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Cognitive Analysis of Navigation Tasks: A Tool for Training Assessment and Equipment Design

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16. Abstract

Automation is becoming more prevalent on commercial ships. When automation is introduced, the mariner's tasks change. Certain manual tasks may no longer be required, and there are new tasks specific to the operation of the automated system. In some cases, tasks which were formerly performed by two or more mariners are now combined into the responsibility of a single crew member. As the knowledge and skills required to operate a vessel change, the U.S. Coast Guard needs to reflect these changes in its qualifications and licensing/certification requirements. However, the U.S. Coast Guard currently lacks a systematic approach for determining the effects of new automation on mariner qualifications.

This paper presents an overview of four different, but complementary, methodologies being developed to assess how a given automated system changes shipboard tasks and the knowledge and skills required of the crew. The report focuses on one of these methods, a powerful new application of cognitive analysis. Cognitive analysis identifies the mental demands (such as visual detection, computation, and memory) placed on the mariner while performing shipboard tasks. A comparison of the mental demands associated with manual versus automated tasks can highlight differences in the knowledge, skills, and abilities required to peform the tasks. Thus, cognitive analysis identifies changes which may be needed in training and licensing/certification as a result of shipboard automation.

The body of the report is a technical documentation of the cognitive analysis method.

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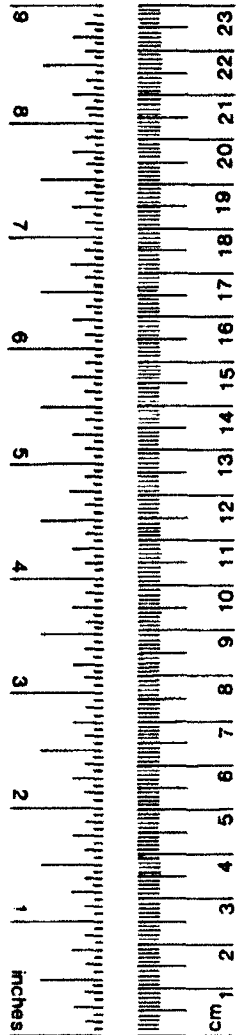
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly).



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

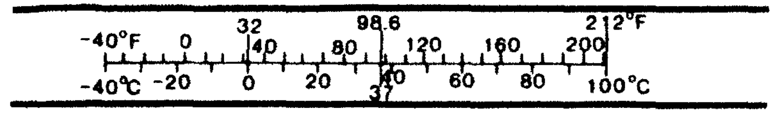


TABLE OF CONTENTS

SECTION PAGE

ACKNOWLEDGEMENTS ix

DISCLAIMER ix

EXECUTIVE SUMMARY/OVERVIEW x

TECHNICAL SUMMARY xv

I. INTRODUCTION 1

1.1 PURPOSE 1

1.2 BACKGROUND 1

II. METHODS 3
2.1 ACTIVITIES SELECTED FOR ANALYSIS 3
2.2 DATA COLLECTION 3
2.3 ANALYTIC METHODS I. OPERATOR FUNCTION MODELING 4
2.4 ANALYTIC METHODS II. SYSTEMS TASK VOCABULARY AND HUMAN INFORMATION PROCESSING 5

III. RESULTS 9
3.1 TERMINOLOGY 9
3.2 GENERAL DESCRIPTION OF OFM REPRESENTATIONS 9
3.3 OFM-COGNITIVE ANALYSIS OF COLLISION AVOIDANCE 13
3.3.1 Radar Grease-Pencil Plot Method 16
3.3.2 ARPA Method 22
3.3.3 Implications of Cognitive Analysis of Collision Avoidance 26
3.4 OFM-COGNITIVE ANALYSIS OF VOYAGE PLANNING 28
3.4.1 Voyage Planning With Paper Charts 28
3.4.2 Voyage Planning with ECDIS 32
3.4.3 Implications of Cognitive Analysis of Voyage Planning 33
3.5 OFM-COGNITIVE ANALYSIS OF TRACK KEEPING 38
3.5.1 Track Keeping with Paper Charts 38
3.5.2 Track Keeping with ECDIS 39
3.5.3 Implications of Cognitive Analysis of Track Keeping 41

IV. DISCUSSION 43
4.1 GENERAL SUMMARY 43
4.2 APPLICATION OF OFM-COGNITIVE ANALYSIS TO RADAR OBSERVER TEST ITEMS 43
4.3 EVALUATION OF OFM-COGNITIVE ANALYSIS 44

V. CONCLUSIONS 47

REFERENCES 48

APPENDIX A
Miller's Terminology: Definitions for the 25 Task Functions Involved in a Generalized Information-Processing System A-1

LIST OF FIGURES

FIGURE **PAGE**

1. Cognitive task analysis of decision making elements (after Rasmussen, 1986) 7
2. Top-level navigation functions. 10
3. Subfunctions for target evaluation function 10
4. Subfunctions for course adjustment function 11
5. Subfunctions for course execution function 11
6. Subfunctions for voyage planning function 12
7. The high level functions are shaded to indicate their involvement in collision avoidance 14
8. The subfunctions of the execute course function are shaded to indicate their involvement in collision avoidance 14
9. The subfunctions of the adjust course function are shaded to indicate their involvement in collision avoidance 15
10. The subfunctions of the evaluate target function involved in collision avoidance 15
11. Sample R-T-M plots 20
12. Subfunctions of voyage planning function 28
13. Subfunctions of course execution function. Shading indicates track keeping subfunctions 38

LIST OF TABLES

TABLE PAGE

1. Miller's Task Transaction Vocabulary 8

2. OFM-Cognitive Analysis of Collision Avoidance Functions with Standard Radar/Grease Pencil Plotting 17

3. OFM-Cognitive Analysis of Collision Avoidance Functions with Automated Radar Plotting Aid (ARPA) 24

4. Classification of System Task Transaction Terms 26

5. Frequency Count of Cognitive Task Transactions for Grease Pencil Method and ARPA 27

6. OFM-Cognitive Analysis of Voyage Planning with Paper Charts 29

7. OFM-Cognitive Analysis of Voyage Planning with ECDIS 34

8. Frequency Count of Cognitive Task Transactions for Voyage Planning 36

9. OFM-Cognitive Analysis of Track Keeping with Paper Charts 40

10. OFM-Cognitive Analysis of Track Keeping with ECDIS 41

11. Frequency Count of Cognitive Task Transactions for Track Keeping 41

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DISCLAIMER

EXECUTIVE SUMMARY/OVERVIEW

INTRODUCTION

One of the goals of the Marine Licensing Program is to ensure that all mariners on U.S. commercial vessels are competent to perform their duties. In order to meet this goal, the U.S. Coast Guard (CG) must determine the minimum standards of experience, physical ability, and knowledge to qualify individuals for each type of license or seaman's document, and it must evaluate applicants against these standards.

Automation is becoming more prevalent on ships, affecting areas such as engineering, navigation, and cargo operations. When automation is introduced, the mariner's tasks change: certain manual tasks may no longer be required, and there are new tasks specific to the operation of the automated system. In some cases, tasks which were formerly performed by two or more mariners are now combined into the responsibility of a single crew member. It is likely that each automated system will require that mariners receive additional training. As the knowledge and skills required to operate a vessel change, the CG should reflect these changes in its qualifications and licensing/certification requirements.

QUALIFICATIONS AND TRAINING FOR AUTOMATED SHIPS

In order to maintain the safety of our waterways, the CG needs a means to assess how a given automated system changes shipboard tasks and the knowledge and skills required of the crew. The "Qualifications and Training for Automated Ships" project was initiated to fulfill this need. The project involves developing systematic methodologies to determine the impact an automated system has on several aspects of crew performance. Four different, but complementary, methods are being developed.

The first method is *task analysis*. A task analysis technique has been devised which breaks down a shipboard function, such as collision avoidance, into a sequence of tasks. Task analysis is not new; the current approach synthesized various existing methods and adapted them to the maritime operating environment.

The second method is a *cognitive analysis* of shipboard tasks. This looks at the *mental demands* (such as remembering other vessel positions, detecting a new contact on the radar, or calculating the CPA) placed on the mariner while performing a given task. The cognitive analysis identifies the types of knowledge, skills and abilities (KSAs) required to perform a task and highlights differences in mental demands as a result of automation. Cognitive analysis is a relatively new technique, and the application described in this report was developed specifically for this project. The body of this report is a technical description of cognitive analysis.

The third method being developed to evaluate the impact of automation is a *skills assessment* technique. It will take the results of the task and cognitive analyses, and will determine the types of training required to instill the needed KSAs for performing the shipboard tasks. These will be compared to current training courses in order to highlight any new training that may be needed.

The fourth and last method is a *comprehension assessment* technique. There has been an unfortunately large number of mishaps in a variety of industries which resulted from an operator's misunderstanding of the capabilities of an automated system. Problems can occur when the operator doesn't understand the limitations of the equipment being used. For example, when the radar signal-to-noise ratio is poor, the ARPA may "swap" the labels of adjacent targets. If the mariner is not aware of this limitation of the ARPA system, he may be navigating under false assumptions about the positions of neighboring vessels, increasing the chances of a casualty. The comprehension assessment technique will identify misconceptions that mariners have about an automated system, which could then be remedied through equipment redesign or training.

The first two of these techniques have been developed and tested; the latter two are currently under development. Together these methods allow us to anticipate the task and training ramifications of automating shipboard systems. The remainder of this summary discusses the cognitive analysis technique and its utility to the Coast Guard.

COGNITIVE ANALYSIS

Cognitive analysis was applied to a form of task analysis (specifically, an operator function model, or OFM) to produce a powerful new technique for assessing the effects of automation. The OFM task analysis provides a breakdown of a function, such as collision avoidance, into the tasks which must be performed, including a description of the *information* needed to perform the task, and the *decisions* which direct the sequence of tasks. This type of task description is independent of the automation; that is, the same tasks, information, and decisions are required, regardless of whether they are performed by a human or by a machine. For example, in collision avoidance, other vessels must be detected, the relative motion analyzed, and a decision made regarding whether a change is needed to ownship's course and/or speed in order to avoid a collision. These tasks must be performed, regardless of who (human) or what (machine) does them.

The cognitive analysis extends the task analysis by considering the mental demands that would be placed on a human operator in performing these tasks. For example, in order for a human to detect a new ship as soon as it appears (within either visual or radar range), vigilance (sustained attention) and discrimination (the ability to spot a target against the background) are required. The mental demands of determining the closest point of approach (CPA) include plotting a series of target range and bearing, and evaluating the ratio of change. The body of this report provides detailed cognitive analyses for the navigation functions of collision avoidance, voyage planning, and track keeping.

Once the task and cognitive analyses are complete, we can determine which steps are performed by the human and which by machine under different types of systems (different levels of automation). In the collision avoidance example, we find that the calculation of CPA is performed by the human in the radar-and-grease-pencil method, whereas CPA is calculated by the machine in the ARPA method. Therefore, this shows that certain computational tasks are no longer required of the human when ARPA is in use.

It is also important to consider any *new tasks* that are imposed on the human due to automation. For Example, the ARPA has an automatic target detection feature, which would seem to be a useful aid to the navigator. However, this feature is prone to false alarms; that is, it tends to acquire many "targets" which turn out to be sea clutter or other things that are not of interest. In this case, then, the cognitive analysis showed that the ARPA does not replace the human in target acquisition, but instead shifts the mariner's task from that of detecting targets to that of validating ARPA targets (and getting rid of "nuisance" targets). Mariners have found the ARPA target detection feature to be so unreliable that it adds to their workload, and most choose not to use the auto-detection feature.

APPLICATION OF COGNITIVE ANALYSIS TO THE MARINE LICENSING PROGRAM

The primary benefit of this technique to the Coast Guard is that it can highlight changes which may be needed in training and licensing/certification. In some cases, the automated system will require new KSAs of the operator. Some of these skills will be equipment-specific, such as how to bring up the correct chart on an ECDIS, or how to perform trial maneuvers on an ARPA. Other knowledge might be technology-specific, such as understanding the capabilities and limitations of different radars. The cognitive analysis technique can be used to identify these KSAs so that they can be considered for possible inclusion in training and testing requirements.

In other cases, the automation will change the relative importance of skills. For example, it was found that the use of ARPA in performing the collision avoidance function virtually eliminated all computational requirements on the mariner, as compared to the radar-and-grease-pencil method. It was also noted that the use of ARPA potentially allows the mariner to keep track of many more targets than before. This suggests that the mariner's task has changed from a *computation-intensive* to an *interpretation-intensive* one. The cognitive analysis technique was then applied to a set of questions taken from a practice test (Van Wyck and Carpenter, 1984) for the radar observer certification. Of the 40 test items analyzed, 30 (75%) were found to test computational skills, while the remainder tested interpretive skills. Given the widespread use of ARPAs on commercial ships, and the influence of ARPA on the skills required for collision avoidance, *it would appear that there needs to be a shift in emphasis from computational to interpretive questions on the radar observer certification exam.*

Training and qualifications are not the only areas that can benefit from the application of cognitive analysis. The cognitive analysis technique can be very useful in pinpointing system design flaws. The cognitive analysis of voyage planning showed that *the particular ECDIS under study was not designed properly to support this task.* For example, in the initial stages of planning a voyage, the navigator is best served by a large-scale chart which encompasses the entire area to be traversed. While this is possible with paper charts, it was not possible with the ECDIS studied. The ECDIS required the navigator to view a series of smaller charts. ECDIS also imposes display manipulation demands such as panning and zooming. These extraneous operations, and the relatively slow and choppy sequence of chart presentation in ECDIS (compared with rapid glances at different areas of a paper chart), interfere with the navigator's ability to conceive of and construct a voyage plan. Several other ECDIS problems were identified, most of which could have been avoided if the developers of the ECDIS system had used an OFM-cognitive analysis approach to understand the information the navigator needs to prepare a voyage plan.

This approach can also be useful in identifying design limitations in the marine system as a whole. The cognitive analysis of track keeping found that the ECDIS was capable of performing the entire function, thereby freeing the mariner from this chore. However, due to legal constraints within the marine system, mariners cannot take advantage of this ECDIS capability. Currently, paper charts constitute the legal record of a voyage. Therefore, manual track keeping must be performed. *In order to make ECDIS a viable alternative to manual track keeping, regulations would have to be changed.* The International Maritime Organization (IMO) is considering this issue in its development of ECDIS Provisional Performance Standards.

Finally, cognitive analysis can be used to generate information pertinent to crewing decisions. The results of a cognitive analysis can help focus attention on potential workload problems and suggest whether multiple crew members might be required to perform a given function.

Thus, there are many potential benefits to employing the cognitive analysis methodology. Because of the specialized psychology and human factors knowledge required to employ this tool effectively, it will initially be implemented through the RDT&E program. Current plans for the Qualifications and Training for Automated Ships project include analyses of automated bridge and cargo-transfer systems (selected with HQ guidance). Cognitive analysis, in conjunction with task analysis, skill assessment, and comprehension assessment, will provide the Coast Guard with a rich and focused view of the impact of automated systems on crew performance and recommend specific changes that may be needed to training and licensing requirements, as well as to system design and manning.

SUMMARY

Cognitive analysis can be used to identify the ways in which an automated system changes shipboard tasks and the mental demands placed on the mariner. It is a powerful technique that can assist the Coast Guard in identifying the knowledge, skills, and abilities required of the mariner to operate an automated system. This information can then be applied to assess any changes that may be necessary in the training and qualifications requirements to ensure that mariners are competent to perform their duties on automated ships. Cognitive analysis is also effective at pinpointing design problems that interfere with the safe and efficient performance of shipboard tasks. In addition, it can be used to provide information pertinent to crewing decisions.

Since cognitive analysis is a new technique, the remainder of this report is a technical documentation of the method. It has been written for the human factors specialist, so that future human factors contractors will be able to understand and replicate the technique in the assessment of other automated shipboard functions for the Coast Guard.

