have often shown that the findings depend considerably on the timing of the ratings in relation to the work-rest cycle - not an unusual result, but an unwanted further complication. Some personality studies of controllers in relation to stress factors have likewise produced complicated results which retard rather than advance progress: the general finding that Type A personality is more susceptible to stress than Type B personality is contradicted for controllers[137]. The notion that boredom can lead to stress cannot be sustained unless there is also a requirement to remain constantly attentive[149]: this is a useful practical finding, but scarcely conducive to the furtherance of studies on stress.

The weight of medical evidence, which is not in full agreement in all countries, is that stress-related symptoms are not among the main reasons for loss of licence among controllers, and that the profession of air traffic control is not one in which stress-related symptoms are particularly prevalent. It could well be that those most likely to develop stress-related medical conditions realise early in their careers that they could not tolerate the stress which air traffic control would engender for them, and leave. Others may find that their symptoms of stress are alleviated as they gain experience and confidence in air traffic control. It is possible that such considerations explain, in part at least, the absence of stress-related symptoms among many controllers even when task demands are heavy. Perhaps other factors such as style of management and conditions of employment are as relevant to stress as the work itself. Differences between countries are significant enough to suggest that the incidence of stress-related symptoms among air traffic controllers is not wholly a consequence of air traffic control demands. In the meantime, stress in air traffic control is not a general system problem but a problem for individuals, and it should be considered as such in terms of solutions and treatment.

## 14d BOREDOM

In comparison with stress, boredom has been neglected in psychological studies, though not to the extent that has recently been claimed[98]. There is therefore perhaps a better excuse for our lack of knowledge about it. Much of the evidence for the importance of boredom in air traffic control is not the outcome of scientific findings, but arises from controllers' complaints. Any job where there is a requirement for continuous manning throughout fluctuating task demands implies periods when the man must occupy his workspace but there may be little for him to do. Reports of boredom seem to be associated with these circumstances, and also with monitoring functions as such in which the job is to watch system functions rather than take an active part in them. A further relevant factor seems to be a change in social attitudes: human expectations that work will be interesting and rewarding have led to a reduced tolerance of jobs that are not, and there is a greater willingness to protest against dull jobs and against boredom, especially if it seems unnecessary. Some people appear to tolerate and even welcome boredom, but most try to avoid it. The problem of boredom in air traffic control is apparently becoming more severe.

The concept of boredom is a subjective one. It does not denote a physiological state, a level of performance, a type of task or a system design characteristic. Purported findings about boredom that are expressed in such terms therefore require supporting evidence of their relevance to it. Such evidence is difficult to obtain without the intrusion of plausible but unwarranted claims and assumptions. Because boredom is an individual subjective condition, a task that is boring to one man may not be to others. The interest aroused by any overt attempt to study boredom may be sufficient to relieve it. Boredom may not be amenable to valid study by experimental methods.

Although there is a marked absence of firm guidelines on the causes, consequences and cures of boredom, some of the commonest preconceptions about it appear to be wrong, or sufficiently suspect not to be suitable as an unchallenged basis for action. Boredom is certainly not associated always with poor task performance: its onset may indeed be more probable when tasks have been mastered and are consistently done well. There is no compelling evidence that boredom is related significantly to safety. Boredom is not confined to simple tasks; almost any task may ultimately become boring, but simple tasks may become more boring or become boring sooner. Boredom is not closely associated with definable physiological states or with personality attributes, although a tendency towards impulsiveness may not be wholly irrelevant to it but slightly increase its probability. Boredom is not necessarily equated with inactivity. Boredom seems less prevalent during learning. There are probably no tasks that always bore everybody, and very few that have never bored anyone. On the whole, it would seem that boredom originates in aspects of the work, but its effects are on attitudes to conditions of work more than on the work itself. It may influence attrition rates, absenteeism, recruitment, sickness rates, and industrial unrest, or aggravate complaints about quite trivial aspects of the workspace or the conditions of employment.

All these are tentative indications. Questions for research that arise are whether any action need be taken to alleviate boredom, what kinds of action might be successful, and what the reasons for reducing boredom can be if its effects on safety and efficiency are marginal. There are three kinds of reason for alleviating boredom: one is humanitarian, to treat people as well as possible; the second is cost effective, to reduce attrition, staff turnover, unrest, and allied factors if that can be done; the third is empirical, to discover if suppositions about boredom are correct or false - does "marginal" mean "negligible" in the context of the effects of boredom on safety, and are there any benefits for safety and efficiency of alleviating boredom? Perhaps there is a fourth kind of reason: to prevent the problem of boredom from becoming more severe until its consequences are better understood.

A provisional list of current trends in system design that may increase boredom would include the following:

(1) Increased passivity of human functions, with more monitoring and less direct participation.

(2) The maintenance of alertness when this generally proves in retrospect to have been unnecessary.

(3) Reduced needs for skills, reduced complexity of skills, and reduced opportunities to exercise skills.

(4) Fewer opportunities for the man to intervene and to innovate.

(5) Reduced options for the man to exercise, and reduced human flexibility.

(6) Reduced activity as an active team member, and increased autonomous functioning in isolation.

(7) The emphasis on requiring the man to adapt to meet technological requirements instead of adapting the technology to meet human needs.

(8) The substitution of routine data entry and retrieval for decision making, problem solving and prediction, and the provision of extensive computer assistance for the latter when they do remain human functions.

(9) The addition of routine human functions such as data entry which seem primarily to compensate for machine inadequacies and to be superfluous for his own tasks.

(10) Reduced challenge, effort and interest of the job.

(11) Reductions in the apparent worth of the job, pride in it, and self-esteem from it.

Evidence even to substantiate the above suppositions about boredom is very sparse. Although boredom is difficult to study, the problems it poses must eventually be tackled more thoroughly than they have been hitherto.

## 14e PERSONALITY

Personality influences the controller in two respects; one concerns his own personality, and the other the personality of others within his work environment, especially his colleagues, instructors and supervisors. In human factors terms these are two facets of the same topic, since if there are desirable personality traits in air traffic controllers they will be applicable to the individual controller and to all those he works with.

The personality of air traffic controllers has been measured extensively from time to time, usually for purposes of selection, as a possible health predictor, or in relation to task performance. Most of the work on personality in air traffic control has been done in the United States, using well known tests for which norms for American controllers have been derived and compared with those for the general American population. As a rule, the norms of a personality test are specific to each nation, being to some extent culture-dependent. Neither the scoring nor the findings of studies of controllers in the United States are likely to apply elsewhere. This may be a bigger disadvantage in other contexts than it is in air traffic control, where the findings about personality have generally been unremarkable.

There is no single personality profile known to be ideal for controllers. In selection, personality tests are used mainly to identify individuals with extreme personality characteristics, not to reject them since there is no rationale strong enough to support such an action on the evidence of personality alone, but to enquire more thoroughly about them than the standard selection procedure allows. Efforts to incorporate personality measures in air traffic control selection have not met with conspicuous success so far, although the belief persists that there should be a place for them, especially to single out individuals with high anxiety states or marked propensity to become anxious, since they might not be able to tolerate the responsibility of controlling real aircraft.

Findings on the relations between performance and personality have fluctuated, but scarcely provided sufficient encouragement to invite persistence. On quite a small sample, Buckley and his colleagues[134] reported significant relations between several 16 PF personality dimensions and air traffic control performance, but the results of most subsequent studies have not been so clear. Whereas to Buckley, controllers who perform better were not depressed, not timid, not naive, not conformist, and not tense, another study using the same personality test characterised controllers as hard headed and practical but lacking in creativity and imagination[150]. The findings relating to Type A and Type B personalities among controllers are puzzling because the more calm, relaxed, patient, and unaggressive Type B personalities showed the greater propensity to develop symptoms of stress. However, the use of the California Psychological Inventory of 18 personality traits in an occupational health study lent support to the explanation that controllers are difficult to manage partly because of their selection procedures, since controllers were characterised as dominant, aggressive, independent, self-confident, disliking external regulation and authority, and somewhat intolerant of non-controllers[137], compared with the United States male population in general.

The formal study of personality is complicated further nowadays because it can become entangled with notions of equality and equal opportunity. Manifestly, all individuals do not have the same personality. If they did, the concept of personality testing would be ludicrous. However, decisions taken on the basis of clinical judgment may need independent support in a form which a standard personality test, with fixed scoring and population norms, can provid

An argument in favour of standardisation and partial automation of air traffic control training and instruction is that the influence of the personality of the instructor, or potential clashes of personality between instructor and pupil, are thereby diminished. Assessments can be seen to be more impartial, less susceptible to bias by subjective judgment or whim.

A mark of a profession is that its members can form satisfactory working relationships, in the interests of the profession and its standards, with colleagues who irritate them, whom they dislike, or with whom they share nothing in common except their membership of the same profession. It is not known how often this normal state gives way to personal clashes in air traffic control, or how far such clashes can affect safety and efficiency, though neither of these difficulties presents a prevalent problem. If there are personality clashes, the natural inclination of members of the air traffic control profession is to resolve any such problems locally within the profession if possible, without managerial intervention. Nevertheless, in principle serious personality clashes could lead to disruption of performance, and they must not be allowed to do so if they persist.

## 14f ATTITUDES

Most air traffic controllers like air traffic control very much. Many would not want to do any other job. They may express unfavourable attitudes towards management, conditions of employment, shifts, equipment, or tasks not directly related to air traffic control, but seldom towards air traffic control itself. These findings were originally reported many years ago in the United States at a time when management/controller relations were somewhat strained, but they have since been substantiated there and elsewhere several times. Because air traffic control is valued so highly, controllers can become very defensive about it when changes are in the offing.

Controllers can and do cope with very high traffic loadings. They do not like to lose the esteem of their colleagues, or to admit that they have tried to do too much, and if seriously overstretched they risk a sudden deterioration in performance. They enjoy being busy, and take pride in achieving an optimum solution. They identify with air traffic control, and with their team or watch in particular, to the extent that on many issues they form common attitudes which all are prepared to defend strongly. These professional attitudes are of interest, since they have become very entrenched in what is, after all, a young profession.

In a study commissioned to define research needs, with the aim of maintaining the motivation and favourable attitudes of controllers in future air traffic control systems, Nealey and his colleagues[151] suggested that controllers felt they had little information about proposed system changes that affected them, and little opportunity to make their views known during the planning and development of changes. Controllers' attitudes seemed well worth obtaining, but it was noted that there was no method available by which their attitudes to future changes could be gauged. A method based largely on demonstrations and questionnaires was then proposed. Although this was not followed up, a major study examining controllers' attitudes to existing air traffic control jobs, tasks, and sub-tasks has been conducted, as a basis for judging the probable effects on attitudes of proposed future changes, with particular emphasis on various forms of computer assistance. The method combined hierarchical task analysis, the repertory grid technique, and a job diagnostic survey[146]. The findings revealed that attitudes were not uniform to all jobs, tasks and sub-tasks in air traffic control, and pinpointed those which engendered favourable and unfavourable attitudes to different degrees. The reactions to various forms of proposed automated assistance could therefore be predicted in general and in specific terms, showing that, in some contexts at least, attitudes towards automated assistance were often at least neutral and sometimes benevolent, provided that in the decision-making functions involving "real" air traffic control the role of the computer would remain subservient in its essentials to that of the controller. The concordance among controllers in their attitudes could also be established.

It is noticeable how quickly controllers' attitudes towards any innovation are formed, often long before they have had sufficient opportunity to become fully proficient in its use. Initially favourable attitudes are repaid in terms of persistence in learning, tolerance of deficiencies or unserviceability, and ultimately full realisation of its potential. Unfavourable attitudes can challenge the controller's ingenuity to make manifest all the inadequacies of the equipment, and thereby demonstrate that it cannot possibly meet its intended requirements. It would seem worthwhile to study how attitudes to innovations are formed, what factors are most influential in attitude formation, and why attitudes are formed so quickly. Perhaps it would be unnecessary to try and optimise details of design to such an extent if the goodwill from favourable attitudes could more than compensate for any minor deficiencies. Attitudes posited as helpful or inappropriate in controllers or supervisors have been examined in terms of the effects they may have on air traffic control system errors, and discussed in terms of ways in which attitude formation can be influenced and ways in which unwanted effects of attitudes can be countered[152].

## 14g TRUST

Air traffic control depends on trust. Pilots cannot see the air traffic pattern of which they form a part and must rely on the controller for safe separation from other aircraft and for an efficient routeing with no unnecessary diversions, manoeuvres, delays or fuel penalties. The controller must in his turn trust pilots to obey his instructions, so that he can plan ahead and achieve a smooth and evenly spaced flow of traffic, with no unnecessary gaps that could lead to cumulative delays for others. Both pilots and controllers have to trust the information presented to them, on which their tasks are based. The more complex that information becomes, the less able they are to verify it in any independent way, and the more they have to trust it. For a factor of such vital importance, surprisingly little is known about how trust is gradually built up , how it can be destroyed, and, once destroyed, whether it can ever be fully restored.

When communication between air and ground is primarily by speech, trust can be established directly. Any information suspected to be untrustworthy can be verified by questioning, repetition, and rephrasing, until the receiver of the information is satisfied that he can trust it. The earliest forms of assistance to the controller, especially primary radar, contained much incidental guidance in the form of blip size, contrast, consistency, signal to noise ratio, etc, on how far specific items of information should be trusted. The controller could also learn by experience how far he should trust information, for example that radar coverage in a certain region, or below a certain height, could be fallible. Comparable impressions of trustworthiness are far more difficult to glean from displayed information in modern systems, whether from secondary radar displays, from alphanumeric displays of tabular air traffic control information, or from menus, options, and man-computer dialogues. The man must go by experience, and where aircraft safety is concerned, he is rightly cautious. A major change has taken place: in air traffic control and elsewhere, the man must act on information which he may or may not fully trust, but which he often cannot verify.

A man using a speech channel, whether telephone or R/T, can hear if the line is poor and if the signal to noise ratio is low or there is high background noise. He can therefore tell that some information is difficult to hear, and may therefore be misheard. He can persist until he is satisfied that he can trust what he has heard, before he acts upon it. When data are transponded, no comparable evidence on the quality of the link may be available. The man's first intimation of trouble may be that the data become nonsensical, vanish or never change: then it is already too late to make much allowance for their loss.

With more complex forms of computer assistance, the man requires a great deal of reassurance that they are to be trusted, particularly if the solutions they advance, though safe, are not the ones that he himself would have adopted. His need for reassurance is the greater if he does not fully understand how they work, what they have taken into account, or how they could fail. A major radar failure, in which the screen goes blank or freezes, is at least apparent when it occurs, and the man can trust the radar display in so far as he believes that if it failed he would know at once. Modern software, usually so reliable, is complex enough to fail in a vast number of different ways, all very rare. How could the man detect such failures? Would there always be some recognizable display characteristic to denote failure?

One practical question concerns the extent to which the man can discriminate between his own errors and those of the system. Consider a simple keying task. Errors and omissions fall into four categories. The man may make an error, detect it and correct it. The machine may be programmed to detect certain categories of error, whether machine errors or man errors, correct them or not accept them. The machine may make an error which it has not been programmed to recognise as such. The man may make an error and remain unaware of it. What is the man's attitude to these last two kinds of error, one by the machine and the other his own? Are there some machine errors that he believes might be his own? Does he attribute any of his own errors unhesitatingly to the machine, as mistakes that he could not possibly have made himself? Anecdotal evidence, awaiting scientific substantiation or disproof, suggests that even when the man is making errors that he fails to recognise, it can be very difficult to convince him that a machine error of apparently similar type was his, even though he is willing to concede his real errors which he had not hitharto noticed. This issue of the plausibility of errors is related to the man's trust of the machine. It would be helpful to have better guidelines on how the man diagnoses an error, so that software could be written to facilitate the human ability to diagnose errors and to minimise mistakes in that diagnosis. If either hardware or software can become seriously deficient or in error before any signs of this become visible on the man's displays, then such deficiencies and errors must not be of major operational significance, for the man can do noth[illegible] counter them until their signs become apparent. But a system that can go seriously wrong befor[illegible] has any inkling of it is not a system he will be willing to trust.

Perhaps it can take as long as a year for the man to accept a com[illegible]ion that he does not really understand as trustworthy enough for him to use without reserva[illegible] single failure occurs during that time, it will set back the development of trust for a long [illegible]ps for ever. If after years without failure a single failure occurs, the original high level [illegible] may never be quite restored again. Does a detailed knowledge of relevant hardware and so[illegible] its user to trust the relevant functions more, or does knowledge of the daunting complexity o[illegible] and software leave him with the overriding impression of so many things that could go wrong that [illegible]ts it less as he learns more about it? The answers to this and previous questions raised in this [illegible] in relation to trust are matters of fact, ascertainable by empirical methods (using very reliable [illegible]ment indeed!), though the answers may not be rational. Human subjective impressions do not accord so well with mathematical probabilities that the actual degree of trust would be expected to agree with the theoretically correct level of trust. Nevertheless, in the matter of trust, controllers act on what they believe; this may disagree with the objective evidence which they may not know of, accept, or interpret impartially. Findings in the form of guidelines to equate the trust actually accorded to information with the trust it should be accorded would be a practical benefit. Trust is currently too arbitrary. Qualitative displayed information may help to make it more realistic, and thereby promote safety and efficiency. The ways in which changes are introduced, and the extent to which the reasons for changes have been explained and the controllers' collaboration sought in advance, may have substantial effects on the extent to which an innovation is initially trusted.

## 14h JOB SATISFACTION

Rightly or wrongly, the impression has been prevalent among controllers for some time that many of the air traffic control functions most important for job satisfaction will no longer be there in future air traffic control systems[151]. When expressing such views, controllers are interpreting job satisfaction in terms of the designs of their jobs, their acquisition and use of knowledge and skills, and the variety, interest and challenge of their work. Other interpretations of job satisfaction have been advanced. One emphasises the satisfaction of psychological needs at work, with resultant benefits in favourable attitudes and strong motivation. Another dwells on the importance of fair rewards for the effort expended and work done. A further interpretation is most concerned with status, progress, responsibility and recognition. Yet another would assign high importance to opportunities for controllers to participate in planning and decision making that have direct effects on their work. There is some substance in all these interpretations, but none alone is complete, and even collectively they may still be incomplete.

Just as there are no universally accepted theories of job satisfaction, so there is no agreement on what is to be gained by achieving it. Everyone seems to nod sagely at the pronouncement that job satisfaction is "a good thing", without asking why. Evidence that job satisfaction brings tangible benefits in the form of enhanced safety, improved efficiency, increased well-being, or reduced costs, is at best inconsistent, and it would certainly be unwise to presume that all that is needed for such benefits to accrue is greater job satisfaction. They might follow: more probably, increased job satisfaction would not have much effect on them at all. Nor is much progress possible by contending that increased job satisfaction brings more happiness, which brings higher productivity in its turn. Plausible as this sounds, the evidence for a relationship between happiness and productivity is equally inconsistent: it would be unwise to rely on it. The ultimate reasons for job satisfaction are usually expressed in such terms as the quality of working life, and in the assumption that everyone is entitled to expect that some effort has been made to provide him or her with a job, conditions of employment, and a working environment that are suited to human needs and foster human talents.

Advocates of the need for job satisfaction usually start from the concept of the socio-technical system, which is broader than the more common notion of the man-machine system. The difference between them is partly a matter of emphasis. Both contain men and machines as system components. The man-machine system is primarily a product of the system designer: his knowledge is technical, so that the tasks and their interrelationships that emerge as the system evolves are largely an offshoot of the technology. The main constraints on the system are technological, and the main adaptation is done by the man. The socio-technical system is a joint product of system designers and human factors specialists, with detailed consultation of management and users. The aim is to enhance both human and technical capabilities on an approximately equal footing. A premise is that technology is now sufficiently advanced and flexible for it to be adaptable to meet human needs and to meet other technical needs. The aims are to increase both technical efficiency and job satisfaction. The contention is that both social and technical factors point to this as the most profitable direction to follow in an attempt to reconcile incompatibilities between social and technical changes.

Among the multitude of concepts spawned by the amorphous job satisfaction literature, a few can be clarified somewhat and distinguished from each other. Job satisfaction, as a general term rather than in any specific theoretical context, refers to the satisfaction from the content of the job, the way it is organised, and the circumstances under which it is done. Job enrichment usually implies some extension of responsibilities, and perhaps of status. Job enlargement usually refers to a bigger variety of tasks at the same level, often without increased responsibilities. Job rotation means moving between jobs which, nominally at least, are all at the same level. Air traffic control practices in relation to job rotation vary. In countries where controllers are trained primarily for a single job at a particular facility, opportunities for job rotation are few, but where controller training has been general and broad and controllers are validated for several jobs, job rotation is commonly practised, and it can add substantially to job satisfaction.

The overriding point is that current air traffic control jobs generally carry a high level of job satisfaction. In air traffic control, the aim is not so much to engender job satisfaction as to maintain it. The main problems are human roles that are subservient to machines, the imposition of changes without adequate explanation, and disillusionment with management and conditions of employment. The reward of job satisfaction is a dedicated, co-operative, stable and enthusiastic workforce.

# CHAPTER 15

## THE MEASUREMENT OF THE AIR TRAFFIC CONTROLLER

### 15a PURPOSES OF MEASUREMENT

There are many reasons for measuring the controller, and many measures that can be employed. There are few purposes for which a single measure can suffice, and none that need all possible measures. The practical requirement is therefore to establish exactly the objectives of measurement and, having done so, to choose the measures which as a group will best ensure that the objectives are fully met. A realistic empirical approach to this choice is essential, as distinct from an idealised theoretically optimum approach. Practical considerations that govern this choice include an assessment of the importance of the objective, the resources that can be devoted to measurement, the timescale within which findings must become available, the specialised techniques that could be used, and the quantities of data that can be handled successfully and interpreted within the timescale. The purpose of measurement is not to collect data, but to obtain findings. Data that have been collected but remain unanalysed and unreported represent a waste of resources that should have been put to more productive use. By now there must be many air traffic control environments that house heaps of data about controllers that no-one has ever examined thoroughly, although the intention remains to look at them one day when there is time. Measurement is not simply data gathering.

Among the main purposes of measuring the controller are the following[30] :

(1) The development or validation of selection procedures for controllers.

(2) The conduct and testing of controller training or re-training.

(3) The allocation of controllers to jobs.

(4) The quantification of differences between individual controllers, and of the consequences of those differences for air traffic control.

(5) The definition of typical or attainable levels of safety, efficiency and performance, and of the main factors that can influence these levels.

(6) The specification of the aetiology of human errors, of their operational consequences, and of ways to eliminate or minimise them.

(7) The optimisation of man-machine relationships and of human roles in relation to automated aids.

(8) The implementation and testing of proposed changes in air traffic control procedures or equipment.

(9) The quantification or improvement of the safety, orderliness, expedition, cost-effectiveness or economy of an air traffic control system or of part of one.

(10) The study of a sub-system consisting of a controller using an item of equipment, particularly to establish possible applications to air traffic control of a technological innovation or advance.

(11) The assessment of the effects of aspects of the workspace or the physical environment, on safety, efficiency, performance or well-being.

(12) The examination of the effects of the air traffic control system or of jobs within it, on controllers in general or on individual controllers, particularly with respect to efficiency, workload, stress, health or job satisfaction.

(13) The establishment of the effects on air traffic control or on the controllers of manning levels, team structure and functioning, or communications networks.

(14) The specification of the effects of conditions of employment, including working hours, rosters, work-rest cycles, retirement, etc, on air traffic control or on controllers.

(15) The derivation and explanation of controllers' beliefs, attitudes, opinions, and professional norms and standards, and the relationships of such factors to safety and efficiency.

(16) The interpretation of controllers' tasks and task performance in terms of fundamental human abilities and limitations, in order to predict possible improvements and explain them in terms of psychological theories and constructs.

(17) The testing and proving of proposed techniques for measuring controllers.

(18) The comparison of air traffic control and other large man-machine systems in their human factors aspects.

### 15b SYSTEM PERFORMANCE

Measures of system performance are important in air traffic control because questions are usually posed, and answers expected, in system terms. Although the actions of controllers can influence many system performance measures, the measures themselves can seldom yield direct evidence about controllers. System measures relate to the system as a whole, or to man-machine sub-systems within it, but not to the man. System performance measures do not normally distinguish between or disentangle the contributions of the man and of the machine. As automated aids are introduced, functions that could once be described in human performance terms become incorporated into a man-machine sub-system, and form part of the measures of that system. System performance measures often provide a framework into which other measures have to be fitted, or a context within which other measures must be interpreted.

In air traffic control and other large man-machine systems, system performance measures refer to inputs to the system or sub-system, changes and transformations wrought within it, or outputs from it. Inputs and outputs generally deal with air traffic itself, and with information about that traffic from sensors, navigation aids, computations, and other sources. Some inputs in particular may relate to the traffic itself only indirectly, and refer for example to serviceability states of radars or to weather conditions.

Measures of traffic are general or are concerned with specified aircraft. General measures deal with types of traffic, flow rates, traffic mixes, distributions of traffic flow, pre-planning of flows and routeings, traffic numbers, traffic peaks, amalgamation or separation of traffic streams and routes, stacking states, and the like. Specific measures centre on the effects of the air traffic control system on each aircraft, and the effects of each aircraft on the system. Effects on aircraft are described by routes, delays, manoeuvres, restrictions, fuel penalties, and allied measures. Effects on the system refer to aircraft characteristics such as height, speed, heading, and performance, and to the serviceable equipment carried on board. Further aircraft characteristics consider supersonic aircraft, low and slow aircraft, climb and descent rates of different aircraft types, IFR and VFR flight, and similar factors.

Some aspects of traffic flows and routeings may be used to derive further system performance measures. Examples are metering and sequencing of traffic, the capacity of routes and the use made of the available capacity, and separation standards and the extent of adherence to them or infringements of them. Such measures, and others derived in similar ways, can form the basis in their turn of further system performance measures. These include safety, the development of queues and blockages in the flow of information through the system, and indices of system efficiency. The last may be descriptive in that judgments of efficiency are based on a factual account of the way in which the system actually functions, or they may be comparative, if an independent assessment of optimum efficiency, based on operational analysis or allied techniques and generally expressed in mathematical terms, is employed as a criterion to assess achieved efficiency.

Many of these techniques incorporate changes and transformations within the system, as well as inputs to it and outputs from it. Some further system performance measurements take more direct account of the effects of the system itself on the information passing through it. As example is the measurement of voice channel occupancy times: this is a system measure, as distinct from measures of the controller which, in relation to voice channels, are more concerned with the content of the transmitted information. Channel occupancy times may give an indication of system loading, but are unreliable as indices of loading on the controller because of the propensity of verbal information to expand to fill the time available. Another system performance measure concerns system reliability, expressed in terms of failure rates or serviceability states of components in the system, perhaps with details of the nature of failures. System reliability is usually estimated in terms of machine components rather than man's fallibility. If the latter is considered, its effects are normally confined to aspects of his task performance. However, as an extreme example, if controllers go on strike this is not generally expressed, though perhaps it should be, as a gross reduction in the overall reliability of the air traffic control system, and probably the severest reduction in reliability that can occur.

When functions are automated, they tend to retain the same functional descriptions, such as decision-making, that they had in their manual form. This can be misleading in measurement, as it seems to imply that like is being compared with like when a manual function is related to an automatic equivalent of it. In system performance terms, this may be correct. In relation to the controller it almost invariably is not. The manual and automated versions of tasks that can fulfil equivalent functions may in other respects be very different from the point of view of the controller.

15c TASK PERFORMANCE

Whereas system performance measures are centred on the system, task performance can be measured at various levels of detail, depending on the purposes of measurement and the corresponding levels of task analysis or synthesis. A recent report [153], concerned with the reactions of controllers to computer assistance, contains examples of task descriptions at five different levels, each of which refers to human functions. At the most detailed level, the number of identifiable functions becomes very large, and the effort involved in measuring them all could be justified only in rare circumstances.

Tasks, functions and groups of sub-tasks are most readily measured in objective terms when the onset and termination of each is invariably defined by a measurable event. The occurrence of this event, and its timing, are recorded and form the fundamental data on which further measures of task performance are based. It does not matter so much, for any given task, if its onset (or termination) is not always signalled by the same event, although it simplifies the measurement and analysis if it is; however it is very important that the task can never begin (or end) in some circumstances without any predefined measurable event at all. If this can happen, then certain categories or conditions of that task may not be represented at all or be represented in a biased fashion in the measures. Furthermore, the measures that can be obtained from the occasions when the event does occur may not be representative of the whole.

In some contexts this remains a theoretical issue of negligible significance. In air traffic control it can assume great practical importance: some tasks such as handovers, may sometimes be marked by overt measurable events so that their onset and completion can be designated as timed occurrences, but in the case of silent handovers there may be no corresponding detectable event. Other air traffic control tasks can be fluid: they may be omitted, postponed, condensed, or done only in part whenever the task demands are heavy, but lingered over, repeated, or done in more detail whenever the task demands are light. The resulting measures may have to be corrected or converted to a form suitable for analysis, and even then they will remain incomplete or inadequate. This constraint is the more serious because it is associated with the conditions of highest task demands; when the measures are of most interest and importance, they are most likely to be inadequate.

Direct measures of task performance that require activity or behaviour to be recorded in terms of events or continuous activities, become less practical as the controller's role becomes more passive because there are fewer activities to measure. Many are replaced by machine events that are not under the man's control, such as the routine updating of displayed information. Little overt measurable activity occurs in monitoring roles, and it may become necessary to resort to techniques such as eye movement recording to discover where the man looks and to make deductions about the information he has gathered. This can involve assumptions that he is attending to what he looks at.

Aids that put forward solutions or decisions for the man to accept or reject pose a considerable problem in measuring the tasks that man performs in using them. The end of his task may be signalled clearly enough because the man presses an appropriate key to accept or reject the solution, or takes another action that can be recorded, but the intervening thinking may not be accompanied by any measurable events that correspond closely to the mental tasks he is doing, and the final action of pressing the key, whether it is correct or not, is uninformative about these intervening mental processes. Various techniques, including subjective reports, eye movement recording, an examination of the appropriate procedures taught to him during training, and deductions from the timing and correctness of his responses, may give some indication of the mental processes that he has been following, but not in a quantified measurable objective way that yields consistent data useful for comparing individuals or conditions.

Alternative methods of recording controller's activities include photographing, filming or video-taping. The apparent attraction of these methods in providing a comprehensive record of controller's actions can be negated by the oppressive analytical load imposed by the classification and reduction of the resulting data: few objectives can justify such a burden, which is almost invariably so time-consuming that it can delay seriously the appearance of the findings. A photographic record is recommended strongly to provide a sample of typical activities, or to perpetuate in some form equipment configurations before they are dismantled, but such a record cannot be recommended as the basic data for analysis.

While such cumbersome methods may be avoidable with visual data, they may be unavoidable with auditory data, particularly with speech. To record speech adequately as an integral part of task performance, it is normally necessary not merely to know the onset and end of each spoken message, but its content. Channel occupancy times are not themselves a useful measure of task performance, particularly in air traffic control where they can expand to fill the time available. The contents of spoken messages must be categorised in advance before they are recorded. The messages and their categorisation may then have to be fitted into the context of other timed events, and converted into a form compatible with other measures before a full analysis of task performance can be undertaken. In certain laboratory tasks with a few spoken messages, it is possible to use a voice key or to replace speech with alternative events with equivalent meaning, in order to provide data suitable for immediate analysis. In air traffic control, with its great variety of spoken messages, speech as such must often be measured as part of the task, and not converted to other forms which are not sufficiently equivalent for measurement purposes.

The advent of the micro-computer has facilitated the measurement of task performance. It has made it easier to specify inputs, to control and explore variables thoroughly in accordance with the orthodox principles of experimental psychology, to present dynamic and interactive tasks, to record activities and outputs in the form of timed events, and to employ appropriate automated statistical techniques to analyse data quickly. In using micro-computers for the measurement of task performance in air traffic control there is only one real problem - they are not within an air traffic control system or context and cannot normally be employed to measure whole air traffic control tasks, but only aspects of them or human abilities postulated as relevant to them. Nevertheless, micro-computers can provide much useful evidence about the capabilities and limitations of people in general, or of air traffic controllers in particular, and they make it easy to assess quantitatively aspects of air traffic control tasks taken out of context. This apparently oblique approach to air traffic control problems can be most useful, and provide many helpful insights. Basic evidence about human cognitive functions should remain valid in any context including air traffic control, but the further the studies with the micro-computer stray from fundamental findings about people towards the direct examination of tasks derived from air traffic control, the more the validity of the findings for real air traffic control becomes suspect, because of the impossibility of representing every aspect of even the simplest air traffic control task on a single display driven by a micro-computer. Studies of aspects of air traffic control tasks on a micro-computer should be encouraged, because they can be highly productive and are far cheaper and quicker than more sophisticated alternatives using air traffic control simulation facilities. However, such studies require from the outset an accompanying rationale showing how their findings should be related to, or validated for, real-life air traffic control. The problem of validation becomes clear when the choice of measurements for an experiment with a micro-computer or for real-life or simulated air traffic control tasks is discussed, since different measurements are likely to be employed. Micro-computers may be best used for task performance measures which pave the way for subsequent work in air traffic control contexts, by distinguishing tasks, measures, variables and conditions that merit fuller study by simulation, from those that do not, and by directing the planning of subsequent simulation studies towards their most productive aspects. Studies with micro-computers are an example of the kind of preparatory work that should routinely precede large simulations and evaluations.

Task performance measures in essence are measures of what the man did and achieved. They record whether a task is done, when it is done, how well it is done, how often it is done, how quickly it is done, and the circumstances under which it is done. They may even attempt to record why the task is done. Measures may be left as a simple factual description, or may be scored against a theoretical or empirical criterion, or compared with corresponding measures by other people, in other conditions or in other places.

From the basic recording of timed discrete events or of continuous events, measures of numerous further factors, related to the controller's task performance rather than to the system, can be derived. Although from these basic measures of task performance it may be possible to make some deductions about these factors retrospectively, this is not the preferred way to attempt to measure them in task performance terms. It is better to start by deciding which factor or factors are to be measured, and the appropriate level of detail required to fulfil the objectives of measurement. Existing or specially devised task performance measures can then be selected to cover the objectives of measurement as thoroughly as possible. For most objectives, task performance measures will not in themselves be sufficient, but once they have been chosen the additional types of measure that will also be needed to meet the objectives can be deduced and added. The experimentation thus begins with a full appreciation of all the measures being taken and of their respective contributions to the objectives.

The following list gives examples of factors that can be measured wholly or in part by task performance measures, and for which at least some task performance measures are normally essential. A brief indication of the types of performance measurement that may be suitable for each is given.

(1) Skill. Measurements of events normally include their sequence, pacing, timing, regularity, and smoothness of flow. Measures may be specific (for example the use of a particular input device), or general (for example competence at a work position).

(2) Safety. Measures concentrate on controller-instigated events with direct implications for safety, including their timing. These events are classified and scored in relation to independent external criteria such as safety standards.

(3) Efficiency. Measures emphasis the total amount of activity, and refer closely to system measures that specify the amount of traffic under control.

(4) Learning. Measures emphasise dimensions that can show learning effects. These may include choice and sequence of events, but are likely to emphasise timing between events, and the gradual reduction of inappropriate actions.

(5) Experience. Measures of task performance often are compared with biographical data and correlated with variables in it.

(6) Loading. Measures of task performance are correlated with individual measures of the controller, and with system performance measures so that the activities of the man can be compared with task demands.

(7) Decision-making. Measures of task performance may be compared with automated functions and with data on the amount of information used. Subjective assessment techniques may provide supporting evidence.

(8) Problem solving. Measures of task performance are related to subsequent events to establish the efficacy of the solution, and may be supported by subjective evidence, system performance data or data derived from automated functions.

(9) Understanding. Measures of task performance may go beyond the normal measures and introduce additional tasks to explore whether all the information required to perform them has in fact been understood. Subjective assessments may provide supplementary information or independent verification.

(10) Memory. Measures of task performance may be related to knowledge provided in advance, or tasks may be repeated in similar form at intervals while data are being gathered. Alternatively, additional measures may be made after completion of the customary ones. Subjective evidence may also be gathered.

(11) Strategies. Measures of task performance to study strategies tend to be general and not detailed, putting particular emphasis on sequences, durations and patterns of events rather than on fine details of the nature of the events themselves.

(12) Tactics. Measures of task performance tend to be related to specific identifiable inputs, often in the form of known problems, where the performance measures trace in detail the events leading to the outcome, and record the outcome itself.

(13) Attention. Measures of task performance tend to be of non-standard non-routine events that cannot be overlearned but that the man cannot deal with except by attending to them. Timing of events may also be measured carefully. Subjective reports may be gathered. Another related measure is eye movement recording.

(14) Time-sharing. Measures of task performance emphasise the sequence, timing and regularity of events, and in certain respects the measures may deliberately lack homogeneity, since the tasks are not designed to be performed as a unified entity. Eye movement recording may also be used. Task measures must be appropriate for each task individually and for tasks in combination, so that appropriate comparisons can be made.

(15) Judgment. Measures of task performance may be at any level of detail to accord with the kinds of judgment studied. The number, range, sequence and timing of recorded events may be of particular interest.

(16) Level of activity. Measures of task performance either emphasise the need for active involvement, in which case many measures will often be made so that different levels of activity can be discriminated in a sensitive fashion, or the measures are of events that are optional, peripheral or subject to automated assistance in order to assess accurately the level of activity that has been chosen when a choice is available.

(17) Divisions of work. Measures of task performance may be most concerned with the work position at which the work is being done, to show how work is allocated among members of a team. The functions of the supervisor or an assistant can be treated according to the same principles in terms of task performance measures. Verbal communications will almost certainly be needed as a further measure.

(18) Intelligibility. Measures of task performance that are taken may be classified primarily according to the content of spoken messages and equally thorough measures of this content are necessary. A common classification for measures of intelligibility and of task performance has to be evolved.

(19) Speech. Measures of task performance can be used in studies of speech but are subservient to it and their main role may concern independent verification or support. Task performance measures must therefore be classified and analysed according to variables determined by speech content and not by measured events.

Most but not all attempts to measure the controller within the air traffic control system involve task performance measures in some way. The reliability and validity of these measures varies greatly according to their objectives and practicality. There has been some tendency to presume that measures of task performance are an essential means for tackling every question, which they are not. They have sometimes been equated too closely with system performance measures. Despite this over-emphasis on task performance measures, they could be employed to examine several further factors which have been comparatively neglected. Among those mentioned above which are in this category are skill, memory, attention and task-sharing. They could also be used to explore further the conditions when data limited or resource limited processes[56] limit the performance of air traffic control tasks and to probe further the controllers' worry about losing his picture of the traffic[35]. The above are largely cognitive functions. More specific air traffic control tasks on which further evidence could probably be gathered using appropriate task performance measures include handovers, the effects on performance of the presence or absence of qualitative information about the presented data, the causes and consequences of boredom, the factors that affect the timescale of air traffic control decisions, and the controller's ability to adapt to, and make optimum use of, additional control over his own workload. Although many measures of task performance have been tried in air traffic control, a few untried ones apparently remain.

15d ERRORS, DELAYS, OMISSIONS AND INCONSISTENCIES

The previous section considered task performance measures broadly, in terms of what the man does or achieves. This section also concerns task performance measures, but its emphasis is on what the man does not do or fails to achieve. Failures in task performance can take so many specific forms in air traffic control tasks that it is impractical, and probably impossible, to compile a comprehensive list of all of them. However, in human factors terms, this multiplicity of failures can be classified under the main headings of errors, delays, omissions and inconsistencies.

(1) Errors. The measurement of human errors in the performance of air traffic control tasks depends initially on a fundamental division between two different types of error at the man-machine interface. This division derives from the machine or system, not from the man: in the case of any given error by the man, the system either will or will not accept it. If it will not, the main event recording can include details of the occurrence of the error, its nature, the solution to it, and the time taken to correct it. The classification of errors unaccepted by the system depends on pre-set recording and categorisation. If these are not comprehensive, fuller details of the nature of the system-detected human errors may not be obtainable subsequently.

In contrast, human errors that are within the tolerance of the system and accepted by it may not be recognised by the system as errors at all. The recorded measures of events may have to be scored according to an external criterion in order to detect them. Their classification depends on the amount of information recorded automatically about them: what constitutes an error is a matter of human judgment, and not a machine decision. It may be difficult or impossible to trace the consequences of such errors in task performance terms if the machine does not recognise them or distinguish them from successes. The measurement of errors in task performance terms is therefore substantially predetermined by system design, by the choice of measures of task performance, and by the predetermined categorisation of the measures for analysis purposes.

Specific instances of human error may occur in an apparently random fashion, but the types of error that occur are not fundamentally random. Most are predetermined by decisions about the workspace design, the physical environment, the type, sensitivity and positioning of controls, the content and layout of displayed information, the communications network, the divisions of responsibility, task designs, and individual characteristics such as skill, training and experience. Because the general nature of many errors can be predicted, it is generally feasible to specify measures to detect their occurrence, and to forestall many of the most serious types of human error by ensuring that the machine will not accept them. This improves safety: it also implies that any errors that do affect safety are likely to be unusual.

Training influences errors, by instilling safe habits and by emphasising the need always to follow standard predictable proven procedures. Re-training has to address the problem that habits that are no longer appropriate are difficult to extinguish, and remain a potent source of errors, particularly under heavy workload or duress. The types of human error under such circumstances are also largely predictable.

Generally it is not helpful to record the occurrence of an error without further details about it. Within reason, the fuller the information about an error, the better the prospects for preventing its recurrence. All errors are not treated alike. There are degrees of error, in terms of their origins, their consequences, the prospects of recovering from them, and whether they can be tolerated or must be corrected. Measures of error should provide the man with enough information to make these practical distinctions. A role of man is the detection and correction of errors. His ability to fulfil this role depends on the presence of information that enables him to recognise an error and diagnose it correctly, and of equipment to resolve it. There appears to be insufficient current human factors knowledge about the factors that help the man to notice his own errors, and of his ability to tell the difference between his own errors and those of other people or of machines.

A problem of increasing severity is that as systems become more complex, and the possible ways in which a machine could fail become very numerous, the man may no longer recognise machine errors if they occur because he has no means of knowing how certain kinds of failure appear. If the man is supposed to have a role in correcting such errors, he needs more information about their causes, the extent of their effects, and successful means for their diagnosis. Such machine errors are not normally included in task performance measures.

(2) Delays. The successful measurement of delays depends on the recording of timed events and the calculation of lapsed durations between designated events. These measured durations are then compared with typical or tolerable durations between events, and judgments are made about durations that are, for whatever reason, too long, and thus constitute a source of delay. Because delays are measured by comparing at least two timed events, to that extent they are more vulnerable to deficiencies in measurement than errors or omissions which can be derived from measures of a single event. A few instances where the second event never occurs, or occurs only after a very long time indeed, pose problems in deciding how very skewed distributions of delays should be handled - the answer in each case is best obtained by reference to the objectives of measurement in general and of the measurement of delays in particular. The extent to which distributions of delays can be successfully derived, and the nature of the distributions found, are main determinants of the feasibility of including human variability in models and fast-time simulations.

The number of separately recorded timed events determines the level of detail at which the delays can be measured. The classification of measures of delays, in terms of tasks, system variables, and especially individual differences, fixes the questions that can be answered. Therefore measures of delays to meet the measurement objectives should be predetermined before they are taken and not attempted retrospectively. The classification and analysis are very different if the objectives are to determine the distribution of time taken by different individuals to complete a particular function, to discover whether experienced individuals tend to be quicker than average on almost all functions, to establish whether the occurrence of delays is associated with a reduction in errors, or to rank functions in order of the time needed to fulfil them. Such questions can all be answered successfully if appropriate measures of delays have been specified and taken.

(3) Omissions. In terms of task performance, omissions refer to events that do not take place. It is therefore necessary to establish the nature and incidence of omissions by reference to other measured events that do occur, and by counting the instances when the omitted event is not associated with them as it should be. Omissions are thus defined in terms of task performance, by reference to other events that are recorded as happening. Measures of omissions are limited to classifying them and counting them. The reasons for them cannot usually be established by task performance measures, nor are these measures sensitive to degrees of omission, since the occurrence of a measured event is an all-or-nothing process. Task performance measures therefore establish the nature and incidence of omissions, so that the seriousness of omissions as a problem can be assessed, but further details about the omissions usually have to be obtained by other means before the reasons for them become clear. The only exception to this concerns omissions caused by high workload which may become evident from the other measures of task performance.

(4) Inconsistencies. These are assessed mainly by comparing and analysing measures, and by statistical analysis of the data the measures yield. Inconsistencies may concern erratic behaviour within a machine, large differences between individuals, or the unpredictability of the activities of a single individual. They can reduce the reliability and validity of other measures, and in extreme cases swamp the variance attributable to the independent variables. Task performance measures, collectively and individually, can establish degrees of inconsistency. A judgment then has to be made about the tolerable or reasonable degrees of inconsistency beyond which steps to reduce it must be taken, by improving the machine, by re-training the group, or by discovering the causes of the inconsistency within the individual.

Inconsistency is easier to deal with if there is known to be one best way to perform each task. If there is not, attempts to reduce inconsistency may not lead to any general improvement in task performance. If several alternative methods of performing tasks produce similar results, there is a good case to allow each individual to choose the method that suits him best, at the cost of an increase in measured inconsistency. However, there is an optimum way to perform most tasks, even those in air traffic control, and widespread inconsistency is often a sign that this optimum is not known or is not followed.

## 15e PHYSIOLOGICAL AND BIOCHEMICAL INDICES

The main purposes for which physiological or biochemical measures have been used in air traffic control relate to occupational health[137], stress (and strain) [97], and effort or workload[154]. Interest in these measures has increased during the past decade although it now seems to be waning. Despite the difficulties of instrumentation, sampling and data reduction and analysis associated with these measures, they have been employed quite widely in air traffic control. None of the results or findings obtained by them has been sufficiently encouraging for any physiological or biochemical measure to be adopted as standard.

Physiological and biochemical indices, when employed as measures of occupational health, seek facts about the health of controllers as a group, and evidence of the effects of air traffic control on health, with a view to removing the sources of any adverse effects where possible. Most effects are neither large nor consistent, and it is by no means certain that the effects found can be attributed to air traffic control. The observed health changes may be an interaction between individual predispositions and the context in which the work is done, and have little to do with the nature of air traffic control work as such.

These indices, when employed to assess stress or strain, attempt to verify or quantify the extensive anecdotal evidence that air traffic control is a particularly stressful profession, in order to trace the causes of stress and alleviate its symptoms. Experience here has been that the basic premise on which much of the work was founded, namely that air traffic control is a highly stressful occupation, cannot be sustained. Unusual stress on the job in air traffic control is the exception rather than the rule.

These indices as measures of effort and workload have indicated some relationship with the amount of traffic, and have shown that a greater effort has to be made to control larger numbers of aircraft, or aircraft with less experienced pilots and fewer fitted aids. However, most of the changes are not gross, particularly in experienced controllers, and the findings have scarcely repaid the major effort entailed in these measurements.