TECHNICAL SUMMARY

Advances in shipboard automation are generating new requirements for training and qualifications, based on the altered job and task structure imposed by technology. In some cases this structure can reduce physical workload, although it can impose increased mental or cognitive demands on the operators. These changes, in turn, will require new approaches to mariner training and licensing. At present, there is not a systematic approach to job/task analysis used by the Coast Guard for training and licensing decisions, with a resulting discontinuity between job requirements and licensing test content. The goal of this project is to develop a job and task analysis method based on the cognitive (mental) requirements of advanced navigation technology that can be used for specifying training and licensing requirements.

The project involved selecting several navigation functions for analysis that would allow comparison across different levels of automation. Based on observational and interview data collected on ship rides in Puget Sound, we selected the functions of collision avoidance, voyage planning, and track keeping for analysis. For collision avoidance, the two levels of automation evaluated were the radar real-time plotting method and automated radar plotting aids (ARPA). For voyage planning and track keeping, the levels of automation were paper chart plotting versus an electronic chart display information system (ECDIS).

A review of methods for evaluating automation impact indicates that a useful approach would be to combine operator function modeling (OFM) with cognitive task analysis. OFM permits an information-flow type characterization of processes that must be accomplished, with or without automation. Cognitive analysis allows specification of the mental operations and resources applied to specific job functions and processes. Together, the two techniques permit a comprehensive description of the human and machine activities necessary to accomplish a job or task at a level that allows comparison across levels of automation.

Application of the OFM-cognitive analysis technique to the three navigation functions demonstrated differences in task performance with and without automation. For example, in collision avoidance, many data handling functions are eliminated by ARPA. Additionally, the interpretation tasks that are required by the manual plotting method may be de-emphasized by ARPA because of the realism of the display. In the case of voyage planning, automated and manual methods appear quantitatively identical, but the cognitive analysis shows that there are distinct differences in how ECDIS supports the task. The principal change in track keeping is the reduced need to take visual or radar bearings to determine location. However, because of relatively low functionality at this time, ECDIS does not support the full range of tasks that can be accomplished via paper chart, such as noticing track line deviations.

The comparison of navigation functions at different levels of automation successfully demonstrated the utility of OFM-cognitive analysis for describing task-level job-function changes. This information is useful for designing systems that encompass a wide range of ship crew job functions within the concept of an integrated bridge. Additionally, the OFM-cognitive analysis technique permits a comparison of licensing test material with the requirements of the job being tested. The latter application was illustrated by coding sample test items from the USCG radar observer test for real-time plot and ARPA methods. The analysis indicated that 75% of the test items evaluated skills that are not routinely required when using ARPA for collision avoidance.

The analyses presented in the report support the following conclusions: 1) it is possible to represent the covert cognitive operations demanded by navigation technology; 2) OFM-cognitive analysis permits a straightforward comparison of task structure and demands across different levels of automation; and 3) the technique is directly applicable to issues related to design, training and licensing. This range of applications of OFM-cognitive analysis suggests that it should be an integral tool in the USCG manning, licensing and training activities.

I. INTRODUCTION

The design of equipment for human use, and training for the operation of that equipment, requires a thorough understanding of the operational requirements of job functions and tasks, and the human knowledges, skills and abilities (KSAs) necessary to perform those functions. In the U.S. Coast Guard, the licensing of mariners, the approval of training courses, and standards for equipment design have traditionally been established by expert mariner input, without the benefit of a structured process (Palmer, 1991). An illustration of the resulting paradox is that while automated radar plotting aids (ARPAs) are used on most commercial ships, the Coast Guard radar observer certification is based on the standard radar grease-pencil plotting method. This differs from other situations, notably the nuclear industry and military applications, which employ a variety of needs analysis and human factors methods to ensure comprehensive consideration of human factors variables in establishing job requirements, training programs, and licensing examinations.

1.1 PURPOSE

The purpose of this report is to describe a research project for formulating a job and task analysis method based on the cognitive requirements of navigation technologies, i.e., the mental operations performed by humans when using technology. The goal of this project is to develop a process for use by USCG personnel concerned with establishing training and licensing requirements, and equipment design standards. The utility of the process will be that it allows training personnel or equipment designers to make comparisons of job/task requirements, equipment characteristics, training content, and licensing examination content within a common framework. This will ensure that training courses and licensing procedures are directly related to the skills required by the job.

1.2 BACKGROUND

Navigation technology is an area in which change is rapidly occurring, with the integration of global positioning system (GPS), radar, collision avoidance systems, and electronic chart display information systems (ECDIS). Together, these technologies have the potential to reduce the manning requirements for commercial ship bridges from four people (captain, watch officer, helmsman and lookout) to one. Recent studies by Schuffel et al. (1988) suggest that under proper conditions, workload is decreased and performance is enhanced with a one-person operation. However, this work addressed only the overt aspects of mariner performance and did not evaluate stressful conditions. Studies of navigation in aviation suggest that advanced automation can sometimes <u>increase</u> workload during stressful operations (Woods, 1987). Research has not yet been done to delineate the system design characteristics underlying increased workload.

The current project is focused on a comparative evaluation of navigation tasks conducted using paper charts and electronic displays. The implementation of ECDIS and ARPA offers a useful testbed for human factors and training design for the following reasons:

- The technology encompasses functions previously performed by more than one person (voyage planning, track keeping, collision avoidance)
- The data streams from several previously independent systems converge (radar, GPS, paper charts)
- Functions that have previously been exclusively cognitive or visual are now assisted with display features (pan, zoom, switch areas within an electronic chart)

In navigation, the following cognitive demands exist regardless of technology: 1) extrapolating ship response, 2) inferring the intention of other ships, 3) evaluating imperfect information sources, and 4) performing competing tasks. While computer-based technologies may reduce some of the repetitive and error-prone tasks of measurement and plotting, they also tend to introduce new cognitive tasks involving monitoring more targets, understanding system functions, and mental scaling to accommodate chart size reductions.

Historical data concerning shipping accidents indicate that many navigation errors are the result of misunderstanding the signals provided by technological aids, such as collision avoidance systems (National Transportation Safety Board, 1990). Further, basic research on the use of electronic chart displays indicates that people make consistent errors of orientation that are induced by both the display and the task to be accomplished (Aretz, 1991). Thus, it is clearly important to obtain a better understanding of the cognitive tasks involved in navigation technology in order to improve the design of equipment and training for mariners.

This project examines the cognitive nature of navigation tasks, because judgment and decision making errors tend to be the largest cause of marine accidents (Perrow, 1984). Traditional approaches to training task analysis have been oriented largely toward the progressive redescription of jobs and tasks, emphasizing the observable aspects of performance (Duncan, 1974; Goldstein, 1986). Psychological methods have not kept pace with the increasingly cognitive nature of jobs (see Lee and Sanquist, 1993), leading to a gap between the ability to describe and analyze human work performance and the need to design equipment and train operators. As maritime jobs involve more complex technology, it is necessary to understand the covert information processing done by mariners, and to design training, qualifications and licensing procedures to reflect these changes. A potential danger in the use of increasingly sophisticated navigation technology is that complex tasks become superficially easy, leading to less emphasis in training. Further, navigational knowledge and skills may degrade because of fewer demands for their use. Finally, advanced technologies may introduce new phenomena that affect mariner decision making, such as steering a ship solely on the basis of a video display, and should thus be accommodated in training and design.

II. METHODS

2.1 ACTIVITIES SELECTED FOR ANALYSIS

Three navigation activities were selected for analysis: 1) collision avoidance, 2) voyage planning, and 3) track keeping. These areas were selected as being the most useful for illustrating the differences in task performance between manual navigation techniques and equipment and advanced automation, i.e., ECDIS and ARPA. For each of these task activities, functional and cognitive task analysis was conducted. These analyses will be discussed further in the Results section.

This set of navigation activities is particularly pertinent to safety considerations, since a mariner must plan a relatively hazard free voyage, monitor the ship's progress along an intended voyage track, and avoid contact with various navigational hazards, such as other ships, ice and land. The functions are highly interrelated in that they all depend fundamentally on detailed knowledge of navigational principles, either to carry out the task, or to interpret the data resulting from task performance.

2.2 DATA COLLECTION

To obtain data for the functional and cognitive task analyses, a number of methods were employed. The analysis of tasks with a high level of cognitive processing involves "opportunistic data collection" (Woods and Hollnagel, 1987). A quote from Woods & Hollnagel (1987) portrays the general approach necessary in field work:

> "The approach is indifferent to particular sources of domain information. Information to carry out the analysis is gathered opportunistically: some questions relate to domain technical knowledge so the knowledge-acquisition problem is finding the right specialist to talk to or to point you to the right documents/analyses; sometimes the path is to look empirically at how the problem is solved, e.g., critical incident analysis, or putting the problem-solver in the situation of interest or simulations of it either formally (experiments) or informally; sometimes the path is to interview people who perform the task or people whose specialties intersect within the task. All of these specific acquisition tactics are potentially useful; the analytic framework helps the cognitive technologist ask meaningful questions and integrate the information acquired from multiple diverse sources....The result of using this approach is a characterization of the kinds of problems to be solved in the domain and what aspects of the psychology of human performance are relevant in those situations." (Woods and Hollnagel, 1987, p. 259).

This statement echoes the description of task analysis provided by Miller (1953), indicating that task analysis is a rational and empirical method, designed to gather data about the behavioral requirements of human-machine systems. These behavioral requirements are given by the equipment itself and the problem-solving situation. The hallmark of the various approaches to task analysis is a flexible set of methods, adaptable to the situation at hand. Recently, these approaches have been compared to anthropological methods (Suchman, 1987; Seifert and Hutchins, 1992).

The specific data collection procedures used in this project are as follows:

- 32 staff hours of observation aboard one bulk cargo ship and one crude oil tanker transiting piloted waters in Puget Sound. Observations during these trips included ARPA, ECDIS, track keeping, voyage planning, and crew communications. Semi-structured interviews were conducted with deck crew members; input was obtained from two pilots, two masters, and two watch mates. Interviews focused on the tasks selected for study, with particular emphasis on the use of technology such as ARPA and ECDIS.

- 24 staff hours in the engineering labs of Offshore Systems, observing and mapping the operations of the prototype ECDIS as used to perform the navigational tasks of interest.

- 16 staff hours of customized ARPA training by Pacific Maritime Training.

- Detailed reviews of technical training materials associated with navigation task performance (Meurn, 1990; Van Wyck and Carpenter, 1984).

These data were combined with prior observations made aboard various tanker ship rides by the research staff.

2.3 ANALYTIC METHODS I. OPERATOR FUNCTION MODELING

The operator function model (OFM) technique can provide a foundation for a cognitive analysis of factors such as information flow and decision making functions that influence performance of complex systems (Mitchell and Miller, 1986; Jones, Mitchell, and Rubin, 1990). OFM is a framework for a precise specification of what information the operator needs, when, and in what form. Furthermore, OFM specifies how this information must be transformed to support system operation (Mitchell and Miller, 1986). Recently, OFM has been used to identify training needs (Bloom et al., 1992). Specifically, OFM was used to differentiate among generic process control knowledge, process specific knowledge, and interface specific knowledge. Thus, this method should help identify potential design flaws, training requirements, and qualification standards associated with the human role in ship navigation.

The OFM method expresses operator behavior in a network of nodes representing input-output relationships. This network represents a normative model of operator behavior, with the top level representing the interrelations among the primary system functions. The hierarchy of nodes decomposes these primary functions into subfunctions, tasks, and control actions. These nodes provide a formal structure for the analysis by defining the links between functions. They are defined by three sets (states, inputs, and outputs), and are governed by two mathematical transformations. The first transformation (state transitions) specifies a new state based on the input and the present state. The other transformation (output function) specifies the output given the input and the current state. Because these transformations are non-deterministic the OFM network provides a means of expressing the probabilistic relationships between inputs and outputs. This is in distinction to more linear, sequential forms of representation such as flow charts and time-line analysis. Thus, the OFM method provides a formal structure that has the flexibility to represent complex behavior.

The input-output relationships of the OFM network can model the effects of external inputs to the system (e.g., the approach of another ship) and the dynamic relations between operator functions (the outputs of the high level nodes act as inputs to lower level nodes, e.g., subfunctions, tasks, and specific control actions). Therefore, the links between nodes in the network represent non-deterministic relationships between human and system behavior. The network can model the variety of control strategies available to the operator, while representing the environmental and system constraints that shape behavior. Thus, the top level functions accept inputs from the environment, and their outputs define the inputs for nodes lower in the hierarchy. For example, in ship navigation, sighting another ship may trigger the function of target evaluation, the subfunctions of which include vessel tracking, communication, and maneuvering. Together the nodes and arcs represent a normative model of the system from the perspective of the human controller.

2.4 ANALYTIC METHODS II. SYSTEMS TASK VOCABULARY AND HUMAN INFORMATION PROCESSING

While OFM illustrates the information requirements, functional structure and interrelationships between operator tasks and overall system functions, it does not indicate the cognitive demands associated with the operator's activity within the system. To establish the cognitive demands imposed by the task requires further analysis. By identifying the cognitive processes associated with each of the tasks of a detailed OFM, the mental demands of those tasks can be documented. Thus, OFM identifies the functions and tasks that the human fulfills, and a cognitive analysis examines the mental demands of those tasks and functions.

There has been a substantial amount of discussion in the literature recently concerning cognitive task analysis, although the term originated with the work of Newell and Simon (1972). The increased concern with this area can be largely attributed to the need to analyze tasks that are becoming increasingly covert because of the nature of the equipment that supports human operators. Because cognitive psychology is a relatively young field, with little standard vocabulary, it is not surprising that a specific method for cognitive task analysis has yet to emerge. The approaches of Roth and Woods (1988) and Rasmussen (1986) are similar in that they represent multi-method applications of the study of cognitive requirements imposed by equipment and the problem solving situation. A variety of other more focused methods exist (see Lee and Sanquist, 1993; Redding, 1989, 1990; Grant and Mayes, 1991), with their application being restricted to a relatively narrow range of the problem solving situation. A further interesting aspect of the recent developments and discussions surrounding cognitive task analysis is that the methods represent a composite of data collection, data analysis and data representation within a single technique. For example, selection of verbal protocol analysis as a method will necessarily constrain the methods of analysis and representation, and the resulting conceptualizations of cognitive functioning. We have attempted to overcome this problem in the present project by adhering to the multi-method cognitive task analysis approach, and by linking our representation technique to well-established models of human and machine information processing.

A basic problem in cognitive task analysis is the need for a consistent vocabulary for mental transactions (Rasumussen, 1986; Miller, 1971). The model presented in Figure 1 (after Rasmussen, 1986) suggests an approach to the vocabulary problem, showing a framework for cognitive task analysis based on decision-making elements. By using a consistent vocabulary to define the cognitive processes intervening between problem formulation and action, the mental operations in task performance can be characterized. This problem was studied extensively by Miller (1971, 1974) in a project for the US Air Force concerned with developing a generalized taxonomy of human task performance. The result of Miller's work was a list of generalized information-processing task-transaction functions, which are shown in Table 1. Like the OFM methodology, these terms may be applied to job functions to describe them according to the operations performed upon particular task content. The vocabulary captures information about task inputs and outputs, the context of the task, the operator's processing resources, and the operation performed on the inputs/outputs. In a more generalized sense, the transactional task analysis language can be used to characterize four fundamental dimensions of task performance: 1) task content, i.e., the inputs and outputs; 2) task environment, i.e., the physical and psychological aspects of the task influencing its difficulty; 3) level of learning, i.e., degree of skill; and 4) task function, i.e., the operation performed on the task content.