Physiological and biochemical indices present a problem of interpretation. They are measures of an individual, and therefore their interpretation must refer to the individual. It is comparatively easy to show by these measures that under certain circumstances in air traffic control, stress, strain, effort or workload are high. This in itself does not constitute a basis for action. The decision is not whether they are high, but whether they are too high, so that practical steps to reduce them must be taken, either to sustain the safety and efficiency of the air traffic control system or to safeguard the well-being of the individual controller. Unless the physiological and biochemical indices produce extreme readings, which they seldom do in air traffic control, evidence for action must be derived partly from other sources. Symptoms of excessive strain are not common among controllers in most countries. Psychosomatic symptoms, particularly those leading to medical disqualification or associated with psychiatric symptoms, are not very common either. Morbidity and mortality rates do not provide strong evidence that would support physiological and biochemical measures. Evidence on a close relationship, or even a tenuous one, between aviation safety and these indices is lacking. Nor do they seem to be associated with efficiency of air traffic control performance. If high stress is present, it does not seem to inflict any permanent harm on most individuals, and if it shows any signs of doing so in a few controllers, then as a problem it has to be tackled at an individual level, and not by indiscriminate attempts to reduce stress, which for the great majority seems benign in its effects. The reduction of the need for effort does not seem a sensible goal in itself but may lead to more difficult problems that it resolves.

The earlier measures in air traffic control were physiological, especially concerned with heart rate and variability, though numerous other measures, such a skin resistance, respiratory rate and volume, blood pressure, and ocular movements and patterns, have been tried from time to time. These all gave results but they tended not to go much beyond the confirmation of the obvious (the more the traffic, the higher the mean heart rate). Later measures have put more emphasis on biochemical indices, derived from samples of blood or urine. Melton[155] attempted to develop a stress index based on biochemical measures, integrating catecholamines and steroids into a single adjusted measure. However, complications arose: epinephrine excretion, but not nonepinephrine excretion, was related to traffic volume, and the findings could perhaps be interpreted better in terms of workload or competitiveness, than in terms of the stressful nature of air traffic control. Recently, physiological and biochemical measures seem to have been used less often in air traffic control. Perhaps a formerly exaggerated view of their importance is giving way to a serious underestimate of their worth. They can produce data, for example on effort, that may not otherwise be obtainable. However they are most valuable when used in conjunction with other kinds of measure which provide a framework for the interpretation of physiological and biochemical findings.

## 15f MODELLING AND ALLIED TECHNIQUES

Various kinds of mathematical model can be developed to measure, predict and explain human performance. Different modelling approaches depend on different theoretical constructs, tenets and assumptions[156]. Allied techniques include control theory, queueing theory, and signal detection theory. Models have a basis in numerical mathematical terms, and often include notions such as variance and probabilities. They are used more often to measure the system, and to form the basis of fast-time simulation studies, than to measure the controller. This is because it is difficult to build models of man performing complex tasks such as air traffic control that include all its aspects and account for most of the observable variability. Nevertheless it is often possible to measure the man by building a model of him, and to use the model to predict how he would behave in unmeasured circumstances, particularly with reference to his task performance. The concept of modelling in the literature is sometimes employed in a further sense, to describe a mental picture or image that the man has of his tasks, but to avoid confusion it is not used in this sense here.

To build a model of the man that can be used to predict his performance, it is necessary to start from a job description or task analysis, and to split his job into functions suitable for description in mathematical terms. The mathematical descriptions can be derived from theory, from evidence in the literature on modelling, or from empirical data. If descriptions can be derived from one kind of evidence, and verified or validated by another, then this confirms the descriptions and increases confidence in the model. For example, a theory may be used to predict, on the basis of uncertainty, relevance, or a comparable principle, the controller's pattern of eye movements in performing a task. Independent measures of performance of actual eye movements during performance of the task may be taken to confirm the predictions, and thus verify the model derived from the theory. A strength of modelling as a technique is that different kinds of measure can be used to assess the model independently, so that it can be built using one kind of measure and verified using another.

Because functions have to be separated to some extent for modelling, a flaw in models may arise if the whole task is not simply the sum of its functions. Either the links between functions remain unrepresented in the model, or there is insufficient information about the nature of the links to include them in the model or to indicate how the formulae representing various functions should be related to each other in the model. A model can be used to make predictions. These predictions can be verified empirically. The verifications in their turn can be used to correct, refine and improve the model. The more this is done, the better the model becomes at measuring and predicting performance. It can be used to identify measures and functions that have the most critical influence on performance. These functions in their turn can give guidance for training, for simulation, and for evaluation. A model can be used to specify what should be included in a real-time or fast-time simulation. It is also possible to use a model to suggest possible selection procedures, though the validity of any procedures derived in this way still has to be established independently.

Models are used to predict how men will perform their tasks; measures are used to show how men do perform their tasks. Measures thus can validate models. Models can prescribe what should be measured.

15g SUBJECTIVE ASSESSMENTS

Subjective assessments are probably the most common technique employed to measure the air traffic controller. They are quick, cheap, and comparatively simple to use and analyse. Some major investigations have relied almost exclusively on subjective evidence. Generally, findings are incomplete if no subjective evidence at all is gathered, since some kinds of information cannot be obtained in any other way. The extensive usage of subjective assessment as a technique has not always been associated with equally extensive understanding of its limitations either in general or with reference to specific methods. This section gives details of kinds of evidence that may be gathered by various subjective assessment techniques if they are correctly chosen and prudently used. The more general limitations of subjective assessments refer mainly to their suspect reliability and validity as techniques.

Subjective assessment techniques are seldom very reliable. Their reliability can be increased to some extent by several stratagems, especially by intensive training of those who make the assessments, by careful standardisation of the conditions, language and terminology of assessments, by clear, unambiguous and (if necessary) repeated instructions, by routine measures and checks of reliability, and by examination of the internal structure of the subjective data when the measures permit the application of such techniques as item analysis. Despite these precautions, which should be taken whenever they are practicable, the reliability of subjective assessments is likely to remain lower than that of many other techniques and measures.

The validity of subjective assessments is a more complex matter to determine. The question of criterion measures in a contentious one. Normally subjective assessments would be validated against more objective ones, concerned for example with task or system performance, or physiological or biochemical indices, but this presumes that it is reasonable to expect good agreement when subjective and objective measures of the same thing are made. In fact a main reason for including subjective measures is that good agreement between their findings and those from other measures may not be expected: if good agreement were consistently obtained, one type of measure would be redundant and could be dispensed with in the interests of parsimony. The validity of subjective assessments about matters of fact can be established by comparing the subjective evidence with the corresponding facts. The validity of subjective assessments on matters of opinion cannot be determined, except by reference to other means for gathering comparable opinions, that is by other subjective techniques. This can become a tautologous procedure that ultimately fails because it cannot take into account sources of lack of validity that are common to many subjective assessment techniques, and therefore cannot establish the true validity of subjective techniques as a whole.

Subjective assessment techniques can indicate what the man knows, understands and has learned. They can be used to extrapolate beyond measured conditions, to generate hypotheses, and to identify further factors of potential relevance. They can show the factors that the man acknowledges, and relevant evidence that he ignores. They can explain the man's reasons for his actions so that even actions that are wrong seem rational rather than capricious. They can reveal discrepancies between what the controller believes he is doing and what he is actually doing and can identify topics on which controllers disagree with others on the correct actions to take. They can reflect the controller's opinions and beliefs, trace the formation of attitudes, and assess their strength. They can provide insight into team functioning, and the problems and successes encountered when tasks are done collaboratively. They can indicate the ways in which supervision, assistance and communication are believed to be successful. They can indicate what the man thinks is important. They are the main means whereby the controller can make his views known and influence the design and management of the system within which he works.

Subjective assessments can be classified as:
- structured or unstructured;
- individual or group;
- direct or indirect.

Five main categories of subjective assessment can be distinguished:

Techniques that yield direct assessments by individuals using structured material:
1. Questionnaires. 2. Rating scales. 3. Checklists. 4. Peer ratings.

Techniques that yield direct assessments by individuals using unstructured material:
5. Narratives. 6. Case histories. 7. Verbal protocols. 8. Replays.

Techniques that yield direct assessments by individuals or groups using unstructured material:
9. Diaries. 10. Log books.

Techniques that yield direct assessments based on dialogues or interchanges, using structured or unstructured material:
11. Debriefings. 12. Discussions. 13. Interviews.

Techniques that yield indirect assessments using structured or unstructured material:
14. Observations. 15. Commentaries. 16. Informed opinions.

Various formalised psychological procedures that obtain subjective assessments constitute psychological tests, and are discussed as such and not as subjective assessment techniques.

(1) Questionnaires. A questionnaire is planned in advance. It covers themes that can be anticipated and are important to the questioner rather than to the respondent. Each question can be multiple choice, where the respondent selects an answer from given alternatives, or open-ended, where the respondent answers as he wishes. Multiple choice questions give less data, are quicker, are easier, and are more impartial to score and analyse than open-ended questions, and they are more appropriate for simple issues with straightforward choices. Open-ended questions provide answers which can be difficult and time-consuming to interpret fairly, but they give better coverage of complex issues and can represent a range of views more fairly. A questionnaire may be broad ranging or confined to specific issues. It can be almost any length. It should have an order, structure and implicit limits. In a questionnaire, everyone can have his say. It is more suitable to obtain the views of each individual than to arrive at a consensus although the latter emerges, if it is present, from the analysis of individual responses collectively. A questionnaire can ask about items of vital or little significance, and be unable to differentiate between them. The wording of each question should deal with one issue only, and be clear and unambiguous. If different respondents can and do construe a question in different ways, this may never become apparent from their answers. Questionnaire responses can be classified in various ways, for example according to the respondents' age, experience, job, or training. Questions may obtain subjective data on functions, tasks or equipment on which objective measures are also taken, so that direct comparisons between subjective assessments and objective facts can be made, for example on the effects of colour coding on task performance. Questions should be framed so that the findings represent the respondents' views, and not the views of those who pose the questions.

(2) Rating scales. These are best for quick assessments on clearly defined dimensions. A graphic rating scale consists of a line, labelled at each end, and the respondent indicates his opinion by marking the appropriate position on the line. Each line must deal with one dimension only. It is possible, in rating scales, though less common than in questionnaires, to ask the respondent to amplify his answers or to comment on them. The position marked on a graphic rating scale line can be measured with a ruler. The scale therefore seems to provide subjective assessments in a quantified form amenable to statistics. Generally it does not. Such treatment attributes a spurious accuracy to the scale marking. It presumes wrongly that if different people mark the same position they must hold exactly the same opinion. It presumes, also wrongly, that a measured separation in one part of the scale is subjectively equivalent to the same measured separation in another part of the scale. An alternative type of rating scale is the multiple step rating scale, in which the dimension is labelled and a verbal description is given of a number of designated points along it. The respondent marks his choice, which may be a position on a line, or one of a number of boxes. Statistical analysis of the data from multiple step rating scales may also rely on unwarranted assumptions. The strengths of the views expressed cannot be derived from rating scales except by separate ratings of strengths.

(3) Checklists. In a checklist, the themes are all provided. A checklist is generally short, requires a series of markings with minimum annotation, and can be used repeatedly to trace trends or the subjective effects of changes. A checklist may serve as an aide memoire for more comprehensive forms of subjective assessment. Checklists are also suitable for quick assessments of a large number of conditions in rapid succession. They gather fleeting impressions rather than information in depth, and are best for quick quantitative assessments.

(4) Peer ratings. In these, controllers assess each other subjectively. Peer ratings have to be obtained and handled with tact and caution. It can be embarrassing to discover that a man is almost universally disparaged by his colleagues, and disconcerting if the views of a controller, which might otherwise be taken seriously, are dismissed as outlandish by his peers. Peer ratings can gather subjective information on certain issues important to controllers, and the evidence they yield often does not overlap much with that from other subjective techniques.

(5) Narratives. A narrative account is potentially the most difficult subjective assessment technique to analyse, interpret, and reconcile with other sources of information. The effort to provide it is considerable, and betokens a committed and interested attitude. It can make clear the issues on which the narrator has strongly held views. The person giving a narrative account is free to make whatever points he chooses: because it is such an unfettered technique, a narrative can give the fairest representation of the individual's views and their relative

importance. Not everyone has the ability to express his views on paper sufficiently cogently to ensure that others do not misinterpret them.

(6) Case histories. In a case history, a real or hypothetical event or sequence of events is considered as an example of a more general trend or problem, and described accordingly. Again, not everyone can provide a good case history. Case histories of the same event, provided independently by different people associated with it, can highlight differences and the interactions between them. The case history can be more successful as a source of insights and hypotheses than as a representative account of a typical problem, although to obtain the latter is often its stated purpose.

(7) Verbal protocols. A verbal protocol, or continuous verbal description, is a technique, employed widely elsewhere though rarely in air traffic control, in which an individual gives a continuous verbal description of what he is doing as he is doing it. As a technique to obtain an understanding of the true nature of actions and the reasons for them it can be supreme. However, it is unsuitable for tasks that themselves require much verbal communication; the act of providing a description may interfere with normal actions; not every aspect of a task and its thought processes need be amenable to succinct verbal description. As a technique it therefore has limited value in air traffic control.

(8) Replays. In this technique an air traffic control task is replayed to a controller who participated in it, and he comments on what he did, on his reasons, or on designated features of the task. Assessments can also be made on factors such as subjective workload and the balance between strategic and tactical thinking. Problems include spuriously precise recollections which betoken a helpful attitude rather than an impressive memory, and a recall of a previous replay rather than the original if the technique is used, as it may be, more than once in succession. The replay, also known sometimes as a review, can be a very useful technique. Best results are most likely to be obtained if the purpose of the replay is specific and clearly defined.

(9) Diaries. These tend to be most useful as memory aids for specific events and as sources of reference in other subjective techniques. Normal conditions may remain unrecorded or be apparently underrepresented in a diary, but it can be particularly useful to record details of unusual events, errors and circumstances that might otherwise not be recorded at all. It is less useful to derive general impressions of normal system functioning. Diaries, thought of primarily as suitable for individuals, can also be effective to record the agreed views of small teams, or topics of disagreement within a team.

(10) Log books. These commonly record facts such as the nature and duration of unserviceability, but they can be used to record subjective events also, particularly on serviceability and related matters. They share with diaries the characteristic that impressions are recorded while fresh, before the perspective on them changes - a characteristic with both advantages and disadvantages.

(11) Debriefings. These are a subjective assessment technique employed widely in military contexts, including air traffic control, but less widely in civil ones. Debriefing usually marks the completion of something. It can be used extensively in feasibility testing. As a technique, it provides an opportunity for each participant to hear and discuss points raised by others, usually in a systematic and quite formal way, dealing with one topic at a time. The themes may be quite similar to those in a questionnaire, though in a debriefing the respondents can raise issues themselves. Debriefing can be used to achieve a group consensus, or to reveal why no group consensus is attainable. Strongly held views may be expressed but they can prevail too much. Debriefing is more successful at revealing the extent of differences than in reconciling them. It can be startlingly effective when it becomes apparent during a debriefing that the controllers did not agree on their procedures, functions or objectives. Debriefing can help to trace the source of such disagreements.

(12) Discussions. These are much less formal than debriefings, to the extent that they may not be adequately recorded while they are taking place, but selectively recorded in retrospect. A discussion allows free rein to ideas, and can be a good source of them. It provides data that can be difficult to integrate with other subjective techniques. Discussions and debriefings share the problem of giving more reticent people a fair hearing, and may have to be deliberately structured so that everyone has a chance to speak and is encouraged to do so. A great deal can be learned if a discussion leads to disputation, provided that all points of view are covered and the topic is given a thorough airing. The extent of disagreement, and the reasoning behind it, then become apparent. Adequate pre-planning for the recording of discussions is essential.

(13) Interviews. Subjective assessments can be gathered by interviewing groups or individuals. The interviewer commonly leads an interview, and decides how it should be conducted. If there is more than one interviewer, the procedure must be standardised and rigorously followed. It is desirable that this should occur even with a single interviewer, although a purpose of some initial interviews may be to explore what is relevant, and hence to develop an appropriate formalised interview structure. Within this constraint, the person interviewed must be free to introduce and expand on the issues that seem most important to him. Interviews as a technique are time-consuming. They may provide in a more expanded, more thorough, but more discursive form much information obtainable from detailed questionnaires. It may be easier administratively to interview groups rather than individuals, but many of the problems of individual interviews are still encountered, often in more complex forms, because it is more difficult to adhere to a formal interview procedure with a group. The method of recording an interview is important and can affect its findings substantially: the choice of writing or a tape recorder can have a major influence on the amount of data gathered, and on the practicality of reducing it all to manageable proportions. An interview must fulfil a stated purpose. It is not an occasion to talk about any topic at all, unless that is the stated purpose. It is not a technique to

be rushed. Much information can be gathered directly about the respondent himself during an interview, and any ambiguities should be resolved as they arise.

(14) Observations. In all the above techniques, the subjective assessments are made by those with first-hand experience by participating in tasks that form the basis of assessments. In observations, and in the following two techniques, onlookers, as distinct from participants, provide the subjective assessments. Observers can be instructed to watch, record, or comment; the success with which they can do so depends on the specificity of their terms of reference, the number of concurrently assessed dimensions, and their training. The value of observations depends greatly on thorough training of the observers until they are capable of following specific instructions exactly. Otherwise, what is recorded depends too much on the identity of the observer. Independent checks on reliability and validity of observations need to be made. The observer must not attribute to the person doing a task the observer's own procedures and thought processes while doing it. Recording can get in the way of observing. Full reliance should not generally be placed, even on trained observers, to assess safety, efficiency, capacity, workload, stress, or training achievement, but observations about such topics should be supported by some objective data. Observations can be effective in describing what a controller was doing in periods of relative inactivity, and in reporting controller decisions to do nothing. The difficulties of observations as a technique should not be underestimated.

(15) Commentaries. It is possible for an informed onlooker to give a continuous or intermittent commentary on air traffic control or aspects of it. A commentary has to be discreet and not interfere with the air traffic control itself. It cannot supply consistent details of actions or speech, but may help to set the scene, and to describe conditions, especially social conditions, under which the work is being done.

(16) Informed opinions. Management, visitors, and others who watch air traffic control, may make formal or informal comments about it, some of which can carry a great deal of influence. Many of these comments can be useful, as those who make them view air traffic control and its problems from a different perspective. To interpret such opinions correctly, it is normally necessary to determine how well-informed the speaker who makes them is.

These subjective assessment techniques have been described separately, but in fact they interact. The suitability of each technique depends greatly on the others also employed. For any purpose for which subjective assessment techniques are employed in air traffic control, the need is normally to select a few techniques which collectively strike the best balance between comprehensive coverage and the utilisation of limited resources for subjective assessment. Generally, techniques to gather individual assessments must precede those for groups, and formal techniques must precede informal ones. Subjective assessment techniques gather much evidence that can be obtained in no other way; in doing so they introduce various forms of bias, and therefore their timing must minimise disruptive effects on other measurements, and on other subjective techniques.

## 15h SOCIAL FACTORS

Measures of social factors in air traffic control are concerned mainly with the controller as a member of a team, a facility, an organisation, or a profession. Basic measures refer to the role of the controller within the social structure, the nature of the structure itself, or the extent to which the controller conforms to, or identifies with, others within the same structure. Most social groupings within air traffic control have a nominal or formalised structure of some kind that can be stated and used as a criterion to establish how closely the actual structure agrees with it.

Methods in which teams of controllers are trained influence their cohesion and functioning. There is debate on the benefits of training people in teams from the outset[140]. The extent to which a team of controllers actually functions as a team can be assessed in various ways. A rough but serviceable method is to note if each team member works rigidly within the strict confines of the tasks assigned to him, for which he is responsible, or helps and is helped by, others whenever opportunities arise. A further measure concerns the extent to which individual team members verify or monitor the activities of other members whenever they can, or rely totally on the competence and reliability of others without cross checking. A team member whose activities are constantly being checked by his peers is not fully accepted by them as a team member. Another team member, whose performance may be in some respects inadequate but who is helped as much as possible in a kindly and unobtrusive way by others, is fully accepted though his deficiencies may be well-known and the subject of sympathy. Patterns of conversation, consultation, and joint decision making beyond the strict requirements of the job are further hallmarks of an integrated team; as is an absence of queries about what other team members are doing. The members of a well-integrated team know without asking what the others are doing. If many such queries are directed towards a single individual, his activities are puzzling to his colleagues, and he is not wholeheartedly accepted.

The most influential team members can be traced by noting who first voices ideas that later become adopted, and by examining the processes by which ideas are formed and disseminated. These processes can be examined directly by recording conversations, or more formally by measuring opinions and attitudes of individual group members and the level of agreement or conformity within the group. The changes in attitudes and opinions can be assessed by repeating the measurements. One index of the strength and cohesiveness of a team or group is the rapidity and strength with which a new member of the group alters his views until they accord with the general group consensus, and the persistence with which he is subsequently prepared to defend his recently acquired point of view.

Some measures of conformity go beyond subjective assessments of the man's beliefs and attitudes, and extend to task performance measures, as the man's actions, procedures and priorities evolve to accord with those of the group. This combination of measures of task performance and subjective assessments can be used to examine various social factors. It may measure cohesion within a team or group, and indicate the extent of group agreement and of the divergence of individuals from it. The application of these combined measures to different groups shows the ways in which all groups agree and in which they differ. The magnitude of differences between groups can thus be established, and compared with the magnitude of the differences between individuals. The measures that most successfully discriminate between groups can be defined and also the measures that are most sensitive to individual differences. Such techniques can show differences between teams, between watches, and between air traffic control facilities, towers or centres. Comparisons of individuals with groups can be used to answer specific questions, such as the extent to which the opinions of supervisors represent those of the controllers they supervise.

If such measures from several large groups are compared, with the emphasis on the degree of agreement rather than on the differences between them, the extent and development of professional norms and standards can be specified in quantitative ways. Views and practices which all group members hold to be correct and stoutly defend, the origins of which can be traced primarily to controllers themselves, form the basis for these norms, and the range and extent of agreement about them indicates their strength. Strength of views can also be measured directly in subjective terms. The rigidity or flexibility of certain practices, measurable in performance terms, may provide further clues to the influence of professional standards, especially in relation to the gradual conformity of people under training to the practices, beliefs, and attitudes of the profession of air traffic control.

Measures of communications may give further evidence, particularly in details which may be characteristic features of a particular group. Some personality variables are relevant to social factors and it may be necessary to measure them also to explain observed interactions. Measures of social factors must also be used to assess aspects of morale and job satisfaction. In the case of the latter, it may be more important to measure the extent to which the man works in isolation or as a member of a team rather than to obtain details of his precise relationships with other team members. Traditional and novel management practices, and the means for assessing their efficacy, have relevance to social factors, particularly in the formation of attitudes. The controller works within an air traffic control organisation to which many of the tenets of organisational psychology apply.

15i QUALITATIVE FACTORS

The development of measures of qualitative factors has lagged far behind that of quantitative factors. The quality of presented information is affected by:

(1) Its accuracy, that is the closeness of a presented quantitative measure to the true measure of that quantity.

(2) Its precision, that is the level of detail or approximation in which all measures of a quantity are expressed.

(3) The smallest change in quantity that has to occur before a change is made in the presented measure of it.

(4) The frequency or rate at which a measure is verified.

(5) The frequency or rate at which a measure is up-dated if it is changing or has changed.

(6) The method of depiction of the information, particularly with reference to the choice of units of measurement, coding dimensions, and presentation in digital or analogue form.

(7) The technical reliability of the information presented, especially its probability of error or failure.

The main determinants of the quality of information can thus be expressed in quantitative terms, and measured.

Although there may be disputation about the relative weighting each determinant should receive in given circumstances, the failure to develop adequate qualitative measures lies more in the depiction of quality than in the calculation of it. If information about the position of an aircraft on a radar display at any given instant is known with great precision and accuracy, or if it is known only very approximately, there may be no coding to provide any indication of this difference to the viewer of the radar display. Qualitative information may be derived from a technical knowledge of the sensors providing that information, and of the subsequent processing of that information before it is presented on the display, but not from the display itself. A rough clue to quality may be deduced from the size of the units in which quantitative information is expressed. Similarly, the only clue to the quality of the height information about aircraft on a tabular information display may come from the units in which aircraft heights are expressed. These same units must then serve under all circumstances: the sensed data may be very much more precise and accurate so that the presented reading is a rounded figure, or the sensed data may be far less precise or accurate so that the presented reading is a best guess, but in both cases the information presented to the controller would look exactly the same, and he has no access to any measure that could differentiate between them. The qualitative information on which the controller can measure or assess the trustworthiness of the data is not present. Accordingly his estimates of how far he should trust it may be grossly wrong. His actions on the basis of these estimates may therefore be inappropriate.

The qualitative information contained in speech may also be difficult to measure directly, and if speech is superceded by data transponded automatically from air to ground no equivalent qualitative information is retained. Put simply, a listener can hear if spoken messages are difficult to hear, and can make judgments (which may be right or wrong) about the confidence, competence, and understanding of the speaker. Judgments of the quality and trustworthiness of spoken messages can be affected by:

(1) The signal to noise ratio.

(2) Pitch, frequency and amplitude of speech.

(3) Pace, fluency, pauses and repetitions.

(4) The format of the messages, their phrasing, and the choice of terminology.

(5) The appropriateness of responses to instructions, questions and requests.

(6) The extent to which spoken messages can be verified from independent non-verbal sources.

Again, it is apparent that measures of the above factors, on which qualitative judgments are based, are in essence quantitative, and that disputations could occur on their relative importance. It should not be impossible to derive quantitative indices of the quality of the information content of spoken messages, though the dimensions in which such indices could be expressed, and the codings that could be devised for such dimensions, are not currently apparent.

Perhaps more vital is to relate measures of quality of information to consequent effects of qualitative judgments on air traffic control safety and efficiency, measured in system performance terms, and to errors, omissions and delays, measured in task performance terms. Until this is done, direct evidence on the importance of qualitative information in air traffic control is not available. Such evidence is of vital importance to predict the consequences of its total removal from the man-machine interface before it is actually removed.

15j TESTS

The whole range of standard psychological tests is available for consideration in relation to air traffic control problems. The possibility of using an appropriate test as a measure of controllers should be borne in mind, as it may often be a more sensitive measuring instrument than specially devised measures that lack a theoretical basis or expository rationale. However, the interpretation of test scores in terms of test norms requires caution, since the norms for controllers as a group may not be the same as those for the general population, and it may be necessary to establish whether they are or not before the scores of individual controllers can be used correctly. Some tests, especially those concerned with personality, may be more culturally dependent than their originators are willing to concede, and again it is essential that norms for the country within which the testing is done, rather than norms for the country within which the test originated, are used to score and interpret the tests. Norms for controllers in a country are also needed if a test is intended for widespread use among them. Controllers, in so far as their selection procedure has been effective, are unlikely to be typical of the population from which they are drawn, and test norms must be amended accordingly for many testing purposes.

A further cautionary note should be sounded about the use of psychological tests in air traffic control. The theory behind many tests is that they tap innate abilities or potential. A customary claim for them is their resistance to the factor of training as a strong influence on test scores. Training in this context refers to training or instruction in the abilities the test purports to measure; it does not mean practice, which refers to repeated performance of the same test, a procedure which ultimately can render the standard scoring of almost any test invalid. Practical experience with some tests suggests that scores obtained on them can be influenced far more by air traffic control training than the compilers of the test are willing to concede or than the theory behind the test can allow for. For some types of tests, such as personality tests, this may not seem surprising, but for other types of tests, such as the perception of embedded figures, it should alert suspicions. If this occurs, it need not invalidate or discourage the use of a test, and indeed it may suggest further possibilities of test usage, for example as an independent index of progress during training, but it does mean that the interpretation of a test score may depend partly on when it is administered.

Psychological tests can be employed in selection, during training, in evaluation, at re-training, for allocation, at various stages or decision points during a controller's career, as an aspect of individual counselling, for clinical applications in relation to an individual's health or well-being, or even as an aid to preparations for retirement. One purpose of testing can be diagnostic - to find out the nature of the problem experienced by a controller, and to establish its cause and prognosis. Another purpose of testing, applicable wherever testing is done, is that, given a requirement to measure any particular attribute of controllers, it is always better, if practical, to employ a ready-made measure that meets the requirement fully, than to devise an ad hoc measure for which no norms exist nor evidence of its validity. Such a measure can almost certainly provide a fuller explanation of findings than any novel one. A further purpose of testing is to employ a measure that can be seen to be independent, both of other measures to which it may be related, and of prejudice in scoring or interpretation. For some purposes, the impartiality of tests can seem impersonal, but this is one of their strengths. Wherever psychological tests are employed in air traffic control the stated conditions under which they must be given, and which are often a condition of the availability of the test, must be strictly adhered to.

A separate category of test in air traffic control is the performance test, which can also be treated as a task performance measure. Its distinguishing characteristic is that it measures air traffic control performance or an aspect of it. It does not seek to measure fundamental human abilities, limitations or attributes, as psychological tests do. However, it is a test in that performance is scored. Preferably the scoring should be standardised, and be, and be seen to be, impartial and objective. There should also be norms, so that the scores are not interpreted solely in isolation, but are compared with the scores of others. Some judgments at least should be partly comparative.

Tests may also be of factual knowledge or understanding. The interest here may be more in the absolute score, to check that each individual does in fact know what he should in order to reach a designated level of competence, progress to further training or experience, or gain a qualification.

These tests also require an impartial scoring method. However, some cumulative evidence is needed about them in the form of norms, to demonstrate that they are practical and serve their purpose. A test of factual knowledge that everyone passes with consummate ease, or that everyone consistently fails to pass, is not of much practical use, and cumulative evidence about test scores is needed to verify that the test is at an appropriate level of difficulty.

## 15k OTHER MEASURES

Many other measures of the controller, not yet mentioned, are possible. In general, they are not suitable for general use in air traffic control, but are fitted to specific objectives, and should be employed whenever these objectives arise. Some of the cited references[27,137] give a glimpse of further measures that can be employed. They may be general, or specific to individuals.

Examples of general measures include indices derived from sources such as medical records or occupational health statistics. Morbidity and mortality rates may be of great relevance in demonstrating the effects, or lack of effects, of air traffic control on the health and well-being of controllers as a group. Data on the incidence of various psychosomatic illnesses among controllers in different countries may help to indicate whether any occupational health problems that seem to be present are prevalent in the same form internationally so that their origins should be found among the conditions that controllers in different countries have in common, or are national characteristics, so that their origins should be found among conditions that are peculiar to controllers in the country affected. Measures relevant to the medical condition of individual controllers, or of controllers in general, can become very numerous, but they are generally orthodox, and the resulting data and findings are classified and categorised in medical terms and not according to air traffic control or psychological concepts.

Specific measures of an individual include biographical data. For some measurement purposes, extensive biographical data may be gathered, which go far beyond the data that are commonly treated as relevant to air traffic control. The data gathered about a particular incident with which a controller has been associated, or to account for symptoms of stress in an individual controller, must include extensive biographical information about him, in order to establish what is relevant or is not. It may be necessary in investigating an incident to check that the controller was not being distracted, for example by domestic or financial worries, or by anxiety about, or irritation with, a colleague, supervisor or assistant. To ascertain sources of stress, the first step is to trace their origins which may be wholly within the air traffic control environment, totally outside, or a fateful interaction between sources within air traffic control and beyond it. Most biographical data are not interpreted in isolation. The significance of a stated problem or condition may depend greatly on how common it is. If it is rare, the cure may be to tackle and resolve the problem. If it is almost universal, but affects only a very few individual controllers in an adverse way, the cure may lie in an examination and treatment of those individuals.

## 15l INTERACTIONS BETWEEN MEASURES

Because there are very few human factors questions in air traffic control that can be answered by the use of only a single measure, a multiplicity of measures is normal, and problems arise in integrating the findings from them and ensuring that the measures themselves do not interfere with each other. Some interactions can be avoided by forethought: an example has been noted with reference to subjective measures, where individual views have to be gathered before consensus group views, because if the latter are collected first they may influence the former too much. Other interactions are more difficult to resolve since they originate in conflicting criteria among the measures themselves, which in turn come from the multiple aims of air traffic control[89].

Some measures are cumbersome, and other measures have to stop while they are taken; examples are obtaining blood and urine samples for biochemical analysis. Occasionally such measures are self-defeating: a few people are so upset by the process of giving a blood sample that their consequent state of arousal can affect the sample itself. Pleasant as it can be for a male controller if a very attractive girl fixes electrodes to him immediately prior to physiological measurement, it does nothing to improve the validity of the measures obtained - she may have to stay out of sight and wait a while. Even under the most favourable circumstances, any form of eye movement recording that requires head-mounted equipment is liable to have certain inhibiting effects on some of the controller's activities in the course of his task performance, and perhaps especially on their pace and variety, and it may thus interfere with other measures to an uncertain degree.

Some measures are too similar to what they purport to measure. An obvious example is the verbal protocol in air traffic control. Most controllers have to speak so much in the course of their work that a running commentary by them on what they are doing either gets in the way of their tasks or must itself be incomplete. A further example concerns secondary tasks, a measurement technique not hitherto mentioned because it is unsatisfactory in air traffic control though it has been used quite widely elsewhere. Its theory is that spare mental capacity or mental workload can be measured by introducing a secondary task, to be done whenever the man can spare the time for it without sacrificing any aspect of his primary task. This leads to several complications and interactions:

(1) Some people are unable to obey such an instruction.

(2) The premise of a fixed or constant mental capacity on which the technique depends is highly suspect.

(3) It is difficult in a complex air traffic control task environment to find any suitable secondary task that would not interfere in some way with any aspect of the air traffic control tasks.

(4) Since air traffic control can to a considerable extent expand or contract to fill the time available, the notion of what constitutes spare time or capacity can become quite arbitrary.

(5) While the man is performing any secondary task an additional unmeasured extra task is introduced because the man must continue to pay sufficient attention to his air traffic control tasks to know when to stop doing the secondary task and return to them.

(6) In air traffic control some tasks appear to be done concurrently in any case because they are overlearned, and the controller can perform much of them while attending to something else, yet to measure mental capacity this must be disentangled, and the switching of attention must be accounted for.

(7) A secondary task introduces a form of task sharing and the validity of measures of it must be impaired by the evidence of a separate task sharing ability which is characteristic of individuals and independent or partly independent of the actual nature of their tasks.

The nature of human factors is interactive, and therefore human factors measures inevitably tend to be interactive also, especially if they seek completeness of measurement. When a range of measures all seem to be in agreement, this may be because their coverage of the relevant sources of information is incomplete. An example, quoted elsewhere in detail[51], notes that in the assessment of whether mental workload is excessive, system measures, performance measures, physiological and biochemical measures, and some subjective measures may all apparently agree, and it is only when a different kind of subjective evidence is gathered that the counter argument begins to emerge, and the fundamental incompleteness of an apparently comprehensive set of measures becomes apparent.

When human factors measures disagree, the options are to ignore some, to integrate them into composite measures, to accord a relative weighting to them, or to accept the disagreement. A very common finding is an inverse relationship between time and errors, with attempts to derive an integral measure such as the number of errors per unit time, or mean time between errors. Because air traffic control must be safe, orderly and expeditious (and also impartial, fuel conserving and economical), measures of such dimensions may interact. In the absence of any clear policy on the relative weighting of such factors (how far should fuel conservation be achieved at the cost of expedition?), some conflict between measures is inevitable. Generally, the specific conflicts that will arise are predictable, and the objectives may point the way to their resolution. It is better to agree on how to integrate the measures before they are gathered, since post hoc decisions carry the imputation of fabrication, justifiably or not. Although the development of measures of performance in man-machine systems is an active research field, some recent studies still find that the interactions between measures have been insufficiently appreciated, and that adequate analytical techniques have not yet been devised to permit the findings from various measures to be interpreted collectively[157], (always assuming that they can be). The real problem may be deeper. The human factors approach is to partition the subject matter, and to take measures of the partitioned dimensions. If the whole subject matter is more than the sum of the partitioned parts, then the sum of all the measures, no matter how they are added or integrated, cannot fully represent the whole, although partitioning may enable the parts to be understood. If the whole is measured, without partitioning, this restricts techniques to those appropriate to system measures or to allied measures such as modelling. While the whole may be adequately described, no adequate understanding of the unmeasured parts can emerge. If both the whole system and the system in its partitioned state, are measured, this represents a major commitment of resources and still leaves the problem of the integration of the whole and the partitioned measures, even assuming that both have been comprehensive. Much definitive work, on the interactions between measures, on their integration, on their completeness, and on their reconciliation when they conflict, remains to be done.

# CHAPTER 16

# HUMAN FACTORS IN AIR TRAFFIC CONTROL RESEARCH AND DEVELOPMENT

## 16a THE CONTRIBUTION OF HUMAN FACTORS

The human factors specialist concerned with air traffic control research and development seeks to apply his knowledge, techniques, findings and interpretations to further the objectives of the research and development and to cover all relevant human factors aspects and implications. Occasionally a research and development programme includes a study that focuses primarily on human factors issues, but most air traffic control research and development problems concern the system, equipment, technical innovations, traffic flows, capacities, and the like. They are not in essence human factors problems. Therefore the role of human factors is to contribute towards their solution, but the main variables, experimental designs, conditions and measurements may not be particularly apposite for human factors purposes, nor the ones that would have been chosen for a purely human factors study. The constraints on research and development are such that a human factors interpretation may be required of findings obtained under conditions where it was completely impractical to insist that the full rigour of traditional human factors experimental designs and control over variables must be enforced. Insistence on such enforcement would mean that few studies could ever start, and fewer still would be completed.

This does not imply that the human factors specialist can afford to be sloppy, casual or unscientific in his approach to air traffic control research and development: far from it. Given a free hand and unlimited resources, he must know exactly what to do to obtain the most reliable and valid possible answer to each problem in human factors terms. He must know how human factors studies should ideally be conducted and be able to recognise any opportunity for a well-designed piece of relevant human factors research. Typically this is a major commitment: it involves a complex and rigorous experimental design, quite large numbers of subjects in order to assess individual differences and the factors relevant to them, multiple measures and a means for weighting and combining them, appropriate scoring and statistical analysis of data, sufficient time for training and instruction of subjects before the experimental design proper is followed, and preferably a theoretical basis from which hypotheses for testing can be derived and according to which findings can be interpreted. But human factors expertise in air traffic control research and development programmes must extend beyond a knowledge of what would be ideal.

In air traffic control research and development the human factors specialist must expect to encounter major obstacles to the conduct of valid human factors experiments. He must therefore be able and willing to compromise, and recognise the full implications of doing so. He may have equipment for only a very limited time, far less than he would like. The cost of using an air traffic control research and development facility may mean that every moment must be put to productive use. Few people may have been trained to do the tasks being studied, and the costs of training others with the facility on line would be prohibitive. There may be no suitable theoretical framework to generate hypotheses or to provide a basis for gauging how far findings might generalise or be extrapolated. Perhaps above all the human factors specialist must have sufficient insight into the nature of experimental designs and their associated statistical techniques and relative power to understand which questions can still be answered validly and which cannot, with various departures from the ideal design. This is often a conspicuous weakness when laboratory trained academic psychologists tackle applied human factors problems. They know what should be done but lack sufficient insight into experimental designs and statistical techniques to appreciate exactly what can still be salvaged and what must be sacrificed in the face of such common woes as a very small number of subjects, confounded variables, incomplete control over variables, progressive familiarity with the experimental material, equipment breakdowns in the middle of experimental runs, abandonment of part of the experimental design, misjudgments of the difficulty or feasibility of new procedures or tasks, or unbalanced experience with compared alternatives. All too often, such difficulties are glossed over in official accounts of research studies. No-one likes to admit to a debacle, especially an expensive one, but, if its occurrence is never conceded and openly acknowledged and described, subsequent researchers can gain a false impression that they are beset by peculiarily baleful vicissitudes, when they are really encountering normal difficulties.

It can also be important in analysing human factors data to know the conditions under which various statistical treatments can be used, and the relative power of alternative statistical treatments that are valid. The ideal statistical method may be difficult to justify if an alternative technique that is almost as powerful requires far fewer resources and is much quicker. In applied work, a relationship that is teetering on the brink of statistical significance is not usually of sufficient practical importance to warrant the application of elaborate time-consuming statistical techniques to it. Note that this does not sanction the use of statistical techniques that are not valid, but does mean that the practical appropriateness of techniques depends partly on their power as techniques and on the effort their application entails in relation to the practical importance of the question which they address. In research and development work, collective decisions must be made on the optimum use of limited resources to gain the maximum amount of relevant valid information. A vital human factors contribution is to explain the measurement techniques that can be employed, the conditions that must be met to ensure their validity, and the questions that cannot be answered if those conditions are not met. There should be full understanding and agreement about the questions that can and cannot be answered before experimental studies begin.

Air traffic control research and development is biased towards techniques of evaluation that employ simulation facilities, and away from simple laboratory studies on the one hand and real-life studies on the other. The contributions of human factors to air traffic control evaluations are considered more fully in the next section. Other human factors contributions to air traffic control research and development are listed here more briefly. This text as a whole implies what the whole range of human factors contributions can and should be.

(1) The application of basic psychological knowledge of human capabilities and limitations. An aim of the human factors contribution to air traffic control research and development is to utilise human strengths and circumvent human weaknesses in the interests of safe and efficient air traffic control, to ensure that the research and development programme does not founder because of a gross mismatch between envisaged human roles and actual human capabilities. Wherever possible the human factors specialist must use his knowledge to suggest practical means to ensure the successful progress of the programme.

(2) The application of applied human factors knowledge from air traffic control and other contexts. The aim is to learn human factors lessons from previous relevant work, and hence to improve specifications and ensure that any former mistakes are not repeated. The particular research and development programme is interpreted in relation to human factors work on other man-machine systems, so that problems are identified as specific to air traffic control or general, and the range of previous relevant evidence can thus be identified. This entails comprehensive knowledge of the relevant literature, and skilled interpretation of it on the part of the human factors specialist.

(3) The identification, classification and interpretation of the whole range of human factors problems relevant to each research and development programme. This requires detailed understanding and knowledge of the aims and content of the programme. A first step is to ensure that all intrinsic human factors problems have been recognised and are discussed, especially new ones. A human factors contribution is to suggest their importance and consequences in human factors terms, to describe what is already known about each, to advise on problems where existing knowledge appears insufficient, and to state the human factors work that would be needed to gain sufficient knowledge for the particular research and development purposes.

(4) Participation in the planning of the research and development programme. Here the role of human factors is not merely to provide relevant evidence and advice, but to indicate the strength and generality of the evidence and the probabilities for each problem that there is a solution and that techniques to discover it can be devised and used. As a member of a collaborative research and development team the human factors specialist must always try to further its aims, be constructive and find ways round the objections and difficulties that he must inevitably raise from time to time. An aim is to optimise each man-machine interface.

(5) Advice on appropriate human factors techniques. In addition to the provision of human factors knowledge the human factors specialist advises on broad categories of technique, such as theoretical studies, model building, laboratory experiments, simulations, and the study of aspects of real-life air traffic control environments. He also advises on specific techniques within each of these categories and makes recommendations on those that should be employed. In doing so he takes account of their practical feasibility, the required resources, the probability of obtaining definitive evidence, the ease of interpretation of findings, and the prospects of successful integration of evidence obtained from different techniques.

(6) The measurement of individual participants in air traffic control research and development studies. Advice is given on the range of measures, especially of performance, individual differences and subjective assessments, on the kinds of evidence that each can and cannot yield, on the amount of data needed to draw conclusions, on the reliability and validity of measures, and on the conditions that have to be met for successful measurement.

(7) Further human factors implications of the research and development programme. These include the development of methods of familiarisation and training associated with proposed innovations, implications for selection, relations to responsibilities and status, and possible effects on well-being and attitudes.

(8) The design of experiments and the choice of statistical techniques to meet human factors requirements. The aim of measures is to gather reliable and valid data to enable judgments about the research and development programme to be formed. To achieve this aim, it is necessary, wherever possible, to adhere to orthodox human factors designs in which no incorrect assumptions are made, particularly about whether the interacting effects between variables have been parcelled out. Specialist human factors advice is needed on the value and interpretation of evidence when the normal requirements for reliability and validity cannot be met.

(9) The interpretation of evidence. The findings during air traffic control research and development are considered primarily in relation to air traffic control. This alone may not ensure that their human factors applications are all recognised. If they are not, the human factors specialist must spell them out in air traffic control terms

(10) The relation of research and development to the air traffic control system in human factors terms. The human factors contribution to air traffic control research and development should also be interpreted in terms of the role of human factors in air traffic control in general (see Chapter 3). Not only should the human factors implications and findings be reported and interpreted, but the stage during the evolution of the air traffic control system at which each becomes relevant should also be stated, so that the findings from human factors contributions to air traffic control research and development are correctly fed back to influence air traffic control itself in the most appropriate way.

16b HUMAN FACTORS APPLICATIONS TO AIR TRAFFIC CONTROL EVALUATIONS

Evaluations for air traffic control research and development generally employ facilities built for that purpose. They must often use current technology to represent proposed future technology. They can seldom last long enough for the participants to reach full proficiency in their tasks. When an evaluation is conducted for research and development purposes, it is more appropriate to seek to establish the feasibility of concepts or to verify that development is proceeding along the right lines than to seek quantitative measures of capacity or definitive evidence on system performance in real-life. The objectives of evaluations vary a great deal, and the human factors contributions to them are therefore not always the same. Nevertheless it is possible to indicate aspects of evaluations to which human factors contributions can be made. These overlap considerably with contributions to operational air traffic control systems.

Given the purpose of an evaluation, human factors advice can be offered on what should be done to obtain findings that are as valid and pertinent as possible. One topic concerns the operational positions that should be included in the evaluation, the equipment required at each, and the authenticity of each operating position. The main positions usually must be replicated with considerable fidelity and completeness, or else the controller's time will not be fully occupied with realistic tasks. However, peripheral and feed operating positions, there to enable the evaluation to take place but not an intrinsic measured part of it, can remain incomplete and some can often be combined. Equipment has to be provided that functions realistically so that the tasks for the controller in the evaluation are similar to those that occur or will occur in real-life, and a full range of his tasks must be included. The extent to which the chosen tasks are representative of others should depend on the objectives of the evaluation.

Similar considerations apply to the air traffic samples used for the evaluation. It is vital that these can be specified in detail and classified in some way, so that any differences attributable to differences between samples can be discovered and expressed in general terms. It is also important that aircraft types should be seen to behave realistically. If they do not, this constitutes a distraction and a constant reminder to the controller that he is participating in an evaluation. If aircraft do not manoeuvre, accelerate, climb or descend as expected, this produces unknown effects on control strategy and efficiency. There are enough potential sources of poor validity present in any air traffic control evaluation, without introducing any further avoidable ones of unknown significance.

Because controllers are not fully conversant with the system being evaluated, measures of their workload, traffic handling capacity, tactics, and proficiency are inherently suspect. However it only takes one successful controller to show that a task is feasible in principle, or to illustrate possible improvements as experience with the system is gained. The question of realism and fidelity in evaluations is bound up with the need to acquire skills during the evaluation and transfer them elsewhere, perhaps even to train others in them. If this is not envisaged, the requirements for realism become less stringent, as they also do if an evaluation is comparative and any inadequacies in it apply equally to all the compared conditions.

Human factors advice covers communications links between controllers, and between controllers and the input operators who represent pilots. A problem in air traffic control evaluations is often that these links are too smooth and trouble free. Contacts can be made without delay; channels are clear; instructions are understood immediately and implemented at once. The participating controller can come to rely too much on this smoothness. For some purposes such as feasibility it may not matter, but it can wreck measures of capacity. Human factors advice can indicate the steps necessary to achieve the kind of communications required for the particular objectives of the evaluation.