In this project, we have adopted Miller's (1971, 1974) terminology for cognitive task analysis, because it offers an analytic and descriptive framework that is consistent with the OFM method of function analysis. The functions characterized as finite state transitions by OFM are further analyzed according to the 25 generalized information processing functions of Miller, which we equate to cognitive operations. The advantage of this approach is that it can be used to describe either human or machine functioning. We have chosen to expand Miller's "level of learning" task dimension to incorporate human information processing subsystems, from generally accepted models (e.g., Kantowitz and Sorkin, 1983; Wickens, 1984). These include the following: 1) Perceptual/Attentional subsystem, 2) Working memory, 3) Long-term memory, and 4) Response selection/execution. The principal advantage of using the Miller (1971) scheme for task analysis and description is parsimony - it does not postulate task-specific cognitive processes (such as situational awareness), and the types of cognitive operations contained in the system are well supported by 20 years of experimental evidence from human information processing studies. A further advantage of using the transactional task analysis language is that in subsequent work, Miller (1974) developed a method for determining work strategies related to the 25 task transactional functions. The purpose of this later work was to provide a basis for developing training programs related to various ways that the task transactions could be accomplished, with the goal of taking trainees through a structured series of exercises that would eventually result in skilled performance (See Fleishman and Quaintance, 1984, Chapter 11). More recent work by Redding and Lierman (1990) describes training system development based on cognitive task analysis, but the methodology is restricted to sorting, recall and protocol analysis, and does not provide the generality of the task transaction vocabulary.

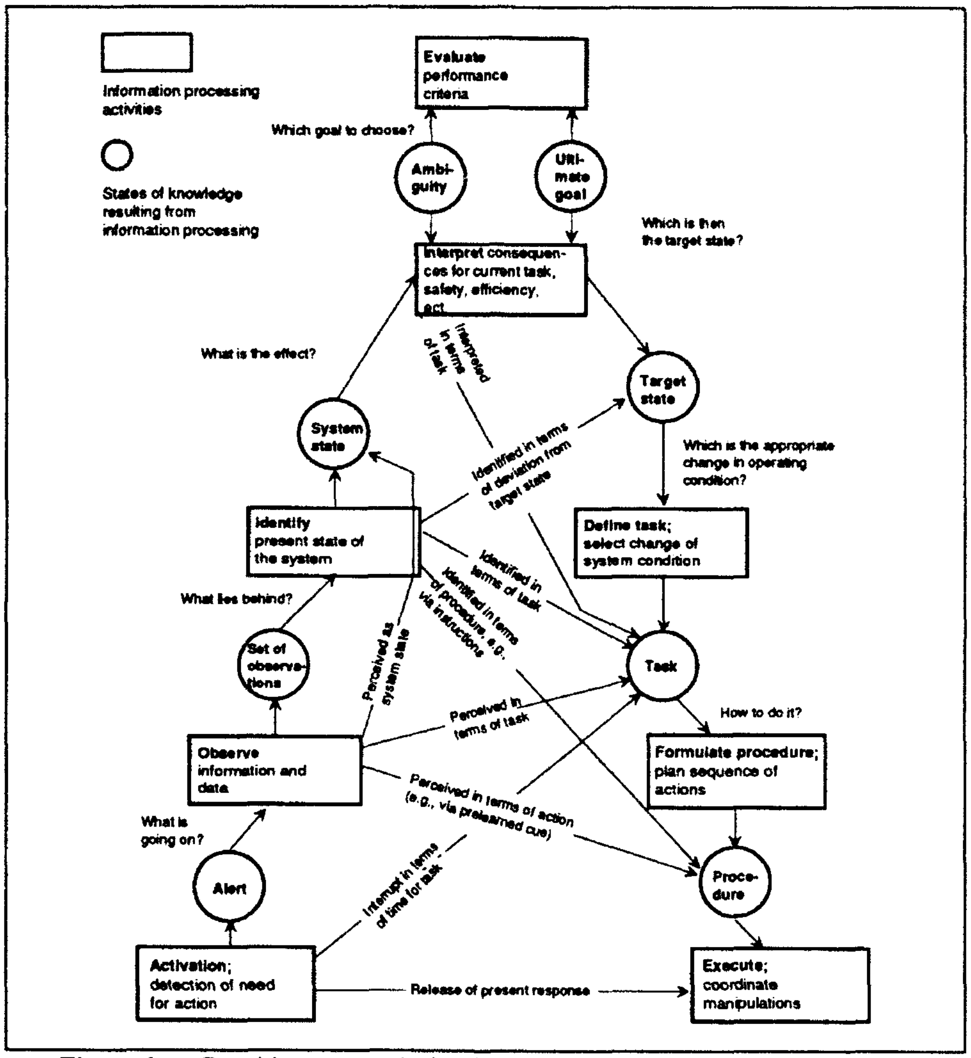

Figure 1. Cognitive task analysis of decision making elements (after Rasmussen, 1986).

Table 1. Miller's Task Transaction Vocabulary

Task functions

1. *Message.* A collection of symbols sent as a meaningful statement.
2. *Input Select.* Selecting what to pay attention to next.
3. *Filter.* Straining out what does not matter.
4. *Queue to channel.* Lining up to get through the gate.
5. *Detect.* Is something there?
6. *Search.* Looking for something.
7. *Identify.* What is it and what is its name?
8. *Code.* Translating the same thing from one form to another.
9. *Interpret.* What does it mean?
10. *Categorize.* Defining and naming a group of things.
11. *Transmit.* Moving something from one place to another.
12. *Store.* Keeping something intact for future use.
13. *Short-Term Memory (buffer).* Holding something temporarily.
14. *Count.* Keeping track of how many.
15. *Compute.* Figuring out a logical or mathematical answer to defined problem.
16. *Decide-Select.* Choosing a response to fit the situation.
17. *Plan.* Matching resources in time to expectations.
18. *Test.* Is it what it should be?
19. *Control.* Changing an action according to plan.
20. *Edit.* Arranging or correcting things according to rules.
21. *Display.* Showing something that makes sense.
22. *Adapt/Learn.* Making and remembering new responses to a learned situation.
23. *Purge.* Getting rid of the dead stuff.
24. *Reset.* Getting ready for some different action.
25. *Goal Image.* A picture of a task well done.

Further definitions and explanations are provided in Appendix A.

III. RESULTS

3.1 TERMINOLOGY

The terminology employed in the following analyses implies a set of relationships. The navigation *activities* of collision avoidance, voyage planning, and track keeping refer to an integrated set of functions, subfunctions and tasks that is routinely carried out during ship navigation. A *function* is a self-contained process involving multiple tasks resulting in a usable output. A *subfunction* involves multiple related tasks. A *task* is an individual step in a process resulting in an output that provides input to another task. Multiple tasks comprise subfunctions.

The analysis presented below shows that navigation *activities* can consist of multiple functions (collision avoidance), single functions (voyage planning) or an aggregate of subfunctions/tasks within a single function (track keeping).

The functions and subfunctions were generated by structured analysis of shipboard observations and review of standard navigation texts. Functions and subfunctions were structured to retain identity with specific navigation terminology, while providing an analytic framework for characterizing data flow and processing. Tasks were generated by analyzing the inputs, processing and outputs of subfunctions. The focus was to identify specific data inputs and outputs and the cognitive processing required.

The terminology described above implies a hierarchy of function, subfunction and task. It also implies a heterarchy, such that activities can be hierarchically organized (as with collision avoidance), or span multiple subfunctions within a single function (as with track keeping). Thus, meaningful navigation behavior can be relatively complex and involve multiple functions (collision avoidance), or relatively simple, entailing parts of a function. The value of this analytic framework is that it can accurately represent data flow and relationships between the elements of navigation activities, while accurately characterizing actual navigator behavior.

3.2 GENERAL DESCRIPTION OF OFM REPRESENTATIONS

Examining navigation tasks in the context of OFM shows that aspects of ship operation can be described by several high level functions. Each of these functions can be broken into subfunctions which together represent a normative model of ship navigation, and indicate the required inputs and outputs. Figure 2 shows the top level functions and their interrelationships, while Figures 3, 4, 5 and 6 show subfunctions associated with each of the top-level functions.

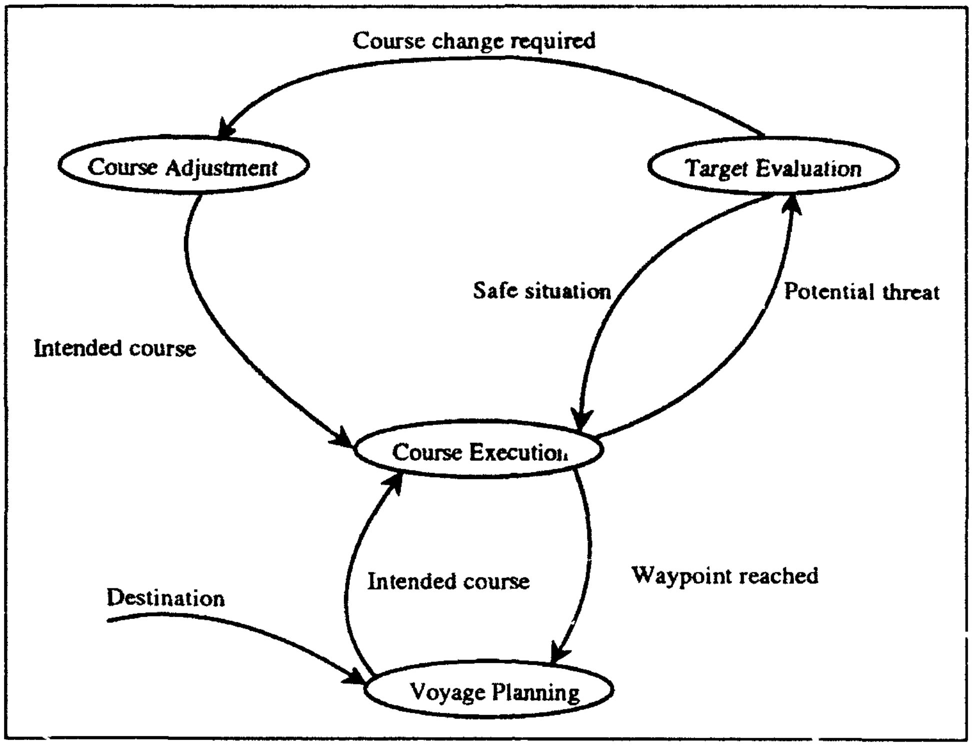

Figure 2. Top-level navigation functions.

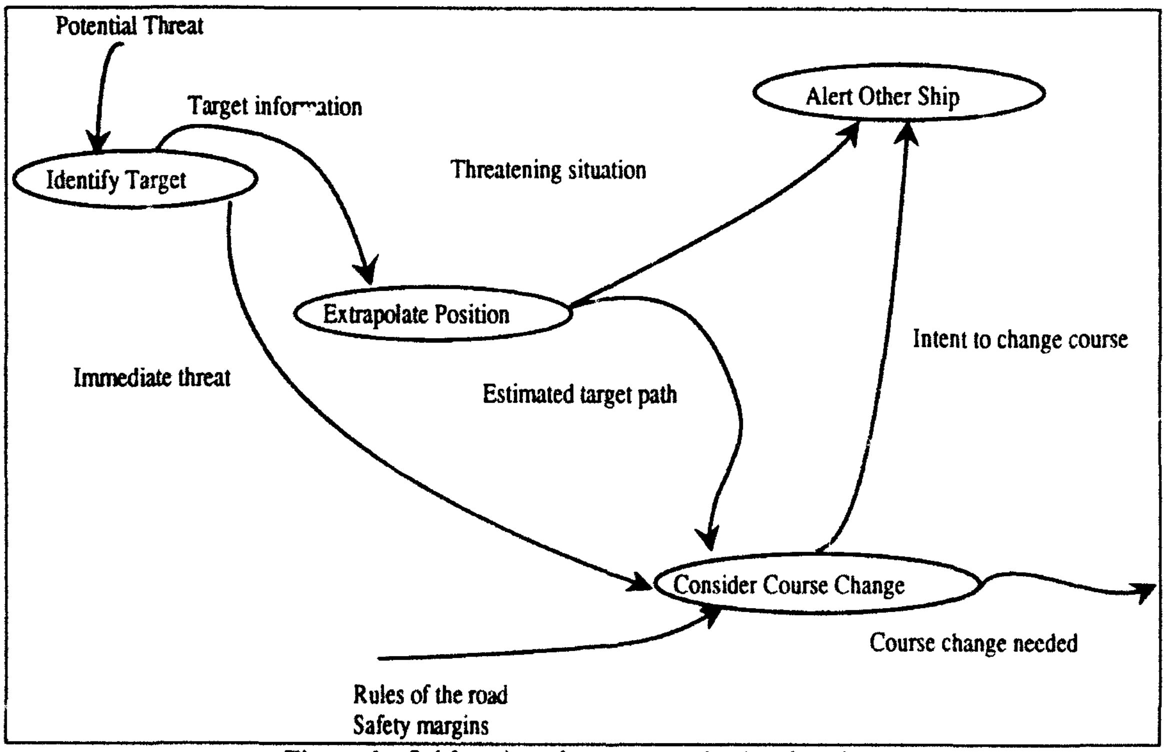

Figure 3. Subfunctions for target evaluation function.

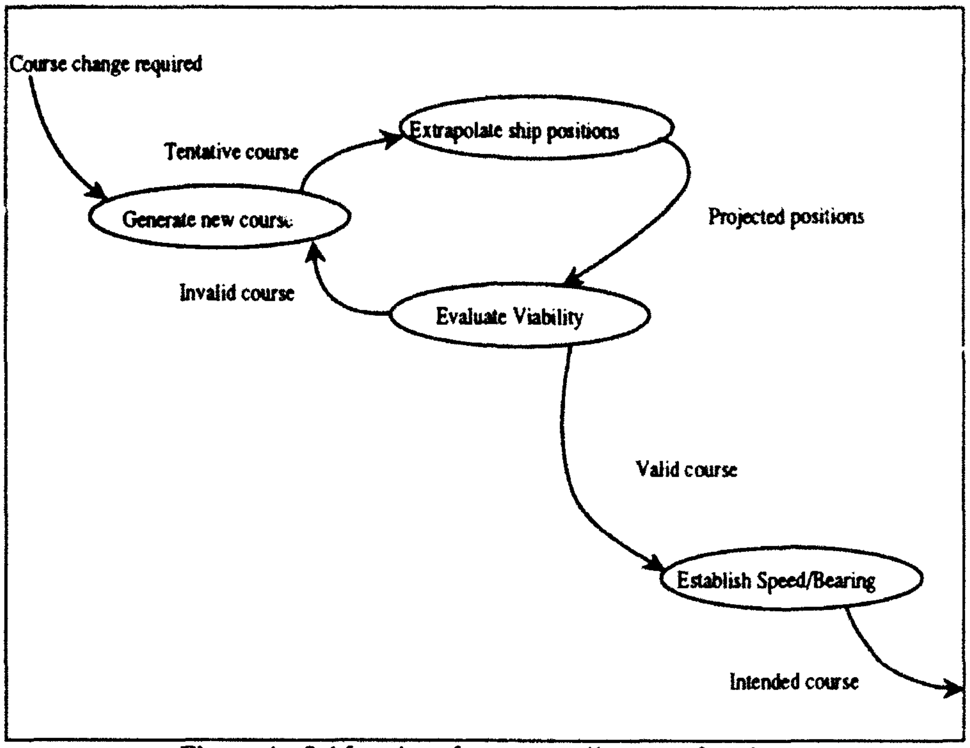

Figure 4. Subfunctions for course adjustment function.