Perhaps the most straightforward application of human factors principles to research and development evaluations concerns the workspace, furniture and man-machine interface. The ergonomic principles for the design of suites and consoles can be implemented as they stand. Physical environmental conditions should not be grossly different in the evaluation from those in real-life, and human factors guidance can be provided on the tolerable limits within which little effect of environmental variables on the findings of the evaluation would be expected. The lighting should replicate operational lighting conditions closely if these are known at the time when the evaluation takes place. The basic recommendations for the design of workspaces to foster the well-being of the operators in them should be followed. Known causes of postural or visual difficulties should be excluded from evaluations, as they would be from real-life systems.

The detailed layout of each operating position for the evaluation should meet human factors requirements. All controls should be correctly chosen, optimally positioned and checked for sensitivity. The basic guidelines for matching control specifications and locations with task requirements should be followed. All controls should be checked to ensure as far as possible that they are not a source of needless errors or delays. Display control relationships should be optimised. Display contents should be specified in relation to task performance and to the objectives of the evaluation: the information on each display should be clear, correctly coded, and laid out to facilitate its use for the envisaged tasks. Displays for the evaluation should be considered collectively so that there are no anomalies between the codings on different displays; these might not matter in the evaluation but would not be acceptable operationally. Likewise, codings known to be inadequate, but introduced as a matter of practical necessity within the technological constraints of the evaluation, must be treated with circumspection. There is some tendency for aspects of the man-machine interface, initially adopted in an evaluation solely for reasons of expediency and with full awareness of their glaring deficiencies, to be perpetuated in subsequent evaluations and even in operational systems because they are never queried thereafter. In evaluations, as in real-life air traffic control, the man-machine interface should be designed as a whole.

The capacity of the displays and controls is not necessarily that required for the evaluation, although it may be if the aim is merely to demonstrate the feasibility of a concept. More commonly, it is essential to establish that a concept being evaluated, such as a particular configuration of displayed information, would remain usable under operational conditions, and particularly with the peak system loadings encountered operationally. The displays can set a limit on system capacity if there is not room on them for the essential information about all the aircraft under control at that operating position. Maximum traffic samples and loadings may be set by the capacity limits appropriate for the evaluation. Extrapolated human factors evidence can indicate some of the problems that will arise with loadings in excess of those covered in the evaluation, and may offer solutions to them. A substantial increase in tabular information, for example, may require additional coding dimensions to impose a better visual structure on it to facilitate searching. These additional codings should be tried in the evaluation. The displays should therefore be able to accommodate the amount of data that would be generated under peak real-life system loading, even though it may not be possible to actually generate this amount during the evaluation.

Some human factors questions can be answered and some cannot using the traffic samples chosen for the evaluation. It is essential to make this clear before the specification of the traffic samples is finally settled, so that adjustments to them can be made if answers are wanted to the questions that would remain unanswered. As a matter of expediency, the amount of traffic in the samples usually has to be increased, progressively or in steps, during the evaluation, since light samples are needed at the beginning while participants are learning how the system functions, and heavier samples are needed later to check that they can be handled. Some aspects of samples can become so familiar that the problems they pose are anticipated. If this happens, it can invalidate many measures and distort procedures. Human factors advice can indicate the aspects of samples that may become too familiar, and the consequences in terms of reduced validity.

The processes of initial verbal or written briefing, instruction, demonstration, familiarisation and training that normally precede an evaluation all have a substantial influence on its findings, and human factors evidence can be used to illustrate this, and if necessary to quantify and allow for some of their effects. The justification for doing this depends in part on the objectives of the evaluation. With experimental equipment that is in an early stage of development and not intended for operational use in its current form, such precautions may be superfluous. In other contexts they may be vital. The first evidence on effective training procedures for an innovation may be obtained when it is evaluated, because some training must be done before the evaluation can take place. Human factors advice on procedures for training should often be obtained and followed at this stage of an evaluation much more thoroughly than it normally is, since the techniques for training and familiarisation, developed for the evaluation and partly dictated by factors of expediency associated with it, may subsequently become more entrenched than is warranted; potentially better methods of training, excluded by the circumstances of the evaluation, may never be tried.

Team structures and manning levels employed for an evaluation must inevitably be incomplete in some respects. Some of their human factors consequences can be specified in terms of functions that are oversimplified, tasks that are not done, and communications that can be dispensed with. In evaluations it is easy to under-represent the amount of time spent in routine communication, co-ordination and liaison, partly because some of these activities can be omitted altogether, and partly because those that remain are shorn of most of their difficulties. It is not always possible in an evaluation for controllers to give as much help as they normally would to their colleagues alongside them, either because such help during the evaluation is formally discouraged in the interests of measurement, or because all the normal means of rendering help are not present. The effects of this can be expressed in human factors terms.

A further human factors contribution to evaluations concerns the implications of their total duration on the validity of the resulting evidence. The number, length and scheduling of exercises in an evaluation affects learning, the attainment of proficiency, the onset of boredom or fatigue, and the understanding of how the evaluated system functions. It can also affect the measures so much that in almost all traffic control evaluations the data have to be classified in terms of the exercises, [illegible] sequence, and the stated differences between them. Human factors knowledge of work-rest cycles [illegible] their effects on various types of measurement can be brought to bear.

More broadly, human factors requirements have a vital interaction with experimental designs, the choice and manipulation of controlled variables, and the selection of appropriate statistical techniques. These must meet human factors constraints as well as mathematical and statistical ones. In particular, a design in which the factors are mathematically balanced is not thereby a design in which they are balanced in human factors terms. If the effects of interactions must be studied and allowed for, this is possible only with a combination of appropriate experimental designs with correct statistical techniques according to human factors criteria.

Many of the methods of measuring the controller, described in the previous chapter, can be applied in evaluations. Indeed they may take particularly rigorous and thorough forms in research and development contexts where in principle there can be greater control over variables and more precise quantification of their effects than in real-life air traffic control. In particular it may be more feasible to measure the man as distinct from a man-machine sub-system, although this is not often done.

The main kinds of measurement in evaluations refer to system performance, task performance, individual differences, and subjective assessments. Each of these can become elaborate and detailed when circumstances warrant, and sometimes when they do not. Many of the measurement techniques mentioned previously are used: there is some tendency to measure everything possible since the system constructed for the evaluation is temporary, and once dismantled no additional evidence that may have been overlooked can be gathered afterwards. While common prudence suggests thoroughness in measurement, practical considerations point in the other direction. As the findings from an evaluation for research and development purposes are wanted quickly to enable further planning to take place, chronic delays because of over-ambitious and unselective data gathering, measurement and analysis may not be viewed favourably. Minutely detailed descriptions of events in a system still being evolved may serve no useful purpose. Human factors guidance can usually make clear the range and detail of the minimum measures needed to meet the objectives of the evaluation: although it may be wise to measure rather more, it may be equally wise not to analyse measures beyond the minimum initially, unless there is time.

Human factors guidance may also be needed to interpret apparent anomalies between measures. The commonest arise between objective measures of task performance and subjective assessments on allied dimensions, though some measurement criteria in air traffic control may be inherently difficult to reconcile[89]. For example, a controller may report that his performance has certainly been improved by the provision of colour coding on his displays, whereas objective measurements of performance show no improvement whatsoever. There is no point in dismissing part of this evidence as wrong. The revelation of such disparities is a major reason for collecting both objective and subjective data in air traffic control evaluations, and may help to explain what might otherwise remain inexplicable. The controller acts according to his beliefs: they are incorrect. There is a human factors problem to discover how they have arisen, and to trace their practical consequences for the safety and efficiency of the system. When these consequences are known, they provide evidence on whether any attempt to change the controller's beliefs should be undertaken. In evaluations, it can be particularly important to measure attitudes and opinions. With innovations it may even be possible to show how and why attitudes to them are formed. Whether equipment is efficient is one thing, and whether it is liked is another: both can be measured by human factors techniques in evaluations.

The final, and perhaps major, human factors contribution to air traffic control evaluations for research and development purposes is in the interpretation of findings, including an estimate of their generality and of the confidence that should be placed in them. It is in the nature of evaluations that excessive extrapolation of their findings must ultimately prove contentious. The human factors specialist can weigh the evidence in human factors terms, relate it to previous experience and to the general literature, assess the seriousness of the constraints imposed by a limited number of participants and by the evaluation itself, estimate the reliability and validity of the data, and gauge the magnitude and relevance of disparities between the evaluation and real-life conditions. These and other kinds of information are used to interpret the findings of the evaluation in human factors terms. The human factors specialist is therefore able to provide an impartial commentary on the evaluation.

## 16c REAL-TIME AND FAST-TIME SIMULATION

The air traffic control evaluations discussed in the previous section are in real-time. This means that they include controllers who perform tasks at a workspace, using displays and controls. Aspects of the system or their performance are measured, often in terms of times, events and errors, and perhaps by other means. In real-time evaluation, there is a real, photographable, physical environment, either simulated or operational.

Real-time simulation has been used very extensively in research and development for air traffic control. As a result, informed judgments can be made of its value and limitations as a technique. A recent appraisal concluded that as a technique it is both indispensable and over-used[40]. It is indispensable because much of the evidence about human interactions with the system can be obtained in no other way, short of operational conditions, and sometimes not even then. It has been over-used partly because of its employment for a much wider range of applications than those for which it is really suited, and partly because in addition to fulfilling its own functions it has had to do duty for simpler laboratory studies that should normally precede it and for real-life verification that should normally follow it.

The assumption seems to be prevalent that different types of finding from real-time simulation studies have equivalent validity, despite extensive evidence to the contrary. Findings from real-time simulation are not definitive, but require verification. They are never wholly useless and never completely valid. The problem is to establish the credence each finding should be afforded. More credence can often be given to comparative findings, about alternative equipment, displays, controls, methods, procedures, instructions, divisions of responsibility, etc, than to absolute findings, about capacities, workload, tactics, strategies, error rates, etc. In the former, most determinants of validity, or of the lack of it, apply about equally to the alternatives, and it may therefore not be of great practical consequence if all these determinants cannot be defined and specified exactly. In the latter, the answer obtained is a direct function of these same determinants of validity; if they cannot be quantified, or even identified, confidence in the findings becomes correspondingly uncertain. Because real-time simulation studies seek general answers, expressed in system terms, the importance of individual differences between controllers can be underestimated, and their measurement neglected - a characteristic weakness of real-time simulation as a technique, which applies even more forcibly to fast-time simulation.

Fast-time simulation, as a technique, is based on a mathematical description or model of a system. It needs no physical equivalent. Its validity depends on the extent to which various functions can be expressed in mathematical terms. In air traffic control research and development and in other large man-machine systems, fast-time simulation is generally weakest when it attempts to express the role and functions of controllers mathematically. Very simple human functions can often be described by a mathematical equation of comparable simplicity, that successfully accounts for most of the variance. Progressively more complex functions require correspondingly more complex formulae, that account for less of the variance. At some point, which varies with the objectives, the effort entailed in the compilation of adequate mathematical descriptions of human functions is no longer repayed in terms of the usefulness of the descriptions or their adequacy as descriptions. A further practical constraint is that many tasks in air traffic control are not understood well enough for a mathematical description of them, even an inadequate one, to be compiled.

It is possible in fast-time simulation to omit human functions altogether. Aspects of system functioning with minimum human intervention can be studied satisfactorily in this way. If human functions are included, in principle they can be represented in various ways in fast-time simulation. In increasing order of complexity, a human function may be introduced as a fixed delay (a mean, median or mode), as a variable delay picked on each occasion at random from a distribution derived from theoretical descriptions of how the man should function or from practical evidence on how he does function, or as a variable delay chosen on each occasion from a distribution according to a predetermined principle. This last option incorporates an allowance for individual differences. For example an experienced man would tend to take shorter times than an inexperienced one on most functions, and the delay on most functions would therefore be below average to represent him. For purposes of fast-time simulation, human errors can be treated similarly, as fixed in nature, fixed in proportion, or both; as random; or as following a predetermined pattern to accord with such factors as an individual's experience. It is thus possible by various means to attempt to represent human variability in fast-time simulation. In practice the attempt is seldom made in air traffic control research and development. It can become very time-consuming.

Fast-time simulation as a technique has the benefit implied by its title. Because it is fast, many replications are possible. Generally these are classified by the input to the fast-time simulation. The same input is made repeatedly while many variations are introduced within the simulation to explore their effects. When this has been done, the input is changed, and the same variations are explored again with the revised input. With this fast-time simulation technique, far more runs, with far greater control and manipulation of variables, are possible than in real-time simulations. The effects of different inputs in the form of traffic samples can be thoroughly defined. The effects of each variable within the system on the traffic samples can be studied in turn and in combination, so that those with the largest effects can be pinpointed, and their most critical conditions defined. Variables can then, if required, be put in an order according to the relative importance of their effects on the system.

Fast-time simulation can be an effective means for narrowing the range of real-time simulation studies, for defining the conditions under which evidence from real-time simulation is needed most, for evolving traffic samples that will be appropriate for real-time simulation studies, and for confirming many of the most important measurements in real-time simulation. Because fast-time simulation can be a highly effective means for demonstrating the effects of each parameter on the system, and for disentangling its effects from those of other parameters, it can provide a framework for the interpretation of the real-time simulation studies, and may be helpful in tracing the true origins of effects observed in real-time.

Although occasional attempts to link real-time and fast-time simulation studies in air traffic control research and development have been made, and the degree of agreement between them has been established for certain measures, nevertheless much earnest extolling of the benefits from closer links between real-time and fast-time simulation has not in fact strengthened the links between them. The potential for mutual benefits from relating real-time and fast-time simulation remains, especially if each is used in support of the other, and fast-time simulation is not treated merely as a routine precursor of real-time simulation.

## 16d ALTERNATIVE TECHNIQUES

The dominance in air traffic control research and development of evaluations using real-time simulation has curtailed other techniques even more than fast-time simulation, often to the detriment of the real-time simulation studies themselves. Other techniques can be categorised as experimental or non-experimental. Real-time simulation belongs within a continuum of experimental techniques, ranging from paper and pencil studies, through simple laboratory studies, dynamic experiments and real-time simulation, to field studies of real-life air traffic control.

Paper and pencil studies, with a minimum of apparatus, can measure human capabilities and limitations in a direct way for certain functions. In these studies, man is measured separately from any man-machine system. This provides useful basic information on what he can do when unassisted by, or unimpeded by, equipment. Simple laboratory studies may not separate man from equipment quite so successfully, but still convey the benefits of stringent control over experimental variables and conditions. These studies indicate the kinds of perceptual judgments or information processing of which the man is capable before or after training. These paper and pencil and laboratory studies indicate what man can do with ease, and what he cannot do at all. They may also define intermediate conditions within which individual differences, training, skills, experience or particular abilities or aptitudes may be critical. The findings from these studies can set limits on what should be attempted in more ambitious evaluations. They can provide a perspective for interpreting findings, and support an explanation of conclusions.

Dynamic experiments are essential where significant aspects of the task itself, as in a tracking task, are themselves dynamic. They mark the onset of the problem where the respective contributions of man and machine cannot be wholly separated, and the man-machine sub-system constitutes the smallest readily measurable entity in terms of input and output. In dynamic experiments, one man may be substituted for another, or one machine for another, and measured changes in output are assumed to be caused by whichever substitution has taken place, but often this has not actually been proved. Dynamic studies can also set a task in its context. As they gain in complexity, control over variables becomes confined more to the inputs, and there is a greater need to measure not only inputs and outputs but other intervening states and actions that may help to trace and explain what is happening and how differences in output originate and develop. With real-time simulation, the system has become dynamic and interactive: participants can initiate actions as well as respond to them, and control over variables is confined to the inputs and to constraints within the system that curtail certain options. Measurement must be an inherently passive process, recording what takes place and not prejudging the categorisation of events. With field studies, control over inputs is generally lost also, and their measurement becomes a matter of passive recording. Prejudgment of the classification of events may be attempted but may not in fact prove to be adequate.

In general, the more preparatory experimental work with simpler techniques that precedes the real-time simulation, the more precisely the aims of the simulation can be focussed, the more the scale of the simulation can be reduced, and the clearer and more insightful the interpretation of the findings can become.

A further group of non-experimental techniques can be employed in air traffic control research and development. The planning of systems, their functions and the tasks within them requires logical analysis and description. From system objectives, broad job descriptions gradually evolve, and from these task analyses and syntheses. Many of the human factors problems to be resolved during air traffic control research and development can be derived from this procedure. Each evaluation using real-time simulation is also evolved from it. The process of conducting an evaluation is itself a very effective stimulus to plan all the procedures and instructions in fine detail. In real-time simulation, the functions studied are confined to those planned and provided for at each simulated workspace. Detailed briefing notes covering every foreseeable eventuality and function have to be written. It is a commonly expressed opinion that by the time the real-time simulation is ready to begin, most of the answers that it will provide are known from the detailed planning and thinking needed to set up the simulation. It might be highly instructive actually to test the validity of this opinion by asking those most intimately concerned with the planning of the real-time simulation to predict its outcome just before it begins. Since it is the building and conduct of the simulation that are so expensive, rather than the planning of it, perhaps many research and development purposes could be fulfilled if all the planning stages for a real-time simulation were followed but the simulation was not actually built and conducted. Much more than is often realised can be learned from the disciplined detailed logical comprehensive planning that is the essential precursor of any real-time simulation, where the success of the simulation depends largely on the thoroughness and prescience of that planning.

Closely related to fast-time simulation is modelling, which is the process of representing the system in mathematical terms. A fast-time simulation normally uses a model of the system. In the same way as much useful information can be learned from the process of planning a real-time simulation, so much useful information can be gained for fast-time simulation from the process of model building. The interaction between the model and its usage for fast-time simulation is dynamic: the findings of the simulation reflect the adequacy of the model; they can also be used to improve or alter the model.

Many hypotheses for study in air traffic control research derive from observations or experience in operational systems, and from field studies in which some of these observations are made under more formal and defined conditions. Occasionally when a major change in an operational system is made, the resultant opportunity for direct comparisons between the original and revised systems can be seized. From these comparisons, the findings from real-time simulation may sometimes be verified, any unforeseen learning difficulties can be identified, and any unwanted interactions between the use of the old and the new system are revealed. Such comparisons may be more useful for research and development purposes than for operational ones however, because the controllers are much less familiar with the revised system than with the original one, and direct comparisons between the two in human factors terms may lead to premature conclusions that prove ill-founded in the light of further experience with the revised system.

A further alternative technique, not much used either in human factors air traffic control research or in operational systems, is the case study, a detailed examination of a particular series of events as an instance of a more general category. The case study cannot itself yield findings that can be treated as scientifically valid and universally applicable in their own right, but as a technique it can nevertheless be highly productive, both in identifying topics that should be the subject of further research and development and in indicating appropriate measures if those topics are studied experimentally. This and the other techniques mentioned are not so much alternatives to real-time simulation as techniques which support it and refine it, and can make real-time simulation studies in air traffic control research and development more productive and less amorphous, because they have been focussed on the most essential issues.

## 16e THE IDENTIFICATION OF RELEVANT MEASURES AND VARIABLES

Many measures mentioned in the previous chapter are suitable for air traffic control research and development: some are seldom employed in any other air traffic control context. The identification of measures does not normally present difficulties. The appraisal of their relevance, and the judicious selection of the most appropriate group of measurements from the very large number available, require the human factors specialist to use his skills and judgment to the full, since the findings of research and development work may be critically dependent on the correct choice of measures, particularly to ensure that no vital aspect has been forgotten.

From the objectives of each air traffic control research or development programme, the measures needed to meet those objective can be specified. A major practical problem is to ensure that the objectives themselves are not so narrow that essential information remains unmeasured. When research and development deal with some innovation or advance, there is almost inevitably some uncertainty about the full range of relevant variables. In particular, the claimed benefits or expected improvements which form the rationale for the research and development itself are hypothesised in advance. Part of the role of human factors is to advise on measures to make them explicit and quantify them, to ensure that as far as possible expectations about them will be realised. The sponsors of the work will be keen to see this done and, if a technological innovation is involved, its proponents will be eager to ensure that those benefits which they believe it will bring are thoroughly demonstrated by the best measures of appropriate variables.

The human factors specialist, seeking a more balanced view, may suggest further measures designed to explore the implications of the innovation more fully and extensively throughout the system or sub-system, or designed to discover whether the innovation also brings disadvantages and to quantify these and the benefits with equal thoroughness. He is also anxious to obtain the earliest possible hints of any human factors problems that an innovation may introduce, so that he can find out more about them and form judgments about further research that may be needed and about means whereby the difficulties might be overcome.

A result of this approach is that the human factors specialist can be construed by others as consistently opposed to any innovations because he queries them and is not willing to take their benefits on trust without evidence and because he is apparently looking for sources of error and difficulty in them. He interprets this as an attempt to be fair minded, knowing that the potential benefits of an innovation are likely to have been explored with more thoroughness than its potential disadvantages. The onus of proof is on the human factors specialist to explain to others what he is trying to do, and particularly to demonstrate that he is not biased but merely trying to be impartial. If he does not adopt this stance, no-one else may. He should be able to spot some at least of the potential sources of error that an innovation brings, and ensure that measures are included to ascertain whether or not he is correct.

If a change is being proposed to try and reduce the errors from a particular source, such as phonetic confusions, errors arising from a keyboard layout, or errors characteristic of a type of input device, his role is to help to achieve and quantify this reduction if it is present. With existing equipment, the main error sources are known or at least suspected. Comparable knowledge of the errors that new equipment may bring does not exist; such error sources must not only be quantified but also discovered during the research and development programme if they are present. This implies the introduction and use of specially tailored human factors measures for new suspected error sources. Some of these measures may not have been used before but are chosen because they are appropriate for the innovation. The human factors specialist may then go on to advise on how comparisons between different kinds of error (e.g. phonetic confusions in speech versus visual misreadings of displays) should be made to be as fair as possible.

In air traffic control research and development, the familiar problems of reconciling apparently contradictory findings from different measures, of interpreting the results of different measures in relation to each other, and of decided the most suitable weightings for different kinds of evidence have to be resolved[89]. Since the difficulties are inherent in the nature of different measures, no new problems normally arise in research and development that cannot occur elsewhere. Despite these customary obstacles to the integration of different measures, it is advisable in research and development wherever possible to employ more than one kind of human factors measure, because the risk is high of obtaining seriously distorted and limited findings from too narrow a range of evidence.

It can be difficult to convince others that sometimes peripheral or apparently trivial measures may be most sensitive in air traffic control contexts. This applies particularly to measures of capacity, workload, and similar notions, where the validity of any measure is unlikely to be impressive in any case. Because many air traffic control tasks can to some extent expand to fill the time available and contract when time is short, and because many functions can be postponed for a time, omitted temporarily, or fulfilled in an abbreviated form, the most fundamental measures of task performance may show very little as loading is increased. One approach to this is to consider those revisions of tactics as themselves indices of loading[57]. Another is to measure carefully those peripheral actions that can be dispensed with, to see when they are. In heavy loading, the least important aspects of air traffic control tasks are affected first. These therefore may constitute the most sensitive measures of loading, and they may have to be measured with most care. It can puzzle other people when, for this reason, the human factors specialist appears to spend a disproportionate amount of time carefully examining measures of trivia. Nevertheless, for some research and development purposes in air traffic control, this can be a sensible approach.

## 16f THE RELIABILITY AND VALIDITY OF EVIDENCE

The value of evidence depends on its reliability and validity. Reliability refers to consistency, either internal consistency in that a measure is always measuring the same thing, or repeatability in the sense that if something is measured again with the same measure the result will be the same. Validity depends on whether a measure actually does measure what it purports to measure.

Human factors evidence varies greatly in both reliability and validity. Normally, validity is the greater problem. Reliability can be established by studying the measure itself: validity needs some independent external criterion which must itself possess both reliability and validity. In air traffic control, such criteria can be difficult to find, and their own validity may be suspect.

These problems are serious when air traffic control is measured directly. In research and development work, there is the additional problem of extrapolating from the controlled and specified conditions of an evaluation, simulation or laboratory, to real-life. A notorious source of unreliability concerns traffic samples used in air traffic control research and development. Even when they have been equated on all known major dimensions, they may still not be of equivalent difficulty when used in a real-time simulation. It is uncertain how difficult they would be in real-life. A measure that is consistent, and therefore reliable in evaluations, may not yield the same results in real-life, and its validity as a measure of real-life conditions decreases as the magnitude of the discrepancy between the results under real-life and simulated conditions increases. Thus air traffic control research and development bring extra problems of reliability and validity of data.

A major human factors contribution is to advise on the reliability and validity of human factors evidence, findings and conclusions, and to act accordingly in that the persistence and confidence with which human factors recommendations are made should reflect the reliability and validity of the evidence upon which they are based. The reliability and validity of human factors data can cover almost the entire possible range. Certain kinds of evidence gained during air traffic control research and development possess very high validity for real-life conditions: examples are reach and viewing distances, the principles for fitting console profiles to anthropometric data, the characteristic types of error associated with well-known data input devices, or the adverse effects of gross departures from tolerable physical and environmental conditions on performance. Other kinds of evidence from research and development conditions may possess poor validity for real-life: examples are effects of emotional state on performance, the role of peer pressure, responses to emergencies, or subjective assessments of boredom. Perhaps the most awkward kinds of evidence concern measures where validity is thought to be high and in fact may be low: examples are system capacity, maximum tolerable task demands, workload, and many measures and procedures used in selection. Another awkward category concerns unpalatable findings where the measures are blamed for the absence of expected evidence, although the measures may in fact be quite valid: examples are studies of the effects of stress, of work-rest cycles, and of sleep patterns on air traffic control efficiency and safety.

Although a great deal of human factors guidance can be given on the reliability and validity of most measures of the controller used in air traffic control research and development, and indeed measures of uncertain value should not be employed if they can be avoided, it is essential to try and establish the reliability and validity of measures wherever possible, rather than merely use them and hope that they are what they seem. The whole issue of the validity of human factors evidence in air traffic control deserves far more attention than it has received. Sooner or later two main problems will have to be faced and resolved. One concerns the quantification of the validity for real-life conditions of the findings from specific air traffic control measures when used in evaluations. The other concerns the derivation of highly valid criterion measures, the quantification of their validity, and the specifications of conditions under which their validity is impaired. The low or uncertain validity of independent criterion measures currently ensures that the validity of many other measures remains low, and therefore constitutes the greater problem.

16g THE INTERPRETATION AND DISSEMINATION OF FINDINGS

An evaluation or simulation is of practical use to the extent that its findings are implemented or influence events and decisions. It must be counted as a human factors failure that many of its findings have been inadequately publicised in the past, and that their influence is often difficult to trace. A report of each evaluation is routinely written for its sponsors. The human factors contributions are normally incorporated in the routine report, and their relative significance varies greatly according to the objectives of the evaluation and the legitimate role of human factors in it. In the few instances where the human factors contribution is the major one, the report may be substantially concerned with human factors, or a human factors supplement to it may be issued. These routine reports should include the human factors interpretation of the findings, as well as the findings themselves. This interpretation should go some way beyond the findings, and consider aspects such as their generality, possible theoretical implications, permissible extrapolations beyond the strict confines of the evaluations, and further issues that have come to light during the evaluation but not been resolved by it. In general, the human factors specialist makes the best use he can of his professional knowledge to promote the objectives of the evaluation.

Often the dissemination of findings ends there. The report has a limited official distribution and is perhaps also sent to a few professional colleagues. Even this does not always happen, either because the human factors specialist has no inclination to publicise his findings further or because the organisation for which he works discourages wider publication. Some accounts, even of quite recent work, seem to vanish without trace or their sources remain very obscure so that the standard methods set up by libraries and other agencies for information retrieval often fail to find them.

Even research and development work on an abandoned air traffic control system may have human factors interest, particularly if the findings are related to those of other studies. If findings, including failures, are not widely known, a body of human factors evidence cannot accumulate, and opportunities to generalise findings are lost because their generality never becomes apparent. Sometimes a report on an evaluation or on contracted work takes years to appear, for reasons which remain totally obscure. They cannot be explained by the contents of the report when it finally appears, but look like bureaucratic pussyfooting. After such a protracted delay, findings have often lost much of the interest and practical value they ever had.

Such delays in the dissemination of information are not in the interests of research and development, particularly since human factors expertise is in short supply and many human factors problems in air traffic control originate from technical innovations and therefore arise in several countries in similar form at about the same time. Everyone can benefit when findings are widely and quickly publicised. This can help to avoid unnecessary duplication of effort within the limited human factors resources that exist, and ensure that everyone concerned with human factors in air traffic control research and development has the widest possible knowledge of all relevant work, not only in terms of findings but also in terms of methods, not only in relation to successes but also to failures. Conclusions that cannot be drawn from any single evaluation may often be drawn from a series of evaluations because they can be seen to be general. Appraisals and reviews can be of great value to others, provided that they reach a wide readership.

The human factors specialist should not take it for granted that others know and understand his findings and achievements. He must be prepared to explain his methods and conclusions, and their significance. This entails the dissemination of his findings not only in the human factors literature but also in professional air traffic control literature and in the professional journals, conferences, and gatherings of other disciplines with which he collaborates. It can be difficult for the human factors specialist to find time for such activities, but they are a vital aspect of interdisciplinary collaboration and the human factors specialist who attends interdisciplinary gatherings learns a great deal as well as teaches. The human factors specialist who purports to know something about learning, knowledge, memory and the acquisition of information should use this knowledge to inform others of what he does and to set up more efficient means for the organisation and dissemination of his own professional work.

# CHAPTER 17

## ADDITIONAL FUNCTIONS WITHIN THE AIR TRAFFIC CONTROL SYSTEM

### 17a GATHERING DATA

Almost all the human factors work in air traffic control has concerned controllers. There are further human functions within the air traffic control system to which human factors principles should be applied. A few of those are indicated briefly in this chapter. The aim is to draw attention to them rather than to provide full details about them.

Many people are employed in air traffic control to gather and sustain the data on which the system and the controllers depend. An air traffic control system may gather data from various sensors and aids, from aircraft, from automated computations, from controllers, from external agencies such as meteorological offices, and, in the future, from satellites. Those sources of data have to be reconciled and integrated. Although data are gathered for many purposes, such as to meet legal requirements or update the information stored in a computer, the main human factors interest is with the data that, directly or indirectly, are intended for use by a man in the performance of his tasks.

Because air traffic control systems are complex, they tend to overflow with data. The gathering of all available data can apparently become an end in itself, and its usage secondary. One example concerns data on system faults and serviceability, where every slight occurrence is punctiliously recorded with little heed to the reasons for doing so or the practical value of such a voluminous unstructured record, which as it stands may be unusable by the man for any purpose. To record and print out every fault in chronological order means that vital items can be lost in a welter of trivia, and long-term trends, such as the gradually increasing incidence of a particular kind of fault, may be impossible to spot by inspection of the printed record. This might not matter so much if logical and comprehensive facilities for selective data retrieval were also available, through a well designed man-machine interface or by other means, but because data gathering has often seemed more important than selective data retrieval, such facilities may be lacking. Much of the point of gathering data is negated if they cannot be found, retrieved and used. Ideally, it should be possible at every relevant position in the system to retrieve selectively any data needed for the efficient performance of the tasks done there, in a form and at a level of detail suitable for immediate use for those tasks. The logic of the man-machine interface should enable the man to deduce easily and correctly what he must do to obtain the selected relevant data about any pertinent question, even one that he has never had to ask before. This applies to the interface for the controller: it is even more vital for those who monitor, test, calibrate, maintain the integrity of, repair, or replace the hardware or software of the system.

Those who work behind the scenes, as it were, in air traffic control need the same general ergonomic advice about their workspace, its layout, lighting and physical environment as is provided for the controller. Their furniture must meet ergonomic requirements, with all controls within reach, and displayed information clearly visible and at the most appropriate level of detail. The same principles, though not the same detailed solutions, apply to general wall-mounted displays, to mimic diagrams, and to other ways of depicting the system for purposes of checking and maintaining its integrity and reliability, and of ensuring that the data that should be gathered are gathered. Visual and postural problems for operators must be avoided. If a maintenance job is peripatetic, dials and information displays should be concentrated at or just below head height, to maximise their legibility, minimise unwanted parallax effects which may lead to errors when they are read, and eliminate unnecessary stooping or stretching as the man takes readings or makes visual checks while he moves about. The same principles of grouping information displays to facilitate task performance and appropriate cross referencing between them also apply. The type, sensitivity and location of controls should be optimised for the man's tasks and functions in data gathering, system maintenance, fault finding and allied jobs.

Many tasks concerned with the functioning of the air traffic control system include man-computer dialogues, decision trees, flow diagrams, and similar aids for obtaining and interpreting information. They too need to be optimised for human use. The general human factors findings on these topics can usually be applied in air traffic control contexts. Work designed to improve the efficiency and reliability of computer programming is also relevant, especially that related to the advantages and disadvantages of different computer languages in terms of their fitness for the purpose, the errors that the man commonly makes when employing them, and the amount of training and experience that the programmer needs to become proficient in using them. Principles to optimise man-software interactions are still being developed[131], but some are already available, and rapid advances can be expected which should apply to the writing and usage of software in air traffic control systems.

### 17b THE MAINTENANCE OF SYSTEM INTEGRITY

The quality of the controller's radar picture depends on the knowledge, skill, competence and equipment of engineers who install and maintain the radar, and keep it serviceable and optimally adjusted. They in turn have tasks of monitoring, checking, fault diagnosis, replacement and testing of components, and other functions that involve a man-machine interface, suitable information displays such a mimic diagrams and totes, appropriate controls and tools, and manuals and other job aids. The future may bring other sources of data, for example derived from satellites or computed from a stored data base. New tasks, skills and techniques may have to be developed to optimise the quality of the data from these new sources, and to provide sufficient information about the factors that can affect quality to enable the tasks of optimisation to be achieved. The man needs some form of visual or auditory feedback about the adjustments he is making and the effects that they have, before he can learn to make them more successfully and with greater refinement. It is necessary to present the data, needed by the maintenance engineer and others concerned with the integrity and reliability of the system, in a form that is intelligible and unambiguous to them, and at the correct level of detail for their tasks.

The efficient functioning of the air traffic control system depends on the reliability of the hardware components, and on the successful application of the techniques of reliability engineering to ensure that most vital components with a known limited life are replaced before they fail. Any consequences of replacements of components can then be planned for, to minimise their disruptive effects on the system. Normally replacements would be made at a time of minimum traffic demands or when the temporary use of a standby system had been arranged in advance. The intention is to minimise the occurrence of unserviceability when the system is very busy and can least tolerate the effects of any sudden unexpected breakdown. Planned maintenance in the form of replacements at known intervals requires the testing of the system once replacements have been installed, but avoids much of the elaborate fault diagnosis procedure, which can be both urgent and time consuming when a major failure occurs without warning while a system is fully operational and handling heavy traffic. With most forms of planned maintenance the system does not have to be stood down while faults are being diagnosed.

Although there is an acknowledged role for human factors in reliability engineering, it has perhaps been too narrow. It has emphasised the reliability of man as a system component when performing various types of task (a legitimate topic for study and for human factors guidance) but has neglected the role of man in the assessment procedures for establishing the reliability of the hardware components themselves. Yet the human act of withdrawing a module and inserting a replacement for it may be as important for the reliability of the system as the module itself. The extent to which ergonomic principles have been correctly applied to the design, visual coding, appearance and labelling of various modules has a major influence on the probability that the correct module for replacement is selected. The design of fitments for modules in relation to their physical dimensions and characteristics also influences reliability. It can determine whether a wrong module can be inserted, whether the act of insertion or withdrawal can damage the module or fitments, whether the installed module can be too loose and make inadequate connections, and whether skilled training for the correct handling of the module is essential. A lot of discarded modules apparently have nothing wrong with them. The disappearance of a fault when a module is replaced may be because the original module was faulty or because the new module has not been inserted in quite the same way as the original one was.

One of the most direct interactions between technical, servicing and maintenance activities on the one hand and the controller's ability to function efficiently and without error on the other is in the effects of the characteristics of a channel for verbal communication on the intelligibility of the spoken messages that it conveys. Human factors advice can indicate minimum requirements that must be met to ensure that the spoken messages do not become degraded so much that safety and efficiency are affected adversely. Alternatively, if these minimum requirements cannot be met, human factors advice can specify the best ways of circumventing this limitation to ensure that the intelligibility of the spoken information is maintained as well as it can be, by repetition and acknowledgements, and by modifications to content, format, pitch, pace, emphasis, method of speaking and choice of wording.

The way the man, be he controller or engineer, treats the system can affect its reliability. The conditions under which maintenance is done may affect its efficacy substantially. From the current state of knowledge about the effects of work-rest cycles on efficiency, it could well be that these effects are greater for maintenance staff than for controllers, if the consequences of lack of sleep, extreme tiredness, or gross disruption of circadian rhythms are more likely to appear as clumsiness, forgetfulness, irritability, and less delicate handling of equipment than as impairments of task performance or as hazards to safety. Many of the points about boredom, made in relation to controllers, apply with equal or greater force to maintenance staff. The human need for some form of activity or involvement may affect the functions of people concerned with data gathering and system integrity most acutely.

A particular problem can arise when a facility is designed to function reliably for considerable periods while unattended, yet is manned during normal working hours. This can apply for example, to radar heads. The greater the success in achieving the objective of reliable functioning while unmanned, the less useful work for the man there is likely to be when the facility is manned. Much of the residual work is routine checking, maintenance and testing, which, vital though it is, can become singularly unrewarding as a full time human occupation, particularly since some curb must be placed on testing activities. The act of testing, carried to excess, can often become self-defeating or even counter-productive, by impairing the self-same system reliability it is intended to enhance. It is partly a human factors problem to determine the optimum role for the man so that reliability is optimised by his tests and checks, which maximise the probability that faults will be detected and minimise the likelihood that his activities will generate faults.

## 17c FAULT FINDING

In recent years, one of the most dramatic changes in human roles in large man-machine systems has concerned fault finding and its relations to system integrity and maintenance. At one time the maintenance of a serviceable fault-free system relied heavily on the skills and knowledge of individuals with long experience of the specific system and its idiosyncrasies and quirks. The abilities of these individuals were often highly specific, and did not transfer well to similar systems prone to fail in different ways. However because of their long experience they were often surprisingly successful at diagnosing faults and repairing them or circumventing their consequences, so that the system remained operational. Such a role enabled the man to experience considerable pride, self-esteem and esteem from others, and he often identified himself closely with his tasks and with the system itself. Sometimes he came near to interpreting any breakdown as a personal affront. His basic tools usually included a means to measure electrical current, and a soldering iron.

Such roles are far removed from the fault finding procedures in modern systems. The skills and knowledge required now are more general and impersonal. They consist largely in the understanding and use of standardised instructions and test procedures for tracing the location of faults. It may never become necessary for the man to understand much about how the system functions or what its purpose is. The faulty unit or module, once diagnosed, is replaced. It may be repaired, but not in situ, and not usually even on site. To diagnose a fault in a module the man may not need to know what the module actually does. He may have no insight into what caused the fault or the probability of its recurrence.

He has far less personal involvement in the system within which he works, but his abilities, though generally more limited, are much more readily transferred to other systems. Since the diagnosis and correction of faults is more routine and less skilled, it may be less satisfying if the same people continue to fulfil roles of fault finding and maintenance in modern systems.

Sometimes in maintenance there is less forewarning than there once was of incipient faults and failures. Just as the controller's displays include little qualitative information as a guide to the trustworthiness of the data presented, so the displays for fault finding and serviceability states tend to be quantitative. They may show two or three serviceability states, or indicate that there is or is not a fault, but give little data about gradual drifts out of adjustment or about degrees of seriousness in a fault. This may be fair if no-one regularly concerned with fault finding has sufficient insight into the system and its functioning to understand the operational implications of the qualitative information that could be presented, but if a consequence is that many apparently sudden failures only appear so because there is no way to depict gradual or incipient ones then the common absence of qualitative and trend information for maintenance should be reappraised.

In fault finding, one characteristic dilemma remains, though in less severe form since the advent of modern methods of fault diagnosis. The more successful the efforts to prevent faults, the fewer the opportunities to gain practical experience of fault diagnosis, and the less the fault finding work to be done. Skill in preventative maintenance may therefore be associated with loss of skill in fault finding. The faults that occur may be puzzling because of their rarity, and few people may become sufficiently familiar with them to permit short-cuts in their diagnosis. While in principle the human tasks associated with modern fault finding methods can be done efficiently, the relevant attributes and skills in the man have altered so much that they should be reflected in revised selection and training procedures for those concerned with fault finding.

17d SUPERVISION

In air traffic control, as in many large man-machine systems, there have traditionally been supervisors. The supervisor, who may also be described by various synonymous terms, is in charge of a team of controllers, for whom he has some responsibility. The extent to which he actually participates in the activities of the control team is determined partly by the equipment with which he is provided, and may to some extent be left to his own discretion. Often he is the most mobile member of an air traffic control team, and may consult his fellow supervisors or other controllers within the same workspace by talking to them directly, as well as through formal communication links. There must be some basis on which his additional responsibilities as a supervisor rest: it may be greater knowledge, experience, ability or skill, access to additional facilities, participation in decisions at a higher level, or formally defined authority.

The role of supervision essentially relates to other people as distinct from equipment. Its feasibility depends on the team structure, on the allocation of functions and equipment within the team, on the information and controls that the supervisor can readily use, and on the physical position that he occupies within the suite or workspace. His role therefore tends to change with changes in manning, team structure, methods of communication and equipment. In particular the provision of various forms of automated assistance to help the individual controller rather than a team of controllers may mean that the supervisor does not have direct access to some of the aids that the controllers under his supervision are using. He therefore cannot supervise directly and effectively their usage of these aids, and may have to rely on the controller's actions and speech, and on the content of the controller's displays, to deduce the adequacy and appropriateness of the controller's actions, and to form indirect judgments about his performance.

As the tasks of individual controllers become more self-contained, as team activities become more fragmented, and as the functions of the controllers emphasise passive monitoring more than active participation, so the role of the supervisor becomes more difficult to sustain effectively, since the tasks themselves gradually become less amenable to supervision. If the supervisor cannot have direct knowledge of all the information that the controller is using, the rationale for his effective intervention is severely curtailed, and the feasibility of supervision becomes dubious. Ultimately, supervision in its traditional form can become impossible in highly automated systems, and some plans for air traffic control teams reallocate functions between the team members, recast the team structure and generally reduce the numbers in each team, and dispense with the supervisor altogether. The controller may assume certain supervisory duties, but of equipment rather than of people.

It does not follow because someone called a supervisor is present, that the tasks of supervision must therefore be possible. Successful supervision is not serendipitous or a matter of labelling but the result of careful planning. The precise division of responsibilities between the supervisor and controllers has to be clear, and there must be no chance that a vital action could be omitted because each thought that the other was doing it. The supervisor is an integral part of the team he is supervising, and his role must be designed from the outset as part of the team structure. Equipment is allocated to him on the same principle as to others, to enable him to do the tasks assigned to him. His role can be a roving commission if it has been designed to be. He can help to relieve the load on an overburdened controller provided that the need for this has been foreseen in the design of the suite and team functions. This entails appropriate provision of equipment and space for the supervisor in the suite and appropriate task design so that the supervisor can intervene efficiently, do some of the controller's tasks in parallel, and not cause duplication, confusion, errors, or omissions, or interrupt or distract the controller while he is busy. On comparable principles, the supervisor can be designed out of the system, provided that all the functions defined as essential for safe and efficient air traffic control, and which were formerly the responsibility of the supervisor, can be reallocated among the members of a restructured control team, again with clearly defined divisions of responsibilities and all the required information and equipment at each position.

17c ASSISTANCE

Progressive automation of the air traffic control system may affect the roles of the assistant and of the supervisor in quite similar ways. As the controller relies more on man-machine relations and man-software relations than on collaborative functions with his colleagues, the feasibility of shared or delegated tasks is diminished. The latter inhibits the supervisor's ability to pass on tasks to the controller, and limits the controller's ability to pass on tasks to an assistant. Furthermore, many of the traditional roles of assistants have themselves been changed by automation, or can be. Most conspicuous is the demise of flight strips. Originally the assistant prepared and delivered these by hand; then there were automatically prepared strips, still delivered by hand; now at many control positions there are electronic data displays containing the equivalent of flight strip information assembled and presented automatically. Some of the functions of the assistant in assembling data and in obtaining information by telephone can also yield to more automated means for gath[illegible]g and presenting the equivalent information.

A further trend is for the controller himself to perform some functions that could in principle be delegated. The commonest reason for this is that the controller takes no longer to perform the actions himself than would be required to explain to someone else what he wanted to be done. If someone else does a delegated task, the controller has the additional task of integrating the outcome of that task into his own knowledge of what is happening, whereas if he performs the task himself it is already integrated substantially with his other functions and information. This line of reasoning seems to apply to many data entry tasks. They can prove burdensome to the controller while he is still acquiring proficiency with a data entry device, but once full proficiency with the device has been achieved they may ultimately become as easy to perform concurrently with other associated control tasks as speaking and radar viewing are to the experienced controller in current systems.

The role of the assistant changes with the introduction of computer aids, and his functions, concerned as they often are with data presentation, data entry, and communications support, can be among the first to be affected by aids. The changes that affect the assistant directly have implications for the controller too, and do not leave him unaffected. The role of assistant cannot be settled in isolation, any more than that of the supervisor can be. As the controller's functions become more self-contained and autonomous, effective means of assistance are more difficult to devise and integrate into the system as a whole. The problem has to be tackled in terms of the full air traffic control team, and suitable roles for assistants, if there are to be any, must be devised within the framework of the team structure and the allocation and grouping of all functions among team members.

To call someone an assistant does not guarantee that he can assist: the specification of suitable tasks for an assistant, the provision of all necessary means to carry them out efficiently, and the successful matching of those tasks with those of all the other team members may do. Divisions of responsibility have to be clear. The tasks must all fall within the constraints set by the assistant's more limited knowledge and training, and they should enable him to develop and exercise skills at an appropriate level. Obviously, it is sensible, efficient and usually cost-effective to delegate from the controller all possible tasks, but there may be a penalty in the controller's reduced understanding of what is happening if the process is carried too far or if the assistant's duties cannot be matched successfully with those of the controller. It may also be more difficult for the assistant to subscribe wholeheartedly to all the professional norms and standards of air traffic control as a profession, if his job in his own eyes is peripheral to it rather than wholly within it.

# CHAPTER 18

## FUTURE TRENDS AND PROBLEMS

More than ten years ago, an attempt was made to identify some neglected human factors problems in air traffic control[158]. It is disheartening to discover how many are still neglected, although salutary to be reminded of how much still needs to be done. The future of human factors work in air traffic control is difficult to predict: the ideal would be a gradual planned long-term expansion of effort, and in some countries this appears to be the intention. Elsewhere, there seems more likely to be either a continual call for more human factors work coupled with a marked disinclination to finance it, or an edict that from henceforth there shall be an immediate gross increase in human factors work, a sure guarantee that some of it will be incompetent since the number of truly experienced human factors specialists in air traffic control is far too small to accommodate the training commitments of such a massive and sudden expansion. Some false dawns, innocently naive proposals, and irredeemable muddles seem inevitable consequences from time to time of the apparent belief in some quarters that those who work only rarely on human factors problems in air traffic control or come fresh to them must know more about them than those who have worked regularly or full-time on them for years. As an aftermath of the resulting disillusionment, the specialist in human factors in air traffic control sometimes has to try and pick up the pieces, restore the good name of his discipline, and demonstrate, if he is given the chance, that human factors work can be highly competent, good value, productive and practical. Fortunately there have been enough successful applications of human factors in air traffic control for this to be readily demonstrated.