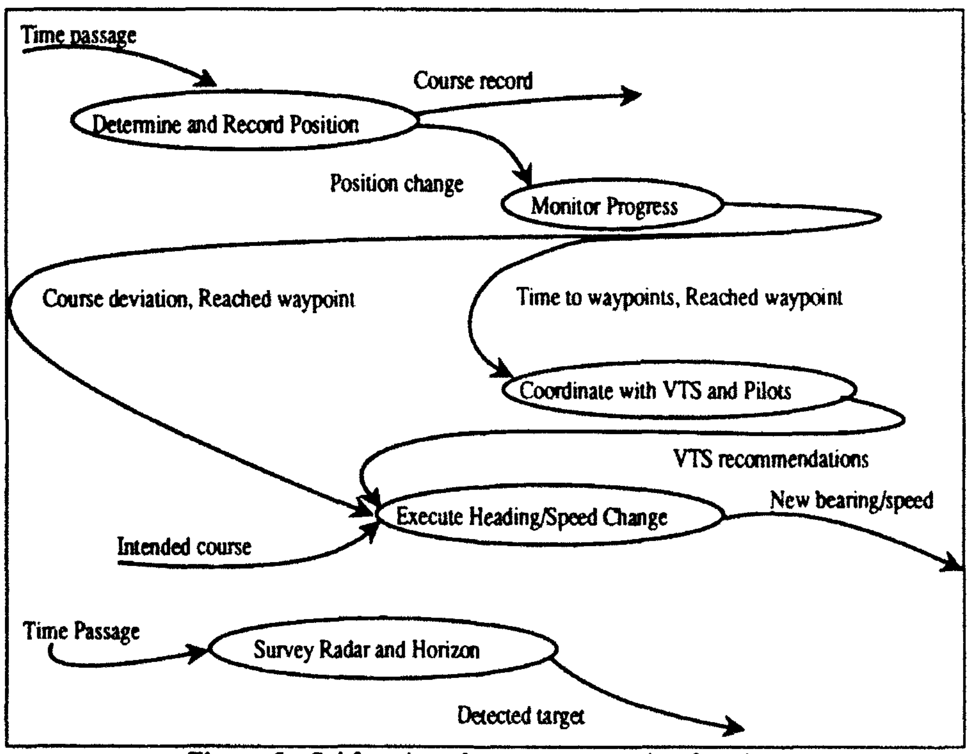

Figure 5. Subfunctions for course execution function.

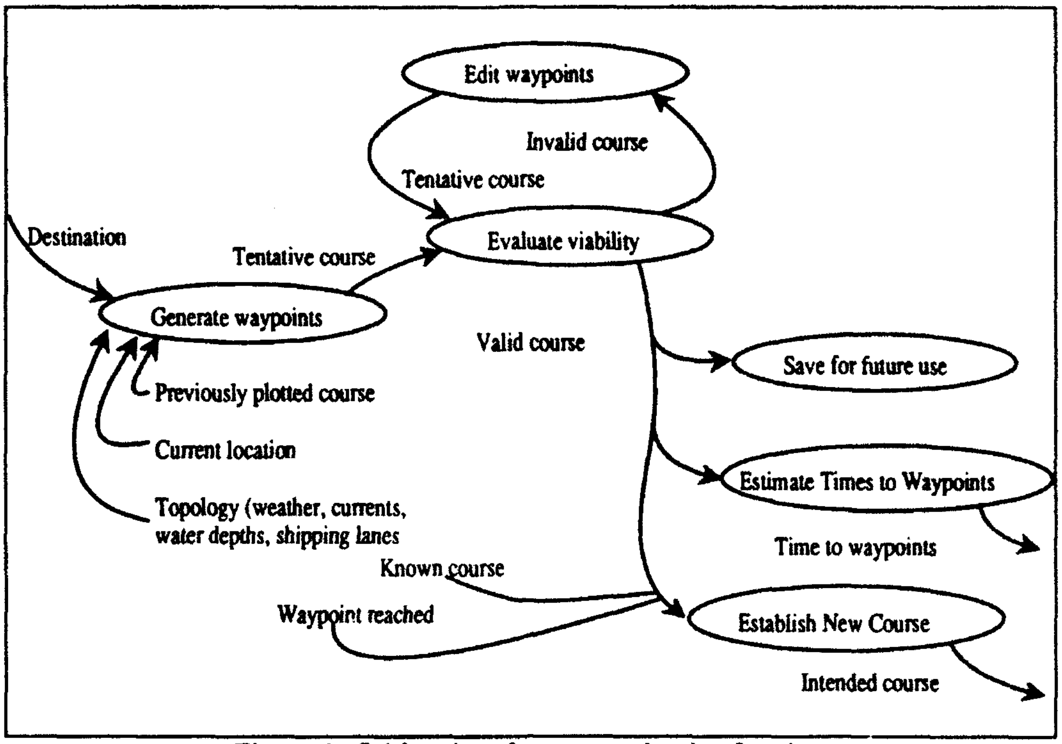

Figure 6. Subfunctions for voyage planning function.

The top-level functions shown in Figure 2 consist of voyage planning, course execution, course adjustment, and target evaluation. Voyage planning provides course changes given the final destination and waypoints that must be reached. Course execution enables the ship to proceed along the intended course. As the ship proceeds, potential threats may be identified which trigger the target-evaluation function. Target evaluation determines whether a threat exists. If a ship or other obstacle threatens ship safety, then the need for a course change triggers the course adjustment function. Course adjustment determines a new course; the revised course triggers course execution and the voyage continues. Together these functions provide a very general description of the essential aspects of ship navigation.

An examination of the subfunctions of the top level functions provides a more detailed description of voyage planning and navigation. For example, Figure 5 shows the subfunctions that support course execution. The activation of any one of these subfunctions depends on some subset of the variables that describe the overall state of the system. For instance, the subfunction "determine and record position" becomes active after a certain interval since the last position estimate. The exact time between position estimates depends on ship location, with the position recorded more frequently close to shore and less frequently in open ocean. Like the "determine and record" subfunction, each of the other subfunctions may become active when the system state changes. These changes in the system state are shown on the arcs of the network. In many cases, the execution of a subfunction, such as "determine and record position," creates information that triggers other subfunctions. In this instance, "determine and record position" identifies the change in ship position that acts as an input to "monitor progress." The subfunctions and the arcs that link them illustrate how changes in the system state and the completion of other subfunctions interact.

At this level, OFM prescribes the same functional requirements for navigation with and without technological aids, because any system must satisfy these demands. Thus, the interactions and information requirements represented in this network do not depend on the type of technology available for navigation. As technology changes, the role of the human in each of these functions may change, but the same information must be generated and transformed.

To understand how technology can affect navigation requires further analysis. While the relatively abstract representation of the system shown in Figures 2-6 remains constant regardless of changes in technology, a more detailed representation that includes the cognitive tasks associated with each subfunction will show the effects of technology. Because OFM only represents input/output relationships using state transitions, the analysis needs to be augmented to include a cognitive analysis of the demands associated with the tasks. This cognitive analysis involves assigning cognitive processes and demands to each of the tasks identified by OFM.

3.3 OFM-COGNITIVE ANALYSIS OF COLLISION AVOIDANCE

The goal of collision avoidance is the safe passage of the vessel through areas where various targets such as other ships or land masses present the threat of collision. This goal is accomplished through the functions of target evaluation, course adjustment and course execution, as shown in Figure 7. The OFM shown in Figures 2-6 represents all the behavioral components of navigation and voyage planning. Rather than examining all fu ons and subfunctions in this model, a more focused approach examines a subset of the total OFM. This subset is defined by prototypical activities. For example, collision avoidance is a prototypical activity made up of a subset of the functions and subfunctions contained in the OFM. Figures 7, 8, 9, and 10 show aspects of the OFM involved in collision avoidance. The collision avoidance activity begins with the sighting of another ship during course execution. The ship sighting triggers target evaluation, and the outcome of this function leads to a course adjustment or a resumption of the course execution function. The three top-level functions involved are shown in Figure 7, while Figures 8, 9, and 10 show the subfunctions involved in collision avoidance. The following sections analyze collision avoidance as performed with standard radar and plotting targets on a screen with a grease pencil (or a maneuvering board), and with ARPA.

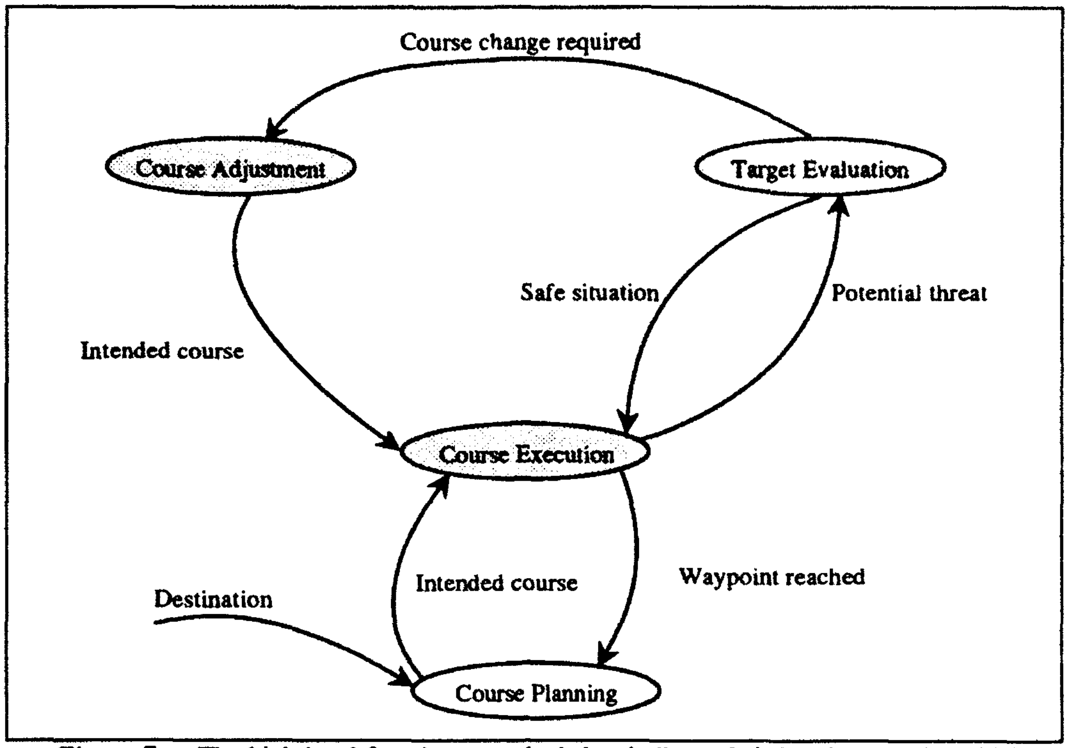

Figure 7. The high level functions are shaded to indicate their involvement in collision avoidance.

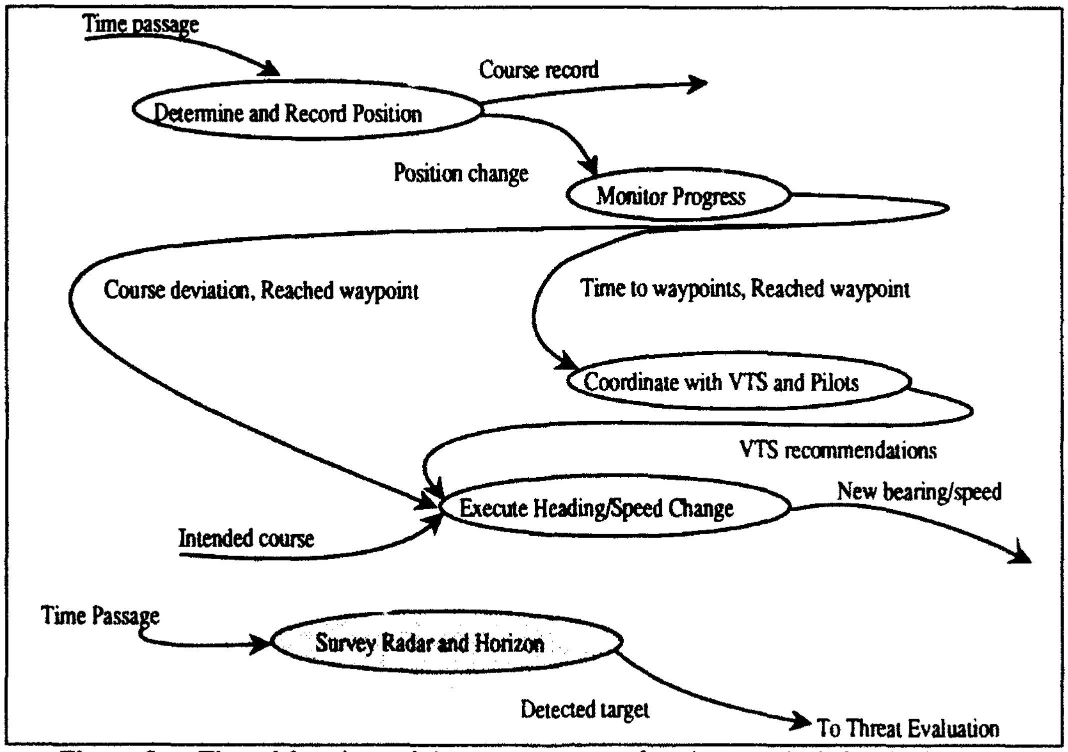

Figure 8. The subfunctions of the execute course function are shaded to indicate their involvement in collision avoidance.

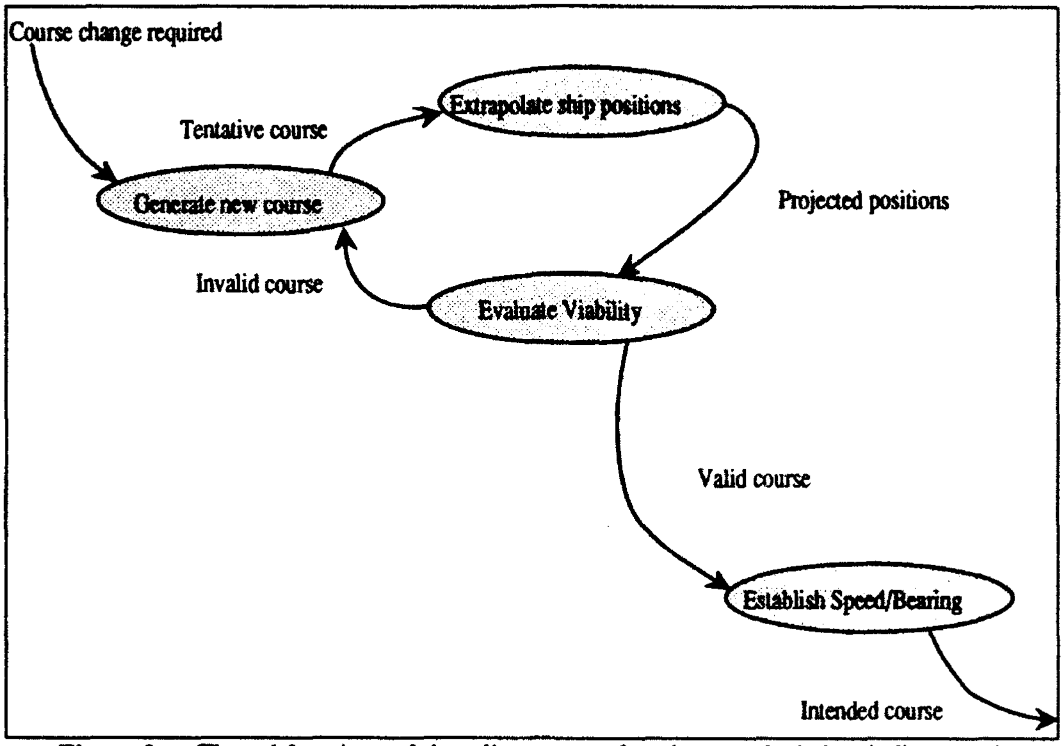

Figure 9. The subfunctions of the adjust course function are shaded to indicate their involvement in collision avoidance.

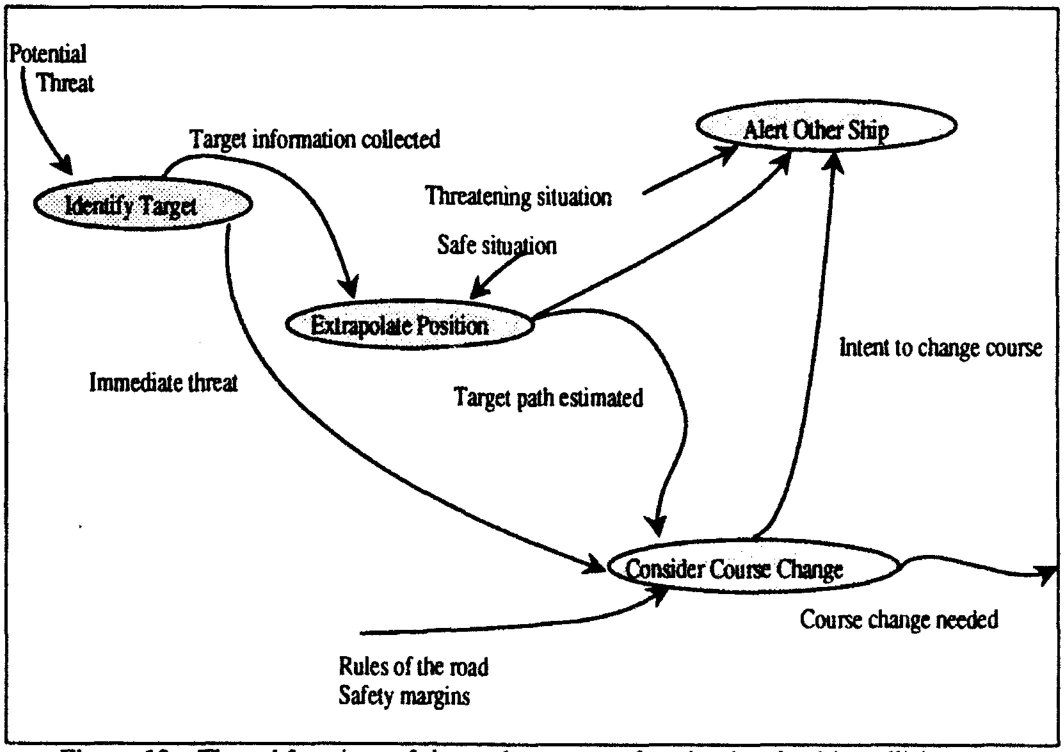

Figure 10. The subfunctions of the evaluate target function involved in collision avoidance.

3.3.1 Radar Grease-Pencil Plot Method

Table 2 presents an analysis of collision avoidance using standard radar and grease-pencil plotting techniques, which is the basis for the current USCG radar observer certification. The linear time line implied in this and subsequent tables is a result of the method of representation; in reality, tasks may be iterative, concurrent, or sequential. Table 2 includes the cognitive tasks associated with each OFM transition function, the underlying human information processing resources required, and the task and environmental factors influencing the mental demands.

Table 2 brings together both the OFM-based information and the cognitive tasks, resources and demands that describe how an operator carries out those functions. The left-most column contains functions and subfunctions identified in Figures 7-10. The cognitive analysis in the table characterizes the processing that is performed to obtain input and to change it into a form that will facilitate the next step in the task sequence. Cognitive analysis focuses on the internal mental operations that mariners need to perform, and the external demands that influence the effectiveness of those processes. It should be noted that the cognitive task column refers to *cognitive agent* tasks, which means that the tasks can be performed either by a machine or a human. The following paragraphs describe the cognitive analysis in detail, and correspond to the structure of Table 2.

In the course execution function and the radar-monitoring subfunction, the principal cognitive tasks are searching and filtering visual input, selecting input and detecting targets, communicating the existence of targets, and further searching a defined set of targets. Radar monitoring is a continuous activity subserved by the human information-processing resources of sustained and selective attention. The mental demands associated with this process include time on task and fatigue level. Perception and visual discrimination of potential signals from noise will eventually result in a target detection, either on the radar or the horizon. The environmental conditions influencing visibility will determine the effectiveness of visual discrimination, as well as the overall effectiveness of vigilance. Assuming that a target is discriminated and detected, knowledge of the target existence is the output, which triggers the next task of announcing the existence and location of that target; this relies on maintaining a working memory model of the target situation.

Table 2. OFM-Cognitive Analysis of Collision Avoidance Functions with Standard Radar/Grease Pencil Plotting

Function/Subfunction	Cognitive Agent Tasks	Input	Human Information Processing	Output	Task & Environmental Demand
Execute course/Monitor Radar	SEARCH & FILTER	Horizon or radar	Sustained & Selective Attention	Narrowed field	Time on task, fatigue level
	DETECT/INPUT SELECT	Sighting on horizon or on radar	Discrimination & Perception	Knowledge of existence	Visibility
	MESSAGE	Existence and location of target	Working memory	Shared knowledge of target	Competing tasks, language difficulty
	SEARCH	Target positions and density, speed, direction, weather, and safety bounds	Working memory	Potential collision situation	Number of items, rates of change
Target evaluation/ Identify target	IDENTIFY	Approximate position from visual sightings	Selective Attention Perception	Position on radar screen	Degree of rotation, complexity of image
	CODE	Position on radar screen	Perception	Reference point for future observations	Discriminability
Target evaluation/ Determine target position and course	INTERPRET	Position and relative motion	Working Memory	Reduced set of targets for detailed plotting	Number of targets, rate of change
	PLAN	Initial target mark	Long-term Memory	Time for second reference mark	Familiarity with procedure
	CODE	Current speed and direction	Perception; Long-term Memory	RT vector; ownship speed and direction	Familiarity with procedure
	CODE	Elapsed time (3 or 6 minutes)	Perception	MO_3 Point and RM_3 vector; target progress	Knowledge of track, Radar return quality
	COMPUTE	MO_3 Point	Working Memory; Long-term Memory	RM vector past ownship: Show if on collision course	Familiarity with procedure
	COMPUTE	MT vector and ownship position	Working Memory; Long-term Memory	True motion vector: Target bearing and speed	Familiarity with procedure

Table 2. (continued)

Function/Subfunction	Cognitive Agent Tasks	Input	Human Information Processing	Output	Task & Environmental Demand
	CODE/DISPLAY	RM line	Perception; Long-term Memory	Perpendicular between ownship and RM line: CPA	Familiarity with procedure
	INTERPRET	Target bearing and position relative to ownship (visual sighting or true motion vector from Radar)	Perception	Aspect of target ship	Availability of visual contact degree of transformation
	CODE/COMPUTE	Distance between M_3 and CPA	Working memory; Response selection/ execution	Distance to CPA	
	CODE/COMPUTE	RM vector	Working memory; Response selection/ execution	Relative speed	
	COMPUTE	Log scale, calculator, table or nomograph	Working Memory; Response selection/ execution	TCPA	
	COMPUTE (alternative)	Use calipers and RM vector to measure M_3-CPA distance in 3 minute intervals	Long-term Memory	TCPA	Accuracy requirements, Familiarity with procedure
Target evaluation/Alert other ship	MESSAGE	CPA, safe margin, and intended course	Perception, Long-term memory	Intent of other ship	Language differences, radio clarity, ambiguities and redundancy in communication
Target evaluation/ Consider course change	CATEGORIZE	Environmental constraints (weather and channel width), Standard operating procedures	Working Memory; Long-term Memory	Plot safety margin: Arc around ship	Interaction of maneuverability and environmental condition; Complexity of the situation, Familiarity with procedures, Ship inertia, Crew response time

Table 2. (continued)

Function/Subfunction	Cognitive Agent Tasks	Input	Human Information Processing	Output	Task & Environmental Demand
	DECIDE/SELECT	Aspect of target ship	Working Memory; Long-term Memory	Applicable rules of the road: possible course changes	Interaction of maneuverability and environmental condition
	COMPUTE	Speed of other ship (MO, Point), knowledge of ship inertia, speed of other ship	Working Memory; Long-term Memory	Target ship position extrapolated	Interaction of maneuverability and environmental condition; Familiarity with procedures
	COMPUTE	Extrapolated target ship position, safety margin as plotted	Long-term Memory	Tangent from predicted target position to safety margin: new direction of relative motion	Ship inertia, crew response time
	COMPUTE	New direction of relative motion	Long-term Memory	New RT line: new speed or direction for course change	Familiarity with procedures; Proximity and number of other ships
	COMPUTE	New relative motion vectors	Long-term Memory	New relative motion vectors for other marked targets: new CPA for other targets, viability of course	Familiarity with procedures
	TEST	New RM vectors for targets, new CPA for targets	Perception/Attention; Working Memory; Long-term Memory	Viability of course	Number of targets

The identified targets are further searched for information concerning their relative threat to the ship. This relies also on developing and maintaining a working memory model of the situation. In essence, this step involves focusing attention on the quadrants of concern on the radar scope, i.e., filtering out those targets that are obviously astern, or will pass without crossing ownship's intended track. The next step in collision avoidance with the grease-pencil method is the target evaluation function and identify target subfunction. This subfunction involves two cognitive tasks: identification of the position on the radar based on the approximate position from visual sightings, and coding or plotting of that position as a reference point for subsequent observations. This is shown as point R00 on the sample plot in Figure 11.[1] Perception and selective attention are required human information-processing resources for performing this task; the external demands include the discriminability of the signal on the screen, and the number of targets being tracked and how quickly they are changing.

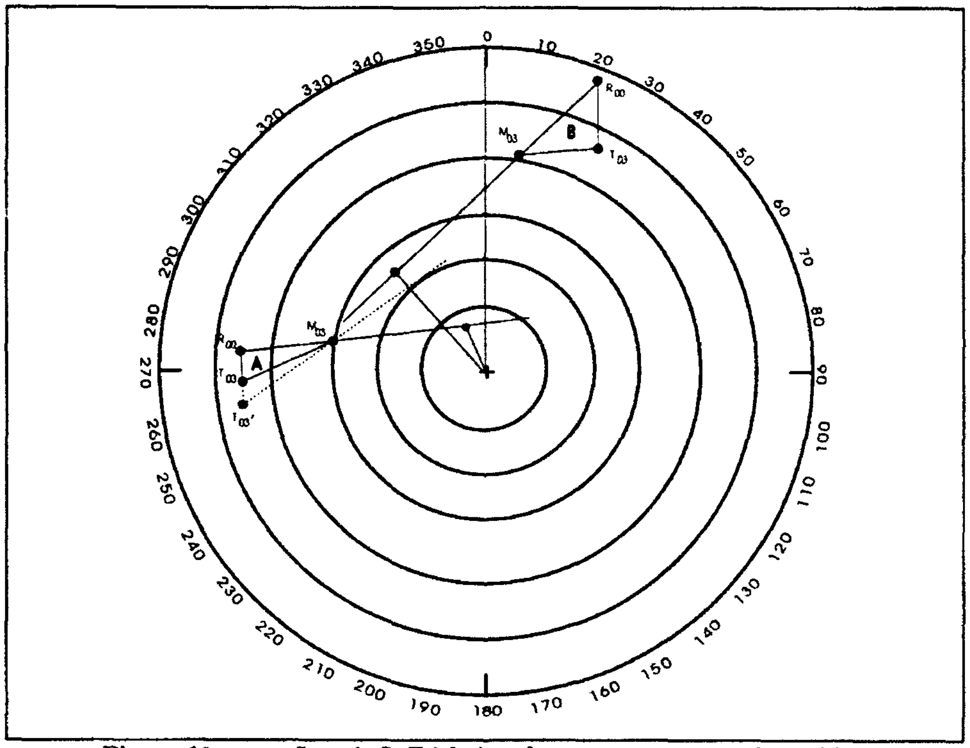

Figure 11. Sample R-T-M plots for two targets (A and B). Plots indicate CPA (closest point of approach) for Targets.

Following the marking of potential targets, the next subfunction of target evaluation is executed: determining target position and course. Based on the initial reference marks, the navigator can interpret the position and relative motion of potential targets, and determine whether they deserve further attention. This results in an updated working memory model containing a reduced set of critical targets for monitoring. With the set of critical targets, the navigator can plan the timing for the

[1]The discussion of various points and vectors applies to both targets A and B in Figure 11. The plots in this Figure illustrate the two target sightings (R_{00} and M_{03}) and vectors necessary to determine closest point of approach if the present course is maintained.

second reference marks on the targets of interest. At this point, the procedure of timing, marking and computing various parameters is invoked. This is (usually) a well-learned sequence of activities that is carried out on the basis of long-term memory. Refer to Figure 11 for prototypical plots for two targets.

The initial coding[2] task in the evaluation of target position and course is to plot the RT vector, which is based on the current speed and direction of ownship. The next coding step involves making the second mark for the target(s) being monitored. This is shown in Figure 11 as M03. The task and environmental demands affecting the perception of the radar input are the navigator's understanding of the radar track line left by the target, and the quality of the radar return. After M03 is plotted, the navigator can compute the direction of relative motion for the target, by drawing the RM vector past the heading flash line of ownship. This will indicate whether the ships are on a collision course (direct intersection with ownship), or if the target will simply pass in close quarters. The length of the RT vector indicates the speed of relative motion of the target. Further information about the target is gained by computing the direction of true motion, based on drawing a line parallel to the MT vector, through ownship. The speed of true motion (i.e., how fast the other ship is actually steaming) is given by the length of the MT vector. Determination of the closest point of approach (CPA) is based on a code/display task, which involves drawing a line perpendicular to the RM vector so that it intersects ownship. The length of this line reflects the CPA. Finally, the aggregate data of target relative motion and bearing is interpreted by the navigator to determine the aspect of the target ship, i.e., position and orientation relative to ownship. This determination involves translating from the relative motion display of the radar to the ship's maneuvering possibilities, such as port/starboard and oncoming versus overtaking. These decisions need to be made because the relative motion plot obscures the status of the other ship; e.g., it could be stationary. By the use of true-motion vectors, the target ship situation can be clarified. The interpretation of aspect is critical in deciding what types of evasive maneuvers to take, if any.

To obtain various parameters that are useful in collision-avoidance decision making, the navigator uses the various vectors and their lengths. The distance to the CPA is a computing[3] task, based on the length of the line between M03 and the intersection of the perpendicular line from ownship. The length of this line is usually measured with calipers, and compared to the rough distance scale based on radar ring settings (e.g., each ring representing one mile). Similarly, using the 3-minute rule, the RM vector can be coded in terms of length based on number of radar rings traversed; the resulting

[2] The term code is used to refer to an operation in which data in one set of units is converted to a different set of units, such as coding the passage of time with a mark on the display.

[3] The term compute is used to refer to operations in which data transformations are made that maintain the same measurement units or framework, such as length of a vector being transformed to distance. In some instances, a task may involve both coding and computing, as for example translating vector length to time (coding), and to distance. While the term compute implies mathematical transformations, as Miller uses the term it can also refer to the geometric operations used in radar plotting.

number is then multiplied times 20 (because 3 minutes is 1/20 of an hour). This yields speed of relative motion. The time to CPA is calculated by using either a log scale, nomograph, calculator or time/speed table, or by using a caliper measurement to the CPA that reflects the speed of relative motion in 3-minute increments. In practice, the "shortcut" computational methods (such as caliper measurement) are used, and rely on the cognitive resources of working memory and response selection and execution (i.e., making an accurate measurement of the proper vector, to which the computational rule is then applied). Based on the results of these various computations, communication (the MESSAGE task) with the other ship is made to determine intent and to coordinate maneuvers.

The final subfunction in collision avoidance with the grease-pencil plotting method is consideration of a course change. This depends on input information that is categorized by the navigator in order to use the data for decision making and control. Based both on a working memory model of the current situation, and long-term memory representations of safe practices, a safety margin is plotted around the ship. A decision and selection process is then applied to the aspect of the target ship(s) to determine potential course changes, based again on the working memory model of the current situation, and long-term memory of rules of the road. This decision is followed by a series of computations to determine potential course changes, based on predicted target positions. In essence, a tangent is drawn from M03 to the desired CPA, and extended back through the original RT line. R00 is placed on the new vector, thus resulting in a new RT line. The length of this new RT line gives the new speed for ownship. This is shown for Target A in Figure 11 by the dotted line extended from the desired CPA. Extension of this line back to the plot shows that slowing the speed of ownship by a small amount will lead to a better safety margin. A vector drawn from ownship that is parallel to the new RT line gives the new course heading. For Target A, this vector is not necessary, since a speed change alone will improve the safety margin. Depending on the number and proximity of other ships, the new course is evaluated for viability.

3.3.2 ARPA Method

ARPA provides significant automated assistance in carrying out many of the cognitive tasks associated with collision avoidance. Inspection of Table 3 shows a substantial reduction in the number of cognitive tasks that need to be performed by the human operator (25 for grease pencil method, vs. 12 for ARPA). The general procedure by which collision avoidance is conducted is the same; the principal difference is the extent to which automated aids can be used to carry out some of the searching, detection and computational tasks. The analysis contained in Table 3 is based on our observations of ARPA usage; five additional subfunctions such as target detection can be automated if the operator wishes.