In the future, the application of established human factors knowledge to solve air traffic control problems should be progressively expanded, to encompass not only the routine incorporation of well-known solutions based on existing evidence, but of novel solutions based on new evidence gathered because assumptions have been challenged and examined afresh. One such assumption concerns the allocation of functions to man or to machine, when many principles, including safety, the origins of errors, the maintenance of attention, and the practising of skills, all suggest that there may be advantages if man and the machine fulfil the same functions in parallel independently wherever possible. Another assumption is that it must be possible to maintain a man's attention indefinitely if only the means to do so could be found, whereas realism indicates that this aim is ultimately unattainable, and that safety should not be predicated on an untenable assumption. The notion that the role of man should be adapted to fit technology seems at variance with the optimum use of man's unique attributes of flexibility and ability to innovate. It leads to roles for which the man is unsuited, or in which he is inefficient and sometimes potentially unsafe. Automated aids are most successful when they do not belie their description but do offer assistance and help for the man's cardinal role. A future trend should be to keep the man active, occupied, busy and involved in air traffic control tasks. The alternative is to remove him from them altogether. Technology should be enlisted to develop satisfactory roles, where the criteria include the effects of the system on the well-being and interest of the man, in the belief that such factors are significant for safety and efficiency. The basis of such relationships does however need further exploration.

A more effective synthesis of theory, constructs and practice is required, and should be reflected in better integration of experimental techniques such as paper and pencil studies, laboratory experiments, dynamic and interactive explorations, simulations and evaluations, and real-life measurements, and of these experimental techniques with others such as fast-time simulation and modelling. Basic work is still needed on how these techniques are best used, what kinds of question they can answer most validly, and which methods of integrating their findings are most productive.

Technological advances and developments in hardware and software introduce new kinds of dialogue. There is widespread ignorance about how these should be optimised, and current dialogues are probably very far removed from the optimum for human use in their present form. They also bring new forms of error, and new kinds of potential failure. The point is still insufficiently recognised, in relation to error, that decisions about the designs of displays, controls, communications, the man-machine interface, and the workspace predetermine most of the types of human error that are possible, and most of the specific errors that will be made.

Perhaps the information that is most essential for the controller to ensure safety and efficiency, concerns how the system functions, how it could fail, how failure could be recognised, and how recovery from failure is possible. The typical man-machine interface in air traffic control conveys very little information on any of these themes. The man-machine interface may fail to make the man's own errors apparent to him, and he may be unable to gauge the consequences of any errors that he makes, even when he can detect them. Incipient failure of the system, or data that are no longer trustworthy, may not be recognisable by the man, and perhaps qualitative information must be restored to him to serve such purposes. In some instances there has been too much emphasis on proving new technology and in developing technological principles as far as they will go, and too little regard for the effects of technology on the man himself, as distinct from his efficiency and safety as a system component. It may be that he can become highly efficient in using automated speech synthesis and recognition, but is no longer able to communicate well with real people, able to function efficiently as a member of a co-ordinated team, or able to cope with the unpredictability and individuality of others. The problems of boredom and lack of involvement may be more prevalent and more difficult to solve than the problems of stress and overloading in air traffic control, but the latter have attracted much more notice.

Air traffic control selection and training need to anticipate changing air traffic control requirements rather than lag behind them. Training may need to emphasise more the understanding of principles rather than follow worked examples and set procedures. The information presented to the controller at his workspace is not generally intelligible to other people, and is intelligible to him only because of the knowledge, understanding and skills he has acquired through years of training. These are not constant, but alter with new air traffic control requirements, equipment and demands. It is therefore not possible to evaluate novel information displays solely with reference to the controller's existing knowledge, without regard to the changes in it that may be a prerequisite for using the new information effectively, or the changes in the information that may be needed to match what the controller already knows and the habits he has already acquired. The dynamic nature of this interaction between the controller's knowledge and the information presented to him seems to have been underestimated, to the extent that serious attempts are not usually made to match the content of the controller's displays with his thought processes. So little is still known about some of these thought processes that it is uncertain how similar the thought processes of different controllers faced with the same task are. This is an insubstantial basis on which to extend the roles of information displays at the man-machine interface so that, for example, they may also make predictions or aid the man's memory.

Most aids in air traffic control are for individuals and not for teams. Their efficiency and their effectiveness are assessed primarily in relation to the individual for whom they are intended, and not in terms of their consequences for team structure and organisation. Yet air traffic control is essentially a team activity: this helps to account for its professionalism, the development of norms and standards, and the close identification of controllers with it. Many aids tend to have the incidental effects that air traffic control teams are least efficient and least cohesive when they are heavily loaded and when concerted team efforts are needed most. The progressive reduction in the role of speech, with the concommitant loss of the qualitative information that speech conveys, also may have effects on team functions that have not yet been properly established. Teams have a major influence on the formation of attitudes, a topic that has not received the attention it deserves in air traffic control, although it may be as essential to instill favourable attitudes towards an innovation or change as to demonstrate its benefits in system terms.

More work is required in air traffic control to determine the reliability and validity of human factors evidence, with particular reference to the development of satisfactory criterion measures of known high validity. Some of the commonsense and empirical assumptions that currently have to suffice do not always stand up to close scrutiny. Recommendations based on them, rather than on human factors evidence derived by scientific principles, can be misleading. The strength of evidence on which recommendations are made should often be stated more clearly than it is, to facilitate judgments on the extent to which human factors recommendations may be compromised to meet other interests, without untoward consequences.

Attempts to predict future trends and problems inevitably underplay past and current achievements. There have been some notable successes and advances in the application of human factors to air traffic control. Perhaps of most significance is the growing recognition that human factors must deal with man as a whole, that the human factors consequences of a technical or planning decision can extend far beyond its ostensible boundaries, and that all the human factors implications should be known when the decision is taken because they will all be influenced by it. The human factors specialist in air traffic control, in speculating on the future, can see that his own work will continue to be challenging and interesting, and that the problems that arise from technological innovations must be matched by equally innovative human factors solutions.

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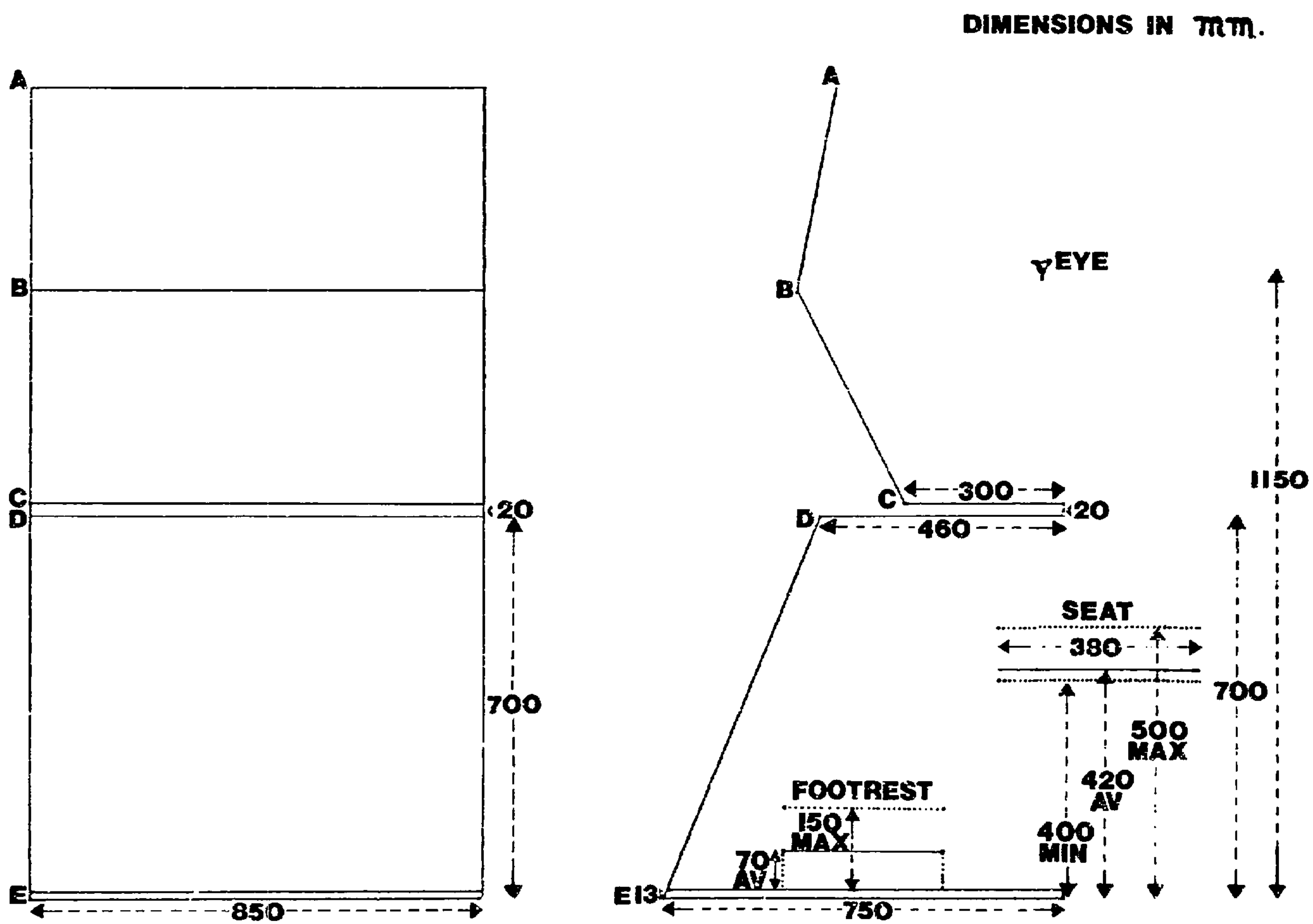


FIGURE 1. CONSOLE PROFILE: LARGE DISPLAY (SEE CH.7C)

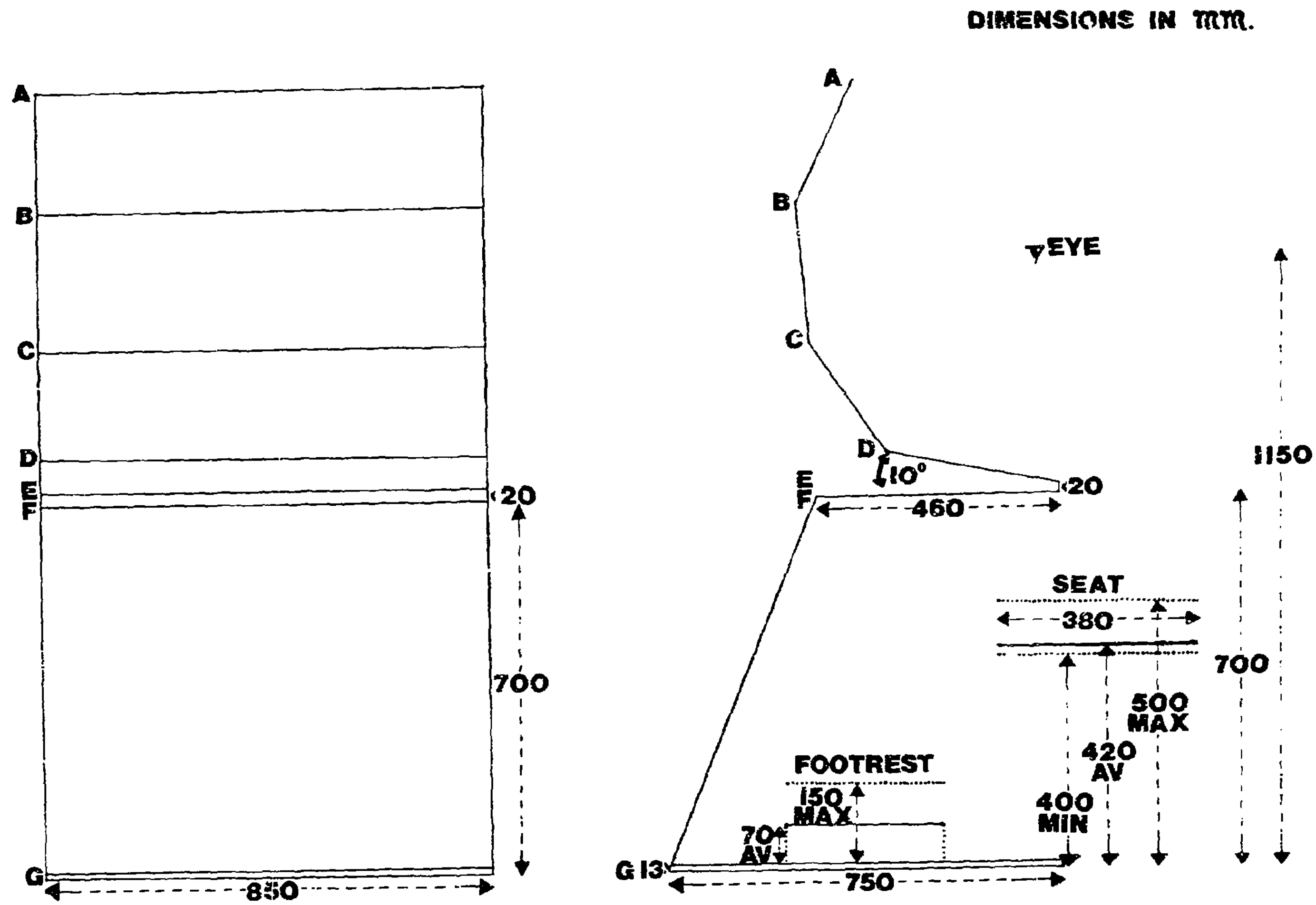


FIGURE 2. CONSOLE PROFILE: SMALL DISPLAYS(SEE CH.7C)

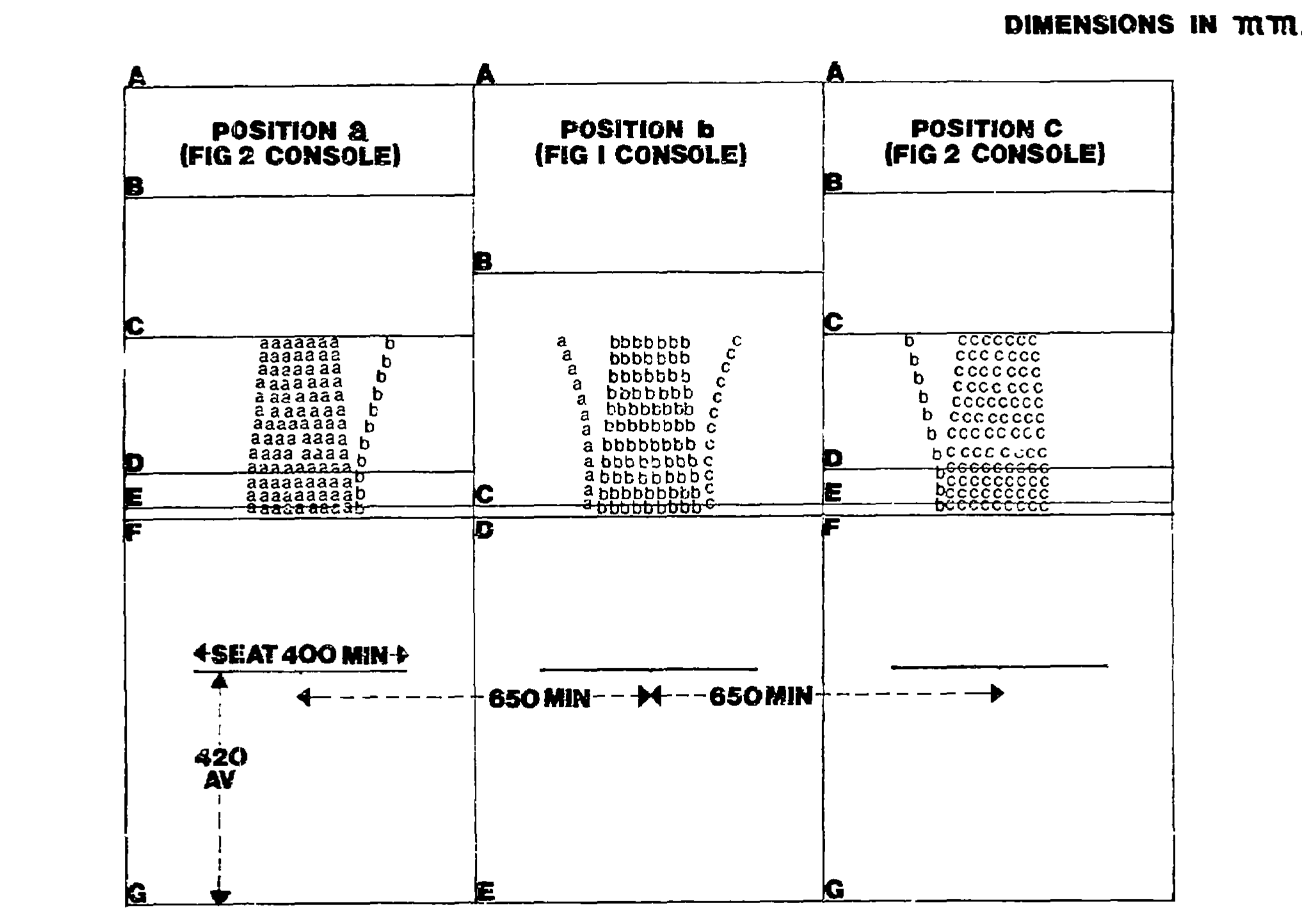


FIGURE 3. RECOMMENDED REACH LIMITS FOR EACH OPERATOR IN SUITE OF THREE CONSOLES AND RECOMMENDED REGIONS FOR CONTROLS FOR BOTH HANDS (SEE CH.7C)

Figure 4  Air traffic control (real or simulated?) with horizontal display, flight strip board, and other controls.

Figure 5  Air traffic control workspace and task performance.

Figure 6 A mock-up of an air traffic control suite for the study of layout and configurations.

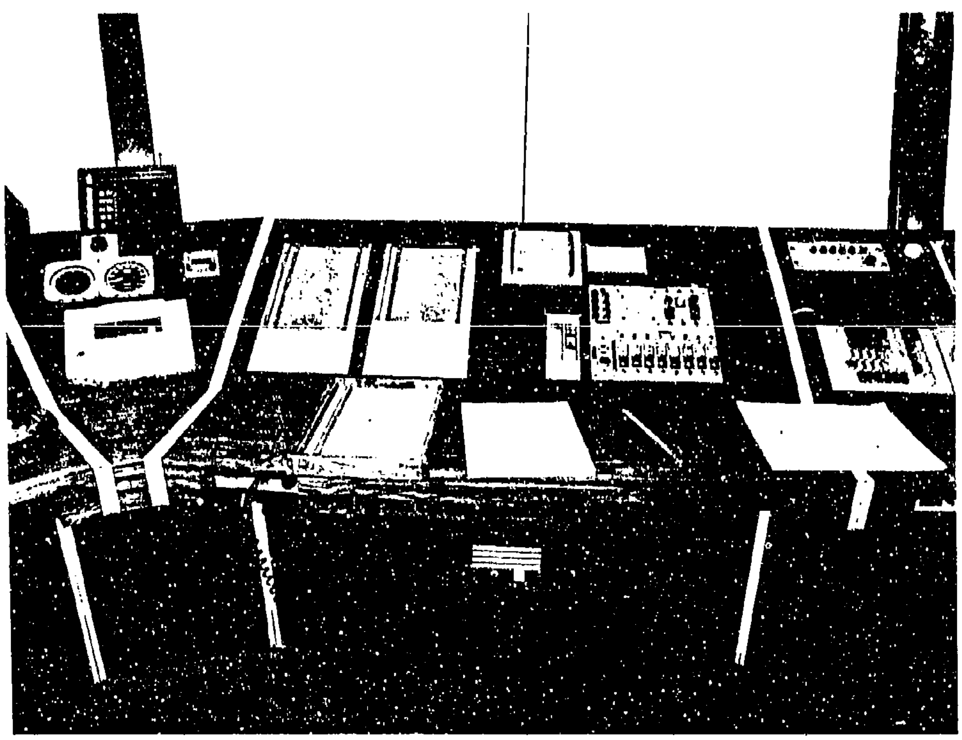

Figure 7 A mock-up of an air traffic control tower without an outside visual world.

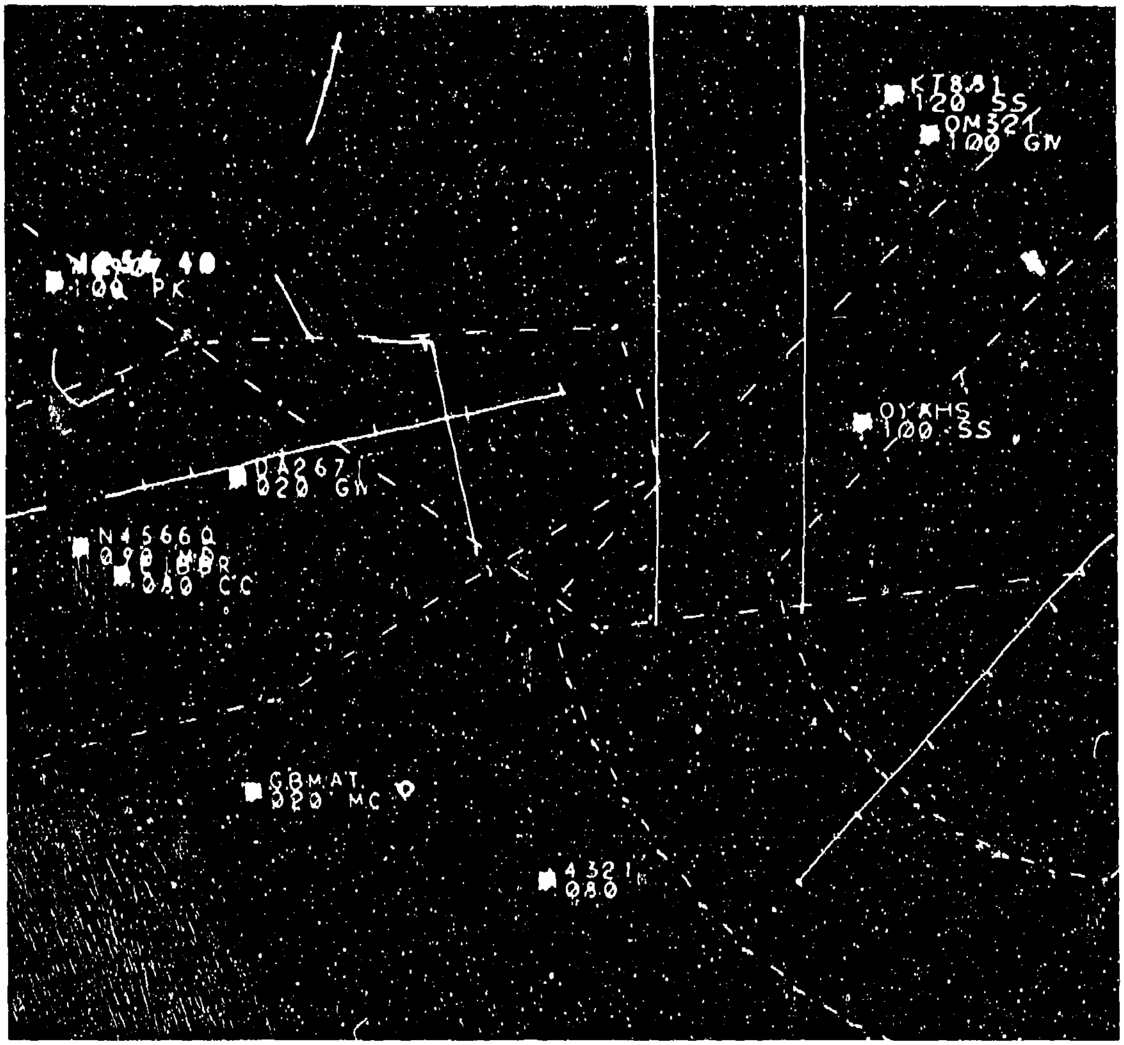


Figure 8 Alphanumerics, showing label overlap and legibility impaired by method of generation.