The initial cognitive tasks of search and filter, detect/input select, message and search can be performed either by a human operator or automatically. If they are performed by a navigator, the same human information-processing and task/environmental demands as delineated for the grease-pencil method apply. In virtually all of our observations to date, automatic target detection has not been used; the reason given is that a high percentage of "nuisance" targets or false alarms, such as rain storms, are acquired as targets. Instead, the navigator tends to perform these cognitive tasks without automation, and relies instead on ARPA to relieve the burden of the various point plotting, vector drawing, measurement and timing activities described above. Thus, up to the subfunction of determining target position and course, and the cognitive task of interpretation, our observations suggest that ARPA functions as a standard radar, in terms of the cognitive tasks performed by the navigator.

Following the interpretation of targets marked for attention, ARPA features are employed to obtain data concerning relative motion, true motion, CPA and time to CPA (TCPA). These automatic operations provide the input data for the cognitive task of interpretation, performed by the navigator, to determine the aspect (i.e., orientation) of the target ship(s). Based on this determination, further targets are selected for ARPA coding and computation of the distance to CPA, relative speed of the targets, and TCPA. Based on these outputs, the navigator communicates (MESSAGE) with the other ship(s) to determine their intent. The cognitive task of determining the safety margin can be done either automatically or manually, based on the task and environmental demands, such as channel width and ship inertia. Based on this information, the navigator will decide on the applicable rules of the road, and, if appropriate, have the ARPA compute new relative motion vectors for the targets based upon a trial maneuver feature.

Table 3. OFM-Cognitive Analysis of Collision Avoidance Functions with Automated Radar Plotting Aid (ARPA) (In the Human Information Processing column, entries followed by /AUTO are typically performed by the operator, but can be done automatically. Other tasks that are exclusively automated are shown with the AUTO entry only.)

Function/Subfunction	Cognitive Agent Tasks	Input	Human Information Processing	Output	Task & Environmental Demand
Execute course/Monitor Radar	SEARCH & FILTER	Horizon or radar	Sustained & Selective Attention/AUTO	Narrowed field	Time on task, fatigue level
	DETECT/INPUT SELECT	Sighting on horizon or on radar	Discrimination & Perception/AUTO	Knowledge of existence	Visibility/Radar return quality
	MESSAGE	Existence and location of target	Working memory/AUTO	Shared knowledge of target	Competing tasks, language difficulty
	SEARCH	Current targets position and density, speed, direction, weather, and safety bounds	Working memory/AUTO	Potential collision situation	Number of items, rates of change
Target evaluation/ Identify target	IDENTIFY	Approximate position from visual sightings	Selective Attention Perception	Position on radar screen	Degree of rotation, complexity of image
	CODE	Position on radar screen	Perception; Response selection/execution	Reference point for future observations	Discriminability/done when Auto mode off for prior tasks
Target evaluation/ Determine target position and course	INTERPRET	Position and relative motion	Working Memory	Reduced set of targets	Number of targets, rate of change
	CODE	Selected targets	AUTO	Target progress	
	COMPUTE	Selected targets	AUTO	RM vector: show if on collision course	
	COMPUTE	Selected targets	AUTO	True motion vector: target bearing and speed	
	DISPLAY	Selected targets	AUTO	Perpendicular between ownship and RM line: CPA	

Table 3. (continued)

Function/Subfunction	Cognitive Agent Tasks	Input	Human Information Processing	Output	Task & Environmental Demand
	INTERPRET	Target bearing and position relative to ownship (visual sighting or true motion vector from Radar)	Perception Working Memory	Aspect of target ship	Availability of visual contact degree of transformation
	CODE	Selected targets	AUTO	Distance to CPA	
	CODE	Selected targets	AUTO	Relative speed	
	COMPUTE	Selected targets	AUTO	TCPA	
Target evaluation/Alert other ship	MESSAGE	CPA, safe margin, and intended course	Perception, Long-term memory	Intent of other ship	Language differences, radio clarity, ambiguities and redundancy in communication
Target evaluation/ Consider course change	CATEGORIZE	Environmental constraints (weather and channel width), Standard operating procedures	Working Memory; Long-term Memory/AUTO	Plot safety margin: arc around ship	Interaction of maneuverability and environmental condition; Complexity of the situation, Familiarity with procedures, Ship inertia, Crew response time
	DECIDE/SELECT	Aspect of target ship	Working Memory; Long-term Memory	Applicable rules of the road: possible course changes	Interaction of maneuverability and environmental condition
	COMPUTE	New relative motion vectors	AUTO	New relative motion vectors for other marked targets: new CPA for other targets, viability of course	
	TEST	New RM vectors for targets; New CPA for targets	Perception/Attention; Working Memory; Long-term Memory	Viability of course	Number of targets

3.3.3 Implications of Cognitive Analysis of Collision Avoidance

To evaluate the implications of the foregoing cognitive task analysis, we considered a classification of Miller's (1971) task transactions related to the relative complexity or type of operations. Table 4 assigns the 25 transactional terms to three categories based on the nature of the operation: data acquisition, data handling and data interpretation. These categories facilitate the analysis of automation effects on human performance.

Table 4. Classification of System Task Transaction Terms

Data Acquisition	Data Handling	Data Interpretation
Filter	Message	Identify
Detect	Queue to channel	Interpret
Search	Code	Categorize
Input Select	Transmit	Decide/Select
	Store	Plan
	Short-term Memory	Test
	Count	Adapt/Learn
	Compute	Goal image
	Control	
	Edit	
	Display	
	Purge	
	Reset	

A summary of the analysis comparing the two methods of collision avoidance is shown in Table 5; ARPA tasks were counted as manually performed if that is how we saw them typically conducted - indicated in Table 3 by double entries in the human information processing column. This table presents frequency counts of the various types of cognitive task transactions required to perform collision avoidance. The OFM-cognitive analysis of the grease-pencil radar plot and ARPA methods of collision avoidance illustrate a substantial reduction in the data-handling cognitive operations. These are task transactions that involve coding, computing and displaying results. Grease-pencil plotting entails 15 data-handling transactions per target plot, whereas ARPA requires only three (i.e., selection of target for further processing and two verbal message tasks).

The data-acquisition cognitive tasks involve searching and filtering input from the sensors. As illustrated in Table 5, there is no change in the number of these tasks from one method to the other. Our observations indicated that automatic data acquisition was not commonly employed, at least in the routes we traversed. Similarly, the data-interpretation cognitive-task transactions (identify, interpret, plan, decide, select, categorize) do not change substantially between methods. The only change is that navigators do not need to plan for the timing of a three-minute reference mark in order to obtain the various plot vectors.

Table 5. Frequency Count of Cognitive Task Transactions for Grease Pencil Method and ARPA

	Data Acquisition	Data Handling	Data Interpretation	Total
Grease Pencil	3	15	7	25
ARPA	3	3	6	12

In terms of human information processing, the transition from standard radar to ARPA reduces the load considerably on working memory and long-term memory, because ARPA performs the computations based on stored data. Thus, the navigator is no longer required to hold representations of target progress in working memory while planning for a timing mark, nor is it necessary to convert various measurements to distance and time. The latter operations can be the source of errors such as digit transpositions in headings and perceptual confusion of multiple targets. Similarly, working memory for executing these computational procedures is not required by ARPA, thus allowing the navigator to consider potential actions based on rules of the road. The automated data-handling capabilities of ARPA enhance the quality and accuracy of information available to the navigator, since the error-prone cognitive operations of computing and coding are handled by computer. Through appropriate human monitoring of the input to these computations, the navigator can be assured of reliable data, and can focus more on interpreting and acting on that information.

The relative lack of change in the cognitive task transactions involving data interpretation reveals a potential problem in terms of the increased salience of these activities. Because the labor intensive coding and computation of the grease-pencil method is eliminated, it is possible to track more targets than could be physically handled within the 3-minute tracking period of standard radar. Paradoxically, *the reduction in data handling task requirements can increase the interpretive requirements*, should the navigator choose to track more targets than they otherwise would with standard radar. While we have not observed this to occur, the possibility remains that ARPA technology can overload a navigator (this might be why navigators choose to manually select the targets they wish ARPA to track).

A second potential issue with the increased salience of data-interpretation cognitive tasks lies in the area of computer-facilitated decision making. For example, ARPA can provide information concerning the effects of alternative collision-avoidance maneuvers (the trial-maneuver feature). However, this information must still be interpreted in the context of rules of the road and the aspect of the target ships. Blind adherence to information presented on a scope regarding potential maneuvers has led to collisions in the past. This phenomenon is particularly evident with the Sperry "PADS" system, which presents a dynamic surround on ownship and marked targets; the nominal task is to steer the ship to keep the "pad" surrounds from overlapping. However, training exercises observed at Pacific Maritime Institute have shown that users consistently steer into each other when both target and ownship are using this system. In this case, ARPA provides too much information about ship and target locations, and no information related to maneuvers, such as rules of the road. This can result in overinterpretation that leads to both ships anticipating each other's moves, without necessarily considering rules of the road. Because ARPA is providing decision-aiding information, the navigator may fail to interpret the data in other than a literal manner, and can maneuver the ship as if the ARPA were a virtual display of the external world.

3.4 OFM-COGNITIVE ANALYSIS OF VOYAGE PLANNING

Voyage planning is a frequently performed task by navigators, even when traveling relatively well-known courses. The basic goal of the process is to generate a visual representation of the course to be traveled by the ship. The process involves visualization of the course, and generation of voyage segments and waypoints, as shown in Figure 12. Voyage planning is both an anticipatory and continuous function. If conditions change, for example because of Vessel Traffic System (VTS) re-direction, a preplanned course will need to be altered. Figure 12 shows the various subfunctions involved in voyage planning, all of which serve as inputs to the subfunction of establishing a new speed and course for the course execution function. The two methods of voyage planning that will be compared in the OFM-cognitive analysis are the use of paper charts for planning, and the use of an ECDIS prototype.

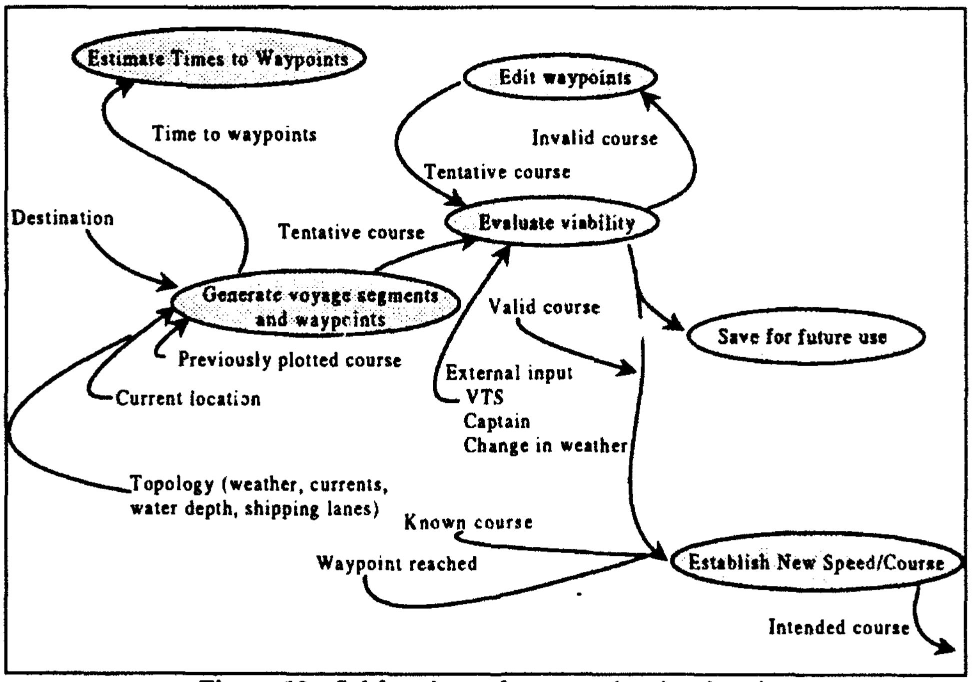

Figure 12. Subfunctions of voyage planning function.

3.4.1 Voyage Planning With Paper Charts

OFM-cognitive analysis of voyage planning with paper charts is shown in Table 6.

Table 6. OFM-Cognitive Analysis of Voyage Planning with Paper Charts

Function/Subfunction	Cognitive Agent Tasks	Input	Human Information Processing	Output	Task & Environmental Demand
Voyage planning/ Generate voyage segments and waypoints	PLAN	Destination, current location, topography, schedule	Long-term Memory, Perception	Goal image	Familiarity with procedure, complexity of route, e.g., number of ports, navigation hazards
	INTERPRET	Goal image	Long-term Memory Perception	Decomposition of goal image	Familiarity with route
	SELECT	Topography, schedule	Working Memory, Long-term Memory	Relevant information	Familiarity availability and currency of information
	IDENTIFY	Decomposition of goal image, relevant information	Perception	Visual boundaries of voyage segments	Familiarity with route, cues from chart
	CODE	Visual boundaries of voyage segment	Perception, Response execution	Segment length and waypoint	Chart features
	CODE	Remaining voyage segments	Perception, Response execution	Intended track and waypoints	Chart features
	DISPLAY	Tracked waypoints	Long-term Memory	Procedure annotations	Familiarity with procedure
Estimate times to waypoints	CODE/COMPUTE	Intended track and waypoints	Response execution, Working memory	Tentative course with times to waypoints, bearings and speeds	Measurement and calculation precision
Voyage planning/ Evaluate viability	INTERPRET	Tentative course, External input	Working memory, Long-term memory	Invalid/Valid course	Familiarity, complexity
	PLAN	Invalid course, External input, Potential routes	Working memory, Long-term memory	Valid alternatives	Specificity
	DECIDE/SELECT	Viable alternatives	Working memory, Long-term memory	Visual boundaries of voyage segments	Familiarity, availability of information

Table 6. (continued)

Function/Subfunction	Cognitive Agent Tasks	Input	Human Information Processing	Output	Task & Environmental Demand
Voyage planning/Edit waypoints	PURGE	Invalid course segments	Response execution	Segment to be traversed	
	CODE	Segment to be traversed, Visual boundaries of voyage segments	Perception, Response execution	Segment length and waypoint	Chart features
	CODE	Remaining voyage segments	Perception, Response execution	Intended track and waypoints	Chart features
Voyage planning/ Estimate times to waypoints	COMPUTE	Intended track and waypoint	Response execution, Working memory	Tentative course with times to waypoints, bearings and speeds	Measurement and calculation precision
Voyage planning/Save for future use	STORE	Valid course		Paper representation	Need for new course plots

The first subfunction involves generating voyage segments and waypoints. The initial cognitive task in this subfunction is labeled as planning; in Miller's (1971) terminology, this refers to "rules for predicting what future sets of conditions will occur and what responses to make to them and in what order." This can be construed as the cognitive task of considering the various factors associated with the task and environmental demands column, i.e., complexity of route, number of ports, and navigation hazards. This is facilitated by knowledge of the destination(s), current location, schedule, and the topography of the region to be traversed, as indicated in a paper chart. The initial planning is best conducted on a large scale chart covering the entire area to be traversed. The output of this planning process is a goal image of the voyage profile, i.e., an image which "embodies the criteria for terminating a task or segment of work or mission with some degree of success" (Miller, 1971). That is, the goal image is the navigator's conceptual understanding of what is required to get from the current location to the desired location.

The subsequent task in voyage planning involves interpreting the goal image so that it is decomposed into discrete segments. As with planning, this task involves the use of long-term memory of the route (if applicable), memory of potential weather/current patterns, and perceptual information from the chart. This task is facilitated by familiarity with the route. The next task is the selection of specific topographic features of the paper chart and schedule information to determine potential routes, based on arrival requirements and potential hazards. This information permits the navigator to identify the visual boundaries of particular voyage segments. For example, a chart shows the location of shipping lanes. Prior studies of human navigation behavior and mental models suggest that people think about navigation through cities in hierarchical terms, such as districts, neighborhoods, and locations within neighborhoods (Chase, 1982). Further, people tend to organize information regarding these clusters into paths, edges, districts, nodes and landmarks (Lynch, 1960). Depending on the sophistication of the navigator and his familiarity with the area, these features are given special attention in planning. Analogues of hierarchical navigation information in a maritime context might include oceans, pilotage approach, pilotage, harbors, and berths.

Based on the identification of visual boundaries, the navigator codes the voyage segment boundaries on the paper chart, with the output being a segment of particular length. The length of the segment defines the location of the waypoints. Waypoint location allows the navigator to perform the display task of annotating particular waypoints with voyage operational information, such as when to perform certain engine and steering tests, or when to call for pilots or tugs. The next subfunction of estimating times to waypoints, is undertaken through the cognitive task of computing time to waypoints based on the length of the intended voyage segment.

The viability of the course is evaluated by three cognitive tasks: interpretation of the tentative course, planning alternative routes for invalid courses or course segments, and deciding and selecting the boundaries of alternative course segments. This set of cognitive tasks is generally supported by input from other members of the ship's crew in addition to the deck officer responsible for planning, e.g., the master or pilot. For example, the second officer may convey VTS instructions to delay departure because of the passage of an inbound laden tanker.

If invalid course segments are identified, the waypoint editing subfunction is undertaken. This involves purging the invalid segments (by means of erasing them from the chart), and coding the new segments to be traversed. Following the course edits, new arrival times at waypoints are computed, and the course is stored, by virtue of its archival nature on the paper chart, for future use.

3.4.2 Voyage Planning with ECDIS

ECDIS provides an electronic analogue of the paper chart that can be used for a voyage-planning function. OFM-cognitive analysis of ECDIS voyage planning is shown in Table 7. Although a number of functions, subfunctions and tasks are not supported by the ECDIS we observed, the analysis presents how ECDIS is used for voyage planning in its current configuration. In reality, the lack of functional support causes mariners to use conventional paper charts; however, for analysis we compared how the current ECDIS features are used for voyage planning.

The first operation performed by the navigator using ECDIS is to decide which electronic chart to bring up on the display. The choice is based on the same information as is used in planning with paper charts, i.e., where the ship is going. However, the resulting goal image is more closely linked to the actual electronic chart display, since it relies on having the proper scale, if not resolution. Because of the more restricted display space for electronic charts, the paper chart's level of resolution cannot be attained with the same display scale. Thus, interpretation of the goal image (i.e., where the ship is going) requires the navigator to coordinate the discrete operations of panning, zooming and redraw, possibly using a two- display window. This set of operations allows the navigator to select and identify the relevant topographic details. As with the goal image interpretation task, this task requires interaction with display manipulation features, and places a heavier load on working memory than does working with paper charts.

Following the identification of voyage segments based on their visual boundaries, the navigator codes them. The procedure that is used for this is the opposite of the paper chart approach; with ECDIS, the waypoints are entered first - these are used to define the voyage segment length. On the basis of waypoint location, the computer automatically generates voyage segments, and draws them on the screen to fill in between the waypoints. This process is repeated for all remaining voyage segments. The display task (showing track annotations) referred to in the paper chart planning process is not currently supported by the ECDIS we observed.

Time estimation to waypoints and evaluating the viability of the course are functions that are not currently supported by the ECDIS we observed. These functions are all performed by human interpretation of the intended voyage track with paper charts; the waypoint time computation cannot be accomplished simply because the function has not been implemented. Similarly, with paper charts, a human intermediary interprets the planned course and determines the extent to which the ship may encounter hazards. At this point in development, the ECDIS we observed does not provide warnings about a planned course through unsafe (e.g., too shallow) waters. If human interpretation of the ECDIS course shows invalid segments, the segments will be purged, by means of eliminating the waypoints (this requires finding them, and they are somewhat difficult to locate with the cursor). New voyage segments are added according to the procedure described above.

3.4.3 Implications of Cognitive Analysis of Voyage Planning

A summary of the cognitive analysis of voyage planning is shown in Table 8. This table shows that both paper chart and ECDIS voyage planning are virtually the same in terms of task transaction structure. ECDIS does involve an additional coding step for voyage-segment distance, based on waypoint location, but this is handled automatically. Thus, there is no apparent decrease in workload brought about by new technology. An examination of the qualitative differences in how tasks are carried out, and the relative loads imposed on human information-processing resources illustrates areas in which designers may improve the system to better support voyage planning. The following paragraphs describe qualitative distinctions in paper chart and ECDIS task performance that illustrate three principal issues: 1) the visual limitations of a cathode ray tube (CRT), 2) the lack of ECDIS functionality, and 3) the need to develop knowledge of specific user-interface operations.

Table 7. OFM-Cognitive Analysis of Voyage Planning with ECDIS

Function/Subfunction	Cognitive Agent Tasks	Input	Human Information Processing	Output	Task & Environmental Demand
Voyage planning/ Generate voyage segments and waypoints	DECIDE/SELECT	Destination, current location, topography schedule	Long-term Memory, Perception	Goal image, electronic chart display	Locating proper scale through menu system, lower resolution of electronic chart
	INTERPRET	Goal image	Long-term Memory perception	Decomposition of goal image	Coordination of pan, zoom, redraw; Familiarity with menu structure
	SELECT	Topography, schedule	Working Memory; Long-term Memory	Relevant information	Familiarity, availability and currency of information
	IDENTITY	Decomposition of goal image, relevant information	Perception	Visual boundaries of voyage segments	Coordination of pan, zoom, redraw; Familiarity with menu structure
	CODE	Visual boundaries of voyage segment	Perception, response execution	Waypoint	Syntax of user interface
	CODE	Waypoints	AUTO	Segment length	
	CODE	Remaining voyage segments	Perception, response execution	Intended track and waypoints	Syntax of user interface
	DISPLAY	Waypoints		Annotations	Not supported
Voyage planning/ Estimate times to waypoints	COMPUTE	Intended track and waypoint		Tentative course with times to waypoints, bearings and speeds	Not supported
Voyage planning/ Evaluate viability	INTERPRET	Tentative course, External input		Invalid/Valid course	Not supported
	PLAN	Invalid course, External input, Potential routes		Valid alternatives	Not supported
	DECIDE/SELECT	Viable alternatives		Visual boundaries of voyage segments	Not supported
Voyage planning/Edit course	PURGE	Invalid course segments	Response execution	Segment to be traversed	Syntax of user interface

Table 7. (continued)

Function/Subfunction	Cognitive Agent Tasks	Input	Human Information Processing	Output	Task & Environmental Demand
	CODE	Visual boundaries of voyage segment	Perception, Response execution	Waypoint	Syntax of user interface
	CODE	Waypoints	AUTO	Segment length	
	CODE	Remaining voyage segments	Perception, Response execution	Intended track and waypoints	Syntax of user interface
Estimate times to waypoints	COMPUTE	Intended track and waypoint		Tentative course with times to waypoints, bearings and speeds	Not supported
Voyage planning/Save for future use	STORE	Valid course	Perception, Working memory, Long-term memory, Response execution	Saved course	Familiarity with menu structure

Table 8. Frequency Count of Cognitive Task Transactions for Voyage Planning

	Data Acquisition	Data Handling	Data Interpretation	Total
Paper Charts	1	9	6	16
ECDIS	1	9	6	16

The technologies that support voyage planning, i.e., paper charts and ECDIS, result in substantially different ways of accomplishing the same overall function. Beginning with the generation of a goal image of the voyage, paper charts support this task in a more fluid way than does ECDIS. In a glance or set of glances at one or several charts laid out on a table, the navigator can define a clear image of the planning task. With the ECDIS we observed, this process is much clumsier, in that the navigator may need to determine how to display more than one chart, of more than one scale, and be able to reconcile differences in scale/location within the display window. Essentially, this is a problem of how much can be displayed within the confines of a single CRT (the "keyhole effect"), and requires the use of panning, zooming and redrawing in order to accomplish the functions that the eye and attentional focus accomplish with paper charts. These differences are carried through the other cognitive tasks of generating voyage segments and waypoints. The task and environmental demands associated with paper-chart planning include route familiarity and visual cues available from the chart. In contrast, the demands when accomplishing the tasks with ECDIS include understanding of the display functions, and familiarity with the menu structure.

In coding voyage segments, another qualitative difference between paper chart and ECDIS planning is evident. In plotting the intended passage on the chart, a paper chart system involves the use of a pencil, triangle and calipers to plot the course lines. This is a highly manipulative method of interacting with a large-scale chart, showing the entire voyage track line that is intended. Particular parts of this track line are transferred to smaller-scale charts, as necessary. This involves physical manipulation and mental computation in the determination of distances. This is typically done on the basis of landmarks shown on the chart, and prior knowledge of the course. The watch officer makes use of the distance scales on the paper chart to set caliper lengths to correspond to particular voyage segments. Chart features provide support for accomplishing this function.

The prototype ECDIS method of voyage planning uses software-based features to provide a means of drawing the intended track. This is based on using a trackball-controlled cursor to move to an intended waypoint and establish a mark. The computer then fills in the track between waypoints marked by the watch officer. This method of drawing an intended voyage track differs qualitatively from the paper chart method, particularly in that individual segments are measures to a waypoint with the paper chart, whereas waypoints are set first with the electronic chart. While the end result is the same, the process by which the result is obtained is quite different, and the electronic method currently violates the mental models established for performing this task. While chart features support this task with a paper system, a task demand is imposed by ECDIS in the form of user-interface knowledge requirements, i.e., the navigator must understand the language of the interface in order to accomplish the task. Additionally, the prototype ECDIS does not provide the elementary support necessary for computing distances between waypoints, i.e., waypoints can be selected, the latitude and longitude determined, and distances calculated on that basis. However, direct distance determination is not currently supported.

The function of evaluating course viability is not readily supported at this time by the ECDIS we observed. That is, it will not provide warnings of a course plotted too close to some hazard. Thus, this function would need to be carried out in the same way it is currently: by consulting with another knowledgeable adviser, such as the master or a pilot. In addition, Table 7 shows that current versions of ECDIS do not support many other functions that mariners require. The ECDIS certainly has the capability to become an expert adviser, but caution should be exercised in interpreting its recommendations. This echoes the problem of over-reliance on technology described above for ARPA.

The final contrasting function between paper charts and ECDIS is the storage of courses for future use. ECDIS will permit the storage of a course plot file; the only limitation is the available disk space. In contrast, paper-chart planning results in a series of charts with pencilled-in track lines (intended and actual). These can be stored for future use, but requirements for alternative plotting on the same chart would necessitate erasure of the saved course. Charts are expensive and often updated, and so are not an ideal medium for saving voyage plans.

The human information-processing demands of ECDIS and paper chart voyage planning appear similar, based on the entries in Tables 6 and 7. Since the cognitive tasks are identical with the two technologies, this is reasonable. However, the qualitative differences in how the tasks are performed has implications for the load on human information-processing resources. For example, working memory and long-term memory might have more demands in terms of visualization of the voyage goal image with ECDIS than with a paper chart. This is because of the requirements imposed by ECDIS to view information within the confines of a CRT. Similarly, working memory would likely be taxed to a greater degree in maintaining information concerned with chart boundaries and required operations to see the undisplayed portions of the electronic chart. This would be coupled with the need to recall how to operate the user interface. Execution of proper user-interface syntax is a response-system demand, and errors in response execution can do anything from displaying the wrong chart, to eliminating important information such as depth markers. Perceptually, the issue of "visual frame" is important. Typical paper charts are displayed on 36" x 48" rectangles for any scale used. Scale can be specified with ECDIS, but the display space is limited to the visual frame offered by the CRT, which is a 19-in. diagonal. Thus, the same scale of information is available but in a smaller space with reduced display area. If a zoom function is used to enhance a certain part of the display, important adjacent data may go off the screen. Further research on the visual and cognitive operations performed with paper charts may help to suggest advanced display techniques.

3.5 OFM-COGNITIVE ANALYSIS OF TRACK KEEPING

Track keeping is a subfunction of the course execution function. The shaded portions in Figure 13 illustrate the subfunctions involved in track keeping. The purposes of track keeping are to ensure that the vessel is within an acceptable margin of the intended voyage track, and to determine if course changes are required based on location, such as reaching a waypoint. Track keeping is presently accomplished with paper charts; ECDIS can offer a fully automated track keeping function. These two approaches are compared below.

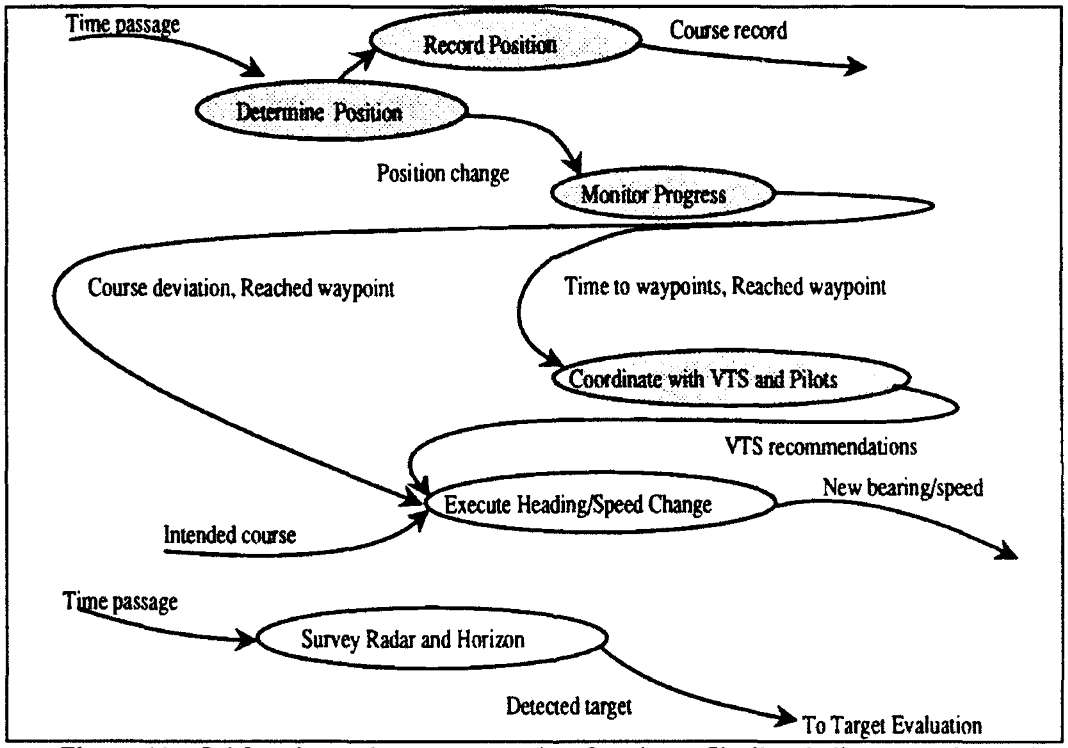

Figure 13. Subfunctions of course execution function. Shading indicates track keeping subfunctions.

3.5.1 Track Keeping with Paper Charts

Table 9 presents the results of the OFM-cognitive analysis of track keeping with paper charts. The initial function involves determining the current position of the ship. This function starts with the cognitive task of searching and filtering landmarks, using charts and the visible environment as guides. The resulting set of potential landmarks is reduced to two or three good points for taking bearing measurements.[4] The bearing of each landmark is coded by means of reading the bearing from the radar electronic bearing line, or the visual bearing, to the selected point. The bearings are coded in written form, and then selected individually for plotting on the paper chart. The position recording

[4]"Good" points are separated by a 90° angle.

function is based on the coding of plotted points and their resulting vector intersections; the intersections reveal the position of the ship. This is plotted on the chart, along with the current time. Monitoring the progress of the track involves comparing ("test") the actual position of the ship with the intended position (based on the voyage plan). The track kept on the paper chart provides both a test of current position relative to intended position, and a historical record of location. This latter function provides a basis for legal documentation in the event of a grounding or collision.

3.5.2 Track Keeping with ECDIS

Table 10 shows the functions and tasks involved in track keeping with ECDIS. The initial task of determining position is completely automated by the GPS. Recording of position and time is supported by an option that will save that information to a file; however, this is not a visual record, and its legal status is uncertain. The ECDIS can automatically test actual position against intended track under an option in which a deviation distance can be specified. If the ship deviates beyond this level, an alarm will be sounded (provided the option was engaged). One critical feature of track keeping that is not yet supported by ECDIS is maintaining a continuous visual record of the vessel track; a track line is shown as long as the same chart or scale is used. However, if the scale is changed, the track line is lost.

Table 9. OFM-Cognitive Analysis of Track Keeping with Paper Charts

Function/Subfunction	Cognitive Agent Tasks	Input	Human Information Processing	Output	Task & Environmental Demand
Course Execution/ Determine position	SEARCH/FILTER	Landmarks, expected landmarks	Perception, Working memory, Long-term memory	Set of potential target landmarks	Chart features, visibility
	SELECT	Set of target landmarks	Perception, Working memory, Long-term memory	Two or three "good" landmarks	Angle between landmarks Quality of radar return
	CODE	Two or three "good" landmarks	Perception, Response execution	Bearing of ship to landmarks	Correspondence between visual/chart landmarks and radar image
	CODE	Bearing	Response execution	Written record of bearing	
	SELECT	Previously identified landmarks	Perception, Long-term memory, Working memory	Points on charts to plot	Correspondence between visual/chart landmarks and radar image
Record position	CODE	Points to plot, Written record of bearing, time	Response execution	Bearing vectors from landmarks, their intersection revealing position, and present time	
Course Execution/ Monitor progress	TEST	Actual position	Perception, working memory	Acceptable/Unacceptable deviation between actual and planned location, or waypoint reached.	Knowledge of location

Table 10. OFM-Cognitive Analysis of Track Keeping with ECDIS

Function/Subfunction	Cognitive Agent Tasks	Input	Human Information Processing	Output	Task & Environmental Demand
Course Execution/ Determine position	SEARCH/FILTER	GPS	AUTO	Current position	
Record position	CODE	Select save option	AUTO	Position, and annotated with the current time	No visual record
Course Execution/ Monitor progress	TEST	Actual position	Perception, working memory/AUTO	Acceptable/Unac-ceptable deviation between actual and planned location, or waypoint reached.	

3.5.3 Implications of Cognitive Analysis of Track Keeping

A summary of the cognitive analysis results is contained in Table 11. The table suggests that ECDIS completely eliminates the work of track keeping as performed with paper charts, in that there are no functions performed manually. However, at this stage of implementation, ECDIS is not routinely used as a track-keeping device. As discussed above, the paper chart has legal status as a record of where the ship has been; the status of ECDIS tracks are not clear. Thus, paper charts will be maintained until this issue has been resolved. A further issue in the comparison of the two approaches is that of information redundancy. Track keeping with paper charts is based on radar bearing readings (in restricted waters); these are supplemented by information read by the navigator from instruments such as the GPS or Loran. It is conceivable that additional functionality could be added to support redundant information in computation of the vessel tracks. However, this should involve some human intervention or confirmation, in order to evaluate the results of the multiple inputs (i.e., GPS and radar bearings).

Table 11. Frequency Count of Cognitive Task Transactions for Track Keeping

	Data Acquisition	Data Handling	Data Interpretation	Total
Paper Charts	1	6	1	8
ECDIS	0	0	0	0

From the standpoint of providing visual continuity, the paper chart appears to be superior at this time. Because the ECDIS track line disappears if display manipulations are made, the vessel track is useless for viewing the trend of a deviation from the intended track. This information could be useful in determining the effects of a deviation; for example, if the ship is parallel to the intended track, there will be little effect. However, if the ship is crossing the intended track line at an angle, the course will be affected. Such information may also be useful in diagnosing the cause of the deviation, e.g., problems with the autopilot or rudder control.

Although Table 11 suggests a prospective absence of workload with ECDIS, there are actually a number of tasks added that are ECDIS-specific. As such, these were not included in the comparative analysis. Among these added tasks are monitoring and evaluating GPS input, chart manipulations (pan, zoom), and selecting or deselecting display features such as depth markers. Thus, ECDIS offers potential for automating the principal functions of track keeping, but may add numerous device-specific tasks, thereby offsetting the potential for workload reductions.

IV. DISCUSSION

4.1 GENERAL SUMMARY

This project has developed and applied an OFM-cognitive task analysis method that is aimed at improving the way in which advanced technologies for maritime applications are developed, the procedures by which the technology is trained, and the process by which mariners are licensed. These areas are related through the common need for job function and task level data that can be used to design and build equipment-user interfaces, to establish training objectives and methods, and to develop licensing examinations to evaluate proficiency. Existing methods of job and task analysis have focused on overt behavior, although maritime and other jobs are changing to involve much more covert cognitive processing. The OFM-cognitive task analysis method focuses on two levels: 1) specification of functions that must be performed regardless of allocation to human or machine, and 2) the cognitive tasks necessary to carry out those functions.

The level of detail provided by a cognitive task analysis is useful for comparing how job functions are performed across different levels of automation. In this report, we demonstrated the application of the method to three navigation tasks: 1) collision avoidance, 2) voyage planning, and 3) track keeping. In each case, the analysis revealed changes in the cognitive structure of the work that would not have been evident through methods that focus on overt behavior. For example, a conventional task analytic approach to voyage planning would fail to identify the difference between forming a goal image based on visual input versus the requirement to select an appropriate chart. Conventional task analysis focuses primarily on the outputs of mental processes, and offers little insight regarding how these outputs are achieved. OFM-cognitive task analysis provides the ability to describe internal events, which may be combined in a variety of ways to achieve the same end-result. This latter aspect of cognition is referred to as a "strategy" in the literature (e.g., Miller, 1974; Rasmussen, 1986); strategies become more important as advanced electronics offer flexible means to accomplish a task. Such information is useful in developing training approaches to new technology, because it can permit the incorporation of a variety of task-specific mental models, and task-facilitating strategies can be given increased attention in the curriculum (e.g., methods for visualizing the impact of trial maneuvers on ARPA targets). At the level of design, cognitive task analysis can be used to compare the extent to which different levels of automation place loads on the human information-processing system. Finally, the method described in this report is applicable to the analysis of item content in licensing exams. Comparison of exam content with a cognitive analysis of new technology can show whether there are potential gaps in the exam, or whether the exam tests skills no longer required. This latter application is described below.

4.2 APPLICATION OF OFM-COGNITIVE ANALYSIS TO RADAR OBSERVER TEST ITEMS

Since one of the principal objectives of this work is to facilitate the development of licensing and qualification procedures for mariners on new technology, OFM-cognitive analysis should be applicable to test item analysis. In order to illustrate its applicability to this problem, we have conducted an analysis of 40 questions taken from practice tests for the radar observer certification (Van Wyck and Carpenter, 1984). Each question was independently assigned by the coauthors to one of the cognitive task entries in Table 2 (Standard Radar Plot Method). The resulting entries were then compared with the cognitive task entries in Table 3 (ARPA Method).

The results indicated that three general categories of cognitive task could be identified from the questions: 1) Computing, which involves derivation of quantitative results, based on a straightforward method, 2) Computing and Interpretation, which entails an iterative process of quantitative manipulation and application of the data to an ambiguous situation, and 3) Interpretation, which involves application of stored knowledge, such as rules of the road. An example of a straightforward computing task is one in which the examinee is asked to determine the direction of true motion and speed of a target. Computing and Interpretation is illustrated by questions that are less constrained to specific parameter derivations, such as determining which of a range of potential maneuvers would result in an increased CPA for all targets. Interpretation might involve determining target ship orientation based on running light configuration.

The Computing category contained 30 test items, the Computing and Interpretation category contained 4 items, and Interpretation contained 6 items. Comparison of the classification of these exam items with the cognitive tasks required by ARPA indicates that the 30 Computing items test skills are completely automated. Thus, 75% of the items in a test similar to the USCG radar observer examination test skills that are not required by the technology. Paradoxically, the capabilities of ARPA to monitor increased targets enhances the need for interpretive skills, and knowledge of the use of various trial maneuver functions. This example, while fairly simple, shows the utility of the OFM-cognitive analysis method. That is, by applying the technique to two different technologies, the extent to which there will be psychological transfer across the systems can be demonstrated. Similarly, by analyzing licensing exam content in comparison with the cognitive requirements of new technology, the extent to which existing tests should be modified can be demonstrated.

4.3 EVALUATION OF OFM-COGNITIVE ANALYSIS

While OFM-cognitive analysis offers considerable advantage for addressing the various issues associated with automation, described above, there are some limitations of the technique. These limitations are based primarily on the early stage of development of the analytic process. As the method evolves, most likely some of the problems will be solved.

OFM-cognitive analysis offers considerable design-relevant data in terms of information flows, functions that must be performed, and the cognitive processing (by human or machine) that must take place to fulfill a function. In this project, we have also addressed the human information-processing resources demanded by the various cognitive tasks. Comparisons of the standard radar and ARPA analyses show numerous instances in which long-term memory and working memory are no longer demanded because of computational automation. This is useful information for job design, since these human information processing-resources may be put to better use, e.g., in communicating or planning. However, there are also many instances within the analysis where the same human information-processing resource may be demanded (e.g., working memory), but the nature of those demands changes dramatically. For example, in comparing visualization of a geographic area of interest on a paper chart to an ECDIS, working memory is required. In the case of the paper chart, visual features are retained from successive eye movement. With an ECDIS, this same procedure may place an entirely different load on working memory, such as the user-interface syntax to manipulate charts. This would then limit the ability to form mental images. While we as cognitive psychologists can recognize this difference and describe it, there is nothing in the OFM-cognitive analysis method that would reveal these distinctions. To the extent that such details are important for design, training and licensing, a more refined assessment of human information processing resources is required. One potential approach to this problem would be the incorporation of error analysis, i.e., asking the question, "what kinds of errors could occur in this cognitive task, given what we know about the cognitive operation, the processing resource limitations, and the input/output information?" (see Seifert and Hutchins, 1992). The difficulty in objectively delineating human information processing resource limitations within tasks also extends to the construct of mental workload. OFM-cognitive analysis yields straightforward comparisons at the nominal scale level, i.e., either a processing resource is demanded by a task, or it is not. As tasks change, though, the nature of the demands on those processing resources can only be characterized indirectly, for example with reaction time or continuous performance error. This problem is inherent in all workload analysis techniques.[5]

There are two other limitations of OFM-cognitive analysis as demonstrated in this paper:
1) representation of personnel allocation, and 2) the sequential representation of tasks. Our analysis concentrated on the cognitive operations, inputs and outputs, independent of personnel. The technique can be easily extended to incorporate information on task allocation, simply by linking the discrete tasks with the crew member performing it. In our analyses, the tasks considered are typically performed by one person, with occasional consulting from another person. By incorporating crew member task allocation data, more complex navigational procedures, such as the multi-person position-fixing teams used on Navy ships, would be amenable to OFM-cognitive analysis (Seifert & Hutchins, 1992).

[5]One potential approach to addressing the workload analysis problem more directly is to extend the cognitive analysis to an even finer level of detail, e.g., the specific user interface knowledge requirements and operations required by ECDIS. Another approach would be to gather task-time data for specific functions and tasks, and to compare the times to accomplish cycles of these functions by means of simulation, or empirically.

The tabular representation of tasks suggests that they are performed sequentially. In many instances this is true; however, there are also situations where the tasks can occur concurrently, or iteratively. This is particularly true in the collision avoidance function. Overcoming this limitation will require adapting the analysis as currently represented to another form, such as Microsaint or a hypertext database. In either of these methods, discrete tasks can be linked through software to indicate their concurrent, sequential or iterative nature. Others have used OFM to develop these types of computer-based models, showing the feasibility of such an approach (Ammons, Govindaraj, & Mitchell, 1988; Mitchell & Saisi, 1987).

The final consideration in evaluating OFM-cognitive analysis as demonstrated in this report is the skill requirement for application. This technique was developed and applied by trained human factors professionals. It is unclear whether the same results would be obtained by other similarly trained individuals, or whether the method can be used by nonspecialists. Validity is always a problem with these types of methods, and the usual solution is incorporation of expert panels to obtain ratings and other validating data. It is our belief that with a moderate amount of validation work, and appropriate training examples, that OFM-cognitive analysis could be applied by training and licensing specialists with appropriate maritime subject matter knowledge. This belief is based on the content of the task transaction vocabulary, which is both psychologically accurate and precisely described.

V. CONCLUSIONS

We draw three principal conclusions from this research: 1) it is possible to represent the covert cognitive operations demanded by navigation technology; 2) OFM-cognitive analysis permits a straightforward comparison of task structure and demands across different levels of automation; and 3) the technique is directly applicable to issues related to design, training and licensing.

Representing the covert cognitive processes is accomplished by analysis of the equipment used to perform a task, and the structure of the task itself. This process yields information that can be characterized by Miller's (1971) task transaction taxonomy, which appears to be the most comprehensive and parsimonious vocabulary available. The results of such a task representation for different levels of automation reflect the extent to which certain cognitive tasks are automated, new cognitive tasks added, or the nature of the human information processing requirements altered. The analytic technique directly specifies input, output and processing requirements, and could therefore be used to generate specifications for equipment design; the information concerning cognitive processing requirements can be used to accommodate any human performance limitations that may exist. The structure resulting from OFM-cognitive analysis yields a detailed set of tasks that can be used for developing training. Finally, applying the analysis to licensing examination content demonstrates the extent to which qualifications tests actually challenge the competencies necessary to perform a job. This range of applications of OFM-cognitive analysis suggests that it should be an integral tool in the USCG manning, licensing, and qualifications activities.

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APPENDIX A

Reproduced from Fleishman, Edwin A., and Quaintance, Marilyn K. (1984),
Taxonomies of Human Performance: The Description of Human Tasks,
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APPENDIX A

Miller's Terminology: Definitions for the 25 Task Functions Involved in a Generalized Information-Processing System[1]

MESSAGE — A collection of symbols sent as a meaningful statement

A pattern of input symbols[2] that is "meaningful" and purposeful in that it activates (or can activate) some processing capability of the system in generating a useful response.

The formal features of a message consist of a set (as "vocabulary") of *elements* and of the *pattern* (syntax, grammar) in which the elements are arranged.

1. The elements or symbol set consist of a limited number of "defined" terms.
2. The patterning of the symbols are grammatical rules for organizing them into meanings.

Example: In human discourse the message unit is the sentence. A sentence consists of words (elements) patterned by rules of grammar. The meaning of a sentence is based on both the words chosen and their grammatical arrangement. An operational message consists, in its simplest form, of subject, predicate, and object, as in: "store number 9 in cell 12."

[1]Adapted with permission from: (1) Miller, R. B. Development of a taxonomy of human performance: Design of a systems task vocabulary. (Tech. Rep. AIR-77 6/2035-3/71-TRII). Silver Spring, MD.: American Institutes for Research, March 1971; and (2) Miller, R. B. A *method for determining task strategies* (Tech. Rep. AFHRL-TR-74-26). Washington, D.C.: American Institutes for Research, May 1974.

[2]A *symbol* is a pattern of signals that can initiate or direct a given processing action.

In system behavior, a message about a state (or stimulus condition) must ultimately be linked to a response action or response decision. In other words, "data" must eventually be linked to an instruction for operating with or on the data.

What is "data" and what is "instruction" content in a message is relative, not absolute. It is relative to the operations performed with or on the message by the system.

In operational terms, the "meaning" of a message is identified by the response it can or does generate.

A message is the smallest conceptual unit of action that produces a system response that is useful to a user of the system. This is in contrast to a *signal*, which is defined as an instigator of action localized to one or more system components.

Pressing a machine STOP button introduces a message. In effect, the message is: "Whatever the present activity or the state of affairs right now (subject) stop (predicate) it (object)." The linkage from the STOP button to the stop controls contains the *context* of the message introduced by pressing the STOP button.

INPUT SELECT — Selecting what to pay attention to next

Rules