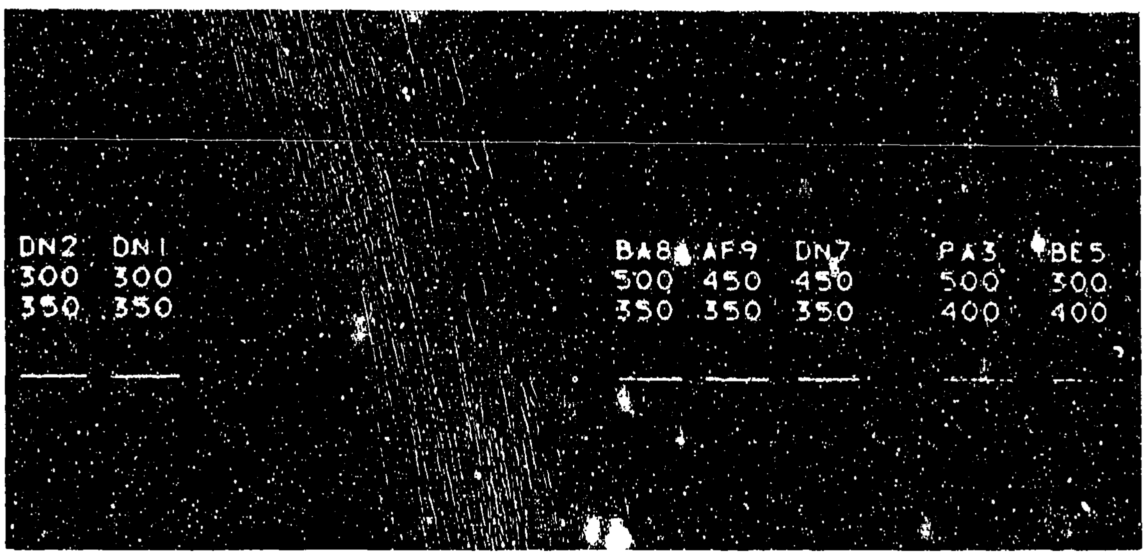


Figure 9 Alphanumerics with improved legibility.

## APPENDIX 1

## VISUAL DISPLAYS: A HUMAN FACTORS CHECKLIST

### INTRODUCTION

Visual displays have recently become much more common because of major improvements in their specification, efficiency, appearance, reliability and cost. Visual display units have now been installed in many work environments where there were none before, and the general experience of them in use has been encouraging enough to lead to their further proliferation. For many users, they offer the prospect of significant advantages, such as a more optimised work environment. In air traffic control, where displays have been familiar for decades, the new display technology offers many human factors advantages and can resolve or reduce many of the most recalcitrant human factors problems of the past.

The following is a comprehensive list of factors which can affect the interaction between the visual display and its operator, and which therefore are potentially relevant to the efficiency of the system and the well-being of the man. It is intended to serve as a checklist of factors that should be considered, and to indicate the range of influence that decisions about displays can have. The list also mentions topics which might otherwise be neglected but which should not be ignored when decisions are taken about display specifications and functions. Physical environments and technical specifications of screens differ: therefore, not every item in the list is applicable to every display.

Two general considerations should guide the use and interpretation of this list: the first is that in many contexts visual displays have now been in use for some time without giving rise to any human factors problems so that in principle the human factors requirements for visual displays can generally be met; the second is that human factors considerations are essentially interactive so that a decision on any single item in this list is likely to influence others, and no decision on an item should be taken in isolation without regard to its ramifications for other items or without specialist human factors advice.

Because human factors interact, no single logical principle can establish an ideal order to be followed whenever the listed items are considered. For some purposes, it may therefore prove advantageous to consider the main headings in a different order.

Normally, the human factors recommendations for a specific context are a function of characteristics of the visual display, the physical environment, the workspace, adjacent facilities, the tasks and the operator. Therefore this list does not, and cannot, include recommended optimum, minimum, or maximum figures. Any sources which give firm figures without qualification should be treated circumspectly. Most probably, the figures have originally be derived for a specific environment other than air traffic control.

The optimum almost always depends on particular circumstances: to take the first item as an example; there is no single optimum screen size for all tasks, environments, workspaces and operators in air traffic control. However, for each specific context the most appropriate size can be determined, given the relevant evidence.

### CHARACTERISTICS OF THE VISUAL DISPLAY

#### Physical Aspects

- Screen Dimensions
  - Size
  - Shape
- Screen Surface
  - Surface texture
  - Reflectance
  - Optical filters
  - Curvature
  - Susceptibility to glare
- Phosphor
  - Colour
  - Persistence
- Safety
  - Standards and legal requirements
  - Radiation
  - Ionisation
  - Shielding
  - Electrical

#### Visual Attributes

- Picture Quality
  - Luminosity
  - Contrast
  - Clarity
  - Stability
  - Oscillating luminance
  - Irradiation

- Sources of Discernible Picture Instability
    - Drift
    - Blur
    - Swim
    - Shimmer
    - Flicker

Visual Coding (Psychophysical Variables)

- Dimensions
    - Point
    - Line
    - Area
    - Volume
- Shape
    - Symmetry
    - Labelling
    - Symbols
    - Alphanumerics
- Size
- Texture
- Contrast
    - Brightness
    - Inversion
- Colour
    - Dominant wavelengths (Hue)
    - Chroma (Saturation)
    - Value (Brightness)
- Stability
    - Movement
    - Apparent movement
    - Blinking
    - Flashing
- Additions to Codings
    - Lines
    - Boxes
    - Asterisks etc
- Absence of Information

Picture Generation

- Maximum Amount of Information
    - Consequences of trying to exceed maximum
- Renewal Rate
    - Sequence of renewal of displayed items
- Principle of Drawing
    - Dot
    - Matrix
    - Line
    - Analogue
- Size of Units
    - Smallest possible change
    - Smallest discriminable change
- Capabilities
    - Pictorial
    - Graphic
    - Symbolic
    - Alphanumeric
- Limitations
    - Dots
        - Discriminable clusters
        - Discriminable separations
    - Straight lines
        - Length
        - Jaggedness
        - Angles of lines on display
        - Minimum change of angle
    - Curves
    - Circles
- Inversion
- Colour
    - Number of colours
        - Interdependence of colours
- Light output
- Number of Horizontal Lines on Screen
    - Number of points per line
- Maximum Number of Rows of Characters on Screen
    - Maximum number of characters per row

Character Design

- Alphanumeric Characters
  - Font (general design, equivalent to typeface)
  - Case
    - Upper
    - Lower
      - Body
- Symbolic Characters
  - Conspicuity
  - Discrimination
  - Labelling
  - Meaningfulness
- Proportions of Characters
  - Height (of characters, equivalent to point size)
  - Width
  - Height/width ratio
  - Stroke thickness
- Gaps
  - Between adjacent characters
  - Between rows of characters
  - Grouping of characters within and across rows
  - Grouping of rows
    - Divisions between groups of rows
  - Grouping of columns
    - Divisions between groups of columns

Adjustable Variables for Setting-up the Display

- Variables
  - Brightness/Contrast
  - Scale
  - Colour
  - Focus
- Tolerances
  - Adjustments independent of physical environment
  - Adjustments matched to visual environment
  - Variability of the visual environment
- Range of Adjustment
  - Operator's preferences
  - Nature and extent of possible mismatches with environment

THE OPERATOR'S WORKSPACE

The Console

- Structure
  - Bulk
  - Effects on workspace
  - Loadbearing supports
  - Accessibility for maintenance
  - Constraints on housing of display and control facilities
- Profile
  - Shelf height
  - Shelf slope
  - Shelf thickness
  - Shelf depth
  - Angle of visual display in relation to horizontal or vertical
    - Size of visual display
  - Angle of other displays within console
    - Size of other displays
  - Flight strip boards
  - Console height
- Operator's Position
  - Anthropometric data
    - Range of body sizes
    - Choice of percentiles to determine design range
  - Seat height
    - Seat adjustment
    - Texture
    - Back support
  - Seat width
  - Seat depth
    - Seat slope
  - Thigh clearance
  - Knee room
  - Leg room
    - Footrest
  - Viewing height
  - Viewing posture
    - Slump

- Viewing distance
- Viewing angle
- Provision for Ancillary Equipment and Job Aids
  - Location
  - Handling
  - Stowage
    - Retr... and replacement

**Man-Machine Interface**

- Positioning of the Visual Display
  - In relation to other displays in the immediate workspace
  - In relation to general wall-mounted displays
  - In relation to job aids
  - In relation to other sources of information (e.g. text, computer print-out, etc)
  - Fixed or adjustable location of visual display position or angle
  - Controls for the visual display picture
- Other Displays
  - Wall displays
  - Displays on the suite
  - Flip strips
  - Displays for use by individuals or teams
  - Displays within operator's workspace
- Controls
  - Type
  - Sensitivity
  - Positioning
  - Reach distance
  - Function
  - Labelling
  - Control-display relationships
    - Displayed information on control states
    - Markers on displays
    - Control state as indicated by controls
    - Display state as indicated by controls
  - Controls for other displays and functions
- Communications
  - Speech
    - R/T
    - Telephone
    - Direct speech
  - Facilities
    - Location
    - Labelling
    - Stowage
    - Usage
- Surface Textures
  - Console
    - Materials
    - Colour
    - Reflectance
  - Control panels and controls
    - Materials
    - Colour
    - Reflectance
  - Other displays
    - Materials
    - Colour
    - Reflectance
  - Other facilities

**Compatibility**

- Display/Display
  - Contents
  - Layout
  - Codings
  - Methods of selection
  - Indications of malfunction
  - Light output
  - Viewing distance
  - Visual accommodation
  - Visual acuity
  - Eyesight standards
- Display/Control
  - Associations between the visual display and controls
  - Associations between other displays and their controls
  - Compatible controls for equivalent display functions
  - Location of controls to show display/control relationships

Control/Control
- Relative positions of panels
- Location of each panel
- Similarity of layouts, functions and logics in different panels
- Variety of control types
- Variety of control sensitivities
- Variety of control codings

Possible Misuses

- Visual Display Information
- Controls
- Facilities
- Equipment
- Environmental Features

THE GENERAL WORK ENVIRONMENT

Physical Environment

- Air Temperature
- Humidity
- Ventilation
- Air Flow
- Radiation
- Noise Levels
  - Type of noise
    - Continuous/intermittent
    - Frequency
    - Amplitude
  - Sources of noise
    - Voice
    - Movement of people
    - Equipment
    - Fans
  - Absorption of noise
    - Floor coverings
    - Ceiling coverings
    - Walls (plaster, curtaining, etc)
  - Headset acoustic properties

Room Lighting

- Adjustability
  - Controlled (no daylight)
  - Variable (daylight or exterior darkness)
    - Range of variability
  - Additional lighting requirements (e.g. for cleaning; maintenance)
- Range of Levels within Room
  - Pools of light
  - Pools of darkness
  - Reflections
  - Glare
  - Light sources directly visible from work positions
- Positioning of Light Fitments
  - The visual display
  - Other displays
  - Job aids
  - The operator
  - The team of operators on a suite
  - The location of suites
  - Controls and control textures
  - Surfaces of equipment and consoles
  - Ceiling, walls, and floor
- Wavelengths (Spectrum) of Room Lighting
  - Relationship to phosphor
  - Appearance of visual display
  - Appearance of other displays
  - Appearance of hard copy
- Supplementary Local Lighting
- Visual Textures
  - Effects of room lighting on appearance
- Relations to Visual Eyesight Standards

Room Layout

- Positioning
  - Relative location of suites
  - General displays
  - Inter-suite liaison
  - Seeing relevant activities and information
  - Not seeing irrelevant activities and information

- Accessibility
    - Handovers
    - Training
    - Cleaning
    - Maintenance
    - Disruptions caused by inadequate accessibility
- Suites
    - Flexibility of plan for suite operation
    - Flexibility of manning
    - Juxtaposition of visual displays within suites
    - Placing of individual workspaces within suite
    - Provision for supervisors
    - Provision for assistants
    - Provision for training on suite
    - Provision for extra manning
    - Bandboxing and combining functions
    - Flexibility of allocating suites to functions
    - Combinations of suites
- Provision for Movement
    - Within individual workspace
    - Within suite
    - Within room
    - To and from room

Off-Watch Facilities and Amenities

- Relations to Workspace
    - Location
    - Proximity
    - Physical environment
        - Lighting
        - Heating
        - Ventilation
- Types of Facilities
    - Canteens
    - Dispensing machines
    - Restrooms
    - Toilets
    - Lockers

TASKS

Choice of Visual Display

- What is the Purpose of the Visual Display?
    - What alternatives to a visual display have been considered?
    - Why have other alternatives been rejected?
    - Why has the particular visual display been preferred?
    - What positive advantages does the visual display have over alternatives?
    - What disadvantages does the visual display have compared with alternatives?
        - How can these disadvantages be minimised?

Tasks as Determinants of Usage

- Sources of Data
    - Visual display exclusively
    - Other sources
        - Visual
            - Other visual displays on suite
        - Wall displays
        - Hard copy and print-outs
        - Job aids
    - Auditory
- Extent of Usage of Visual Display
    - Full-time
    - Part-time
        - What proportion of time is spent with the visual display?
        - What is the visual display usage shared with?
        - How long is the visual display viewed continuously without looking elsewhere?
        - What is pattern of usage among displays?
        - What will consequent pattern of head and eye movements be?
        - Will this pattern generate any postural and visual problems?
        - Can the workspace be optimised for this pattern of usage?
        - Can the physical environment (especially the lighting) be optimised for this pattern of usage?
- Main Influences on the Pattern of Usage
    - The operator
    - The task
    - The appearance of information on the visual display
    - The appearance of information elsewhere
    - Auditory information
    - The timing of machine events

Other factors

Task Groupings

What are the tasks to be performed by each operator?
How have they been allocated to the operator?
How have tasks been grouped together?
How has the grouping of tasks influenced the choice and location of the visual display and of other displays?
Has a job analysis been conducted?
Are the tasks all clearly defined?
What can the operator improvise?
Is it intended that he should be flexible?
To what extent must he adapt to the system?

Tasks and Contents of the Visual Display

Does the operator mainly respond to events on the visual display so that its content largely determines his actions?
Does he mainly initiate events so that the visual display content is a response to his actions?
How much of the information on the visual display can the operator himself generate?
How have the tasks influenced:
The type of display chosen?
The amount of information on the visual display?
The layout of information within the visual display?
The choice of information codings?
Is the information on the visual display dynamic or static?
Is it necessary to discriminate between these on the display?
Is the information on the visual display temporary or permanent?
Is it necessary to discriminate between these on the display?
Is the updating of information generally manual or automatic?
Is it necessary to discriminate between these on the display?
Is the introduction of new information generally automatic or manual?
Is it necessary to show that information is new?
Does the conduct of the task automatically determine the visual display content?
Does the operator have to select appropriate visual display contents depending on task progress?
Does the task require selective call-down of information?
Is all the information required for the task available on selective call-down?
Can the operator retrieve all the data which the task demands?
Can the operator cancel any data?
Can the operator cancel data selectively?
Is there a need for an automatic reminder to cancel data?
Is there a need for an automatic reminder that data have been cancelled?

Functions

In relation to the Task Demands, does the Visual Display Function as:
An information display?
A memory aid?
A problem solver?
A decision maker?
An attention getter?
A predictor?
A feedback of the effects of actions?
A teaching aid?
An indicator of requirements?
A warning indicator?
An indicator of delays?
An indicator of errors?
An indicator of omissions?
An indicator of system status?
An indicator of task progress?
An indicator of serviceability?
A summary?

Human Limitations

Is all the Information which Job Analysis shows to be Necessary on the Display Presented in Most Usable Form in terms of:
Its rate of presentation?
Its order of presentation?
Its level of detail?
Its total amount?
Its level of collation and integration?
Its use of codings?
Its use of meaningful symbology?
Its use of the operator's existing knowledge?
The minimising of errors, delays and omissions?
The requirements for the acquisition, development and exercise of skills?
The provision of adequate knowledge of results and of progress?

What Information Required for the Tasks Cannot be Presented on the Visual Display or Obtained from Other Information Sources?
- What provision has been made to provide this information?
- What are the consequences for task performance of not providing it?

In What Respects Does Task Performance Rely Not on Information Displayed on the Visual Display or Available Elsewhere, but on the Following Attributes of the Operator?
- Knowledge
- Experience
- Training
- Obeying instructions
- Following procedures
- Memory
- Understanding
- Interpretation
- Prediction

What Information Appears on the Visual Display:
- Automatically whenever it occurs?
- Optionally, depending on circumstances?
- Never, unless the operator puts it there?

Flexibility and Visual Display

How Variable are the Tasks and the Circumstances Under Which They are Done?
- What provision has been made for the operator to generate his own display and to put the information of his own choice on it?
- How does the operator know what information is available for display?
  - How far does the display indicate the options available to him?
  - To what extent does it lead the operator through these options
- What feedback is there on the display of the operator's actions and their consequences?
  - How far can the display function as an automated teaching aid

How Does the Display Cope with:
- Errors?
- Omissions?
- Discrepancies?
- Unintelligible information?
- Unserviceability?

Teams and the Visual Display

Are the Tasks for Which the Visual Display is Used Team Tasks or Individual Tasks?
- Do team members share the same tasks?
- Do different team members do different tasks:
  - Concurrently
  - Consecutively

Does the Visual Display Permit the Following Team Functions to be Performed Efficiently:
- Co-ordination?
- Liaison?
- Handovers?
- Supervision?
- Assistance?
- On-the-job training?
- Consultation?
- Task splitting?
- Task sharing?
- Bandboxing?
- Extra tasks?

What does the Visual Display Show about the Performance and Efficiency of Other Team Members?
- What flexibility of team composition and manning levels is envisaged?

Is the Visual Display Used in Relation to Team Composition and Manning for:
- Task allocation?
- Task sharing?
- Dividing responsibilities?
- Showing the current allocation of responsibilities?
- Regrouping?
- The separation of groups of tasks?
- The combination of groups of tasks?

Loading

Capacity of the Visual Display
- How does the visual display represent variations in task demands?
- What is its programmed maximum capacity for information display?
  - What sets the limits on that capacity?
  - What probability is there that task demands will exceed these limits?
  - How does the information on the visual display indicate:
    - That the limits have been exceeded?
    - That the limits are about to be exceeded?

Task Demands
- How have all the task demands been envisaged and met?
- What new task demands could the visual display be adapted to meet?
- How does the visual display help the recovery from failures to meet task demands?

What classification of tasks has been employed?
- Does this classification show their importance and frequency?
- Have any tasks been omitted from the classification?

How does the visual display influence workload?
- Does the operator control and set the pace of work?
- What aspects of the information on the visual display would be measurable in order to assess workload?

What measures of the efficiency of task performance could be derived from the visual display and its usage?

## THE INDIVIDUAL OPERATOR

### Biographical Data

- Age
- Sex
- Training
- Courses
- Experience
- Knowledge
- Previously Experienced Displays Relevant to the Visual Display
- Previously Experienced Tasks, Acquired Habits, and Their Compatibility with Tasks Using the Visual Display
  - Possible consequent misinterpretations
- Familiarity of:
  - Instructions
  - Procedures
  - Required level of flexibility
  - Codings

### Physical Factors

- Physical and Medical Standards
- Eyesight
- Posture
- Anthropometric Body Dimensions
- Tolerance of the Physical Environment
- Reach Distances
- Viewing Distances
  - Tasks requiring the whole visual display
  - Tasks requiring part of the visual display
- Influence of Selection and Training on the Usage of the Visual Display

### Individual Work Needs

- Opportunities for:
  - Skill
  - Effort
  - Challenge
  - Initiative
  - Innovation
  - Adaptability
  - Flexibility
- Job Interest
  - Job satisfaction
- Advancement
  - Career prospects
  - Responsibilities
  - Status
  - Morale
- Unwanted Attributes
  - Irrelevant information
  - Irrelevant skills
  - Failure to forget what is no long relevant

### Adverse Individual Reactions

- Possible Reported Adverse Symptoms in Individuals Using a Visual Display
  - Nausea
  - Tired eyes
  - Fatigue
  - Headaches
  - General malaise
  - Stiffness
  - Muscle ache
  - Discomfort
- Prevalence of Reported Symptoms:
  - Timing
  - Severity
  - Persistence
  - Onset
  - Disappearance

Acceptability of the Visual Display Unit

Physical Appearance
- Aesthetic qualities in relation to the visual environment
- Immediacy of aesthetic judgements and attitude formation
- Impression of thought and care in design and layout
- Use of attributes of high acceptability (e.g. colour coding)

Evidence of Acceptability
- Extent to which the advantages of the visual display have been successfully conveyed to users
- Knowledge of visual displays in successful operation elsewhere
- Correct understanding of what the visual display is for
- Willingness and ability to use the visual display as it is intended to be used
  - Misunderstandings of the designer's intentions
- The roles of supervision, of management and of assistance in relation to the visual display user
- The experience of learning to use the visual display
- Success in overcoming any difficulties in using the visual display
- Direct or indirect reports of success by others
- Interactions between task demands, display format and content, and subjective impressions of the visual display
- The expected pace of tasks using the visual display

VIEWING PATTERNS

Short Term

Head and Eye Movements
- Scanning patterns
- Task demands
  - Continuous/intermittent use of the visual display
  - Patterns in using other displays
  - Degree of operator's control over task demands and scanning patterns
  - Frequency of changing view between the visual display and other displays
- Constancy/variability of visual viewing distances
  - Refocusing
- Constancy/variability of luminous flux of visual display and other displays
  - Changes in pupil size
- Duration of continuous viewing of each display

Medium Term

Work-Rest Cycles
- Normal maximum period of continuous work in the visual display environment
- Rest environment facilities
- Daily schedule
- Hours per week
- Shift work
- Traditional practices
  - Work demands
  - Acceptability

Work and Home Environments
- Visual displays in the home (TV)
- Similar postures and visual tasks at home and work
  - Interactions
  - Cumulative effects
- Optimisation of visual environment
  - At work - guidelines followed
  - At home - not usually possible
- Attribution to work environment or to home environment of any physical symptoms apparently associated with visual displays

Long Term

Attribution of Effects
- Selection according to minimum eyesight standards
  - Expected frequency of astigmatism among controllers compared with whole population
- Long term changes in eyesight
  - Normal changes in eyesight with ageing
  - Changes associated with use of visual display
- Robustness of eyes
  - Eyes generally not affected much by tasks
  - Eyes generally not affected much by any optimised visual display
  - Visual displays considered in ocular contexts (cf. e.g. jeweller, cartographer)
- Long term visual symptoms
  - Physical environment
  - Non-optimised installation
  - Inadequate selection of operators
  - Visual display itself
  - Failure to adapt general visual environment to visual displays installed

The Worst Case

The visual display must be satisfactory for:

- The operator when he is most tired
- The operator with minimum experience
- The operator with minimum eyesight standards

The most adverse physical environmental conditions that can occur

The visual display at the end of its useful life

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The author first considers air traffic control systems and human factors in relation to them; man as a system component and the relevance of various human attributes are then discussed. Man's functions in air traffic control are described, together with desirable characteristics of his physical working environment. Having considered what controllers do, their facilities and their working environment it is possible to suggest how they should be selected and trained, what might be desirable attributes in controllers and what they need to know. The relevance of various aspects of their conditions of employment is examined, together with characteristics of the controller as an individual. Questions of measuring controllers and of conducting human factors research on air traffic control problems are then discussed. The human factors aspects of other functions within air traffic control systems are briefly examined and the text concludes with suggestions for progress in applying human factors to air traffic control.

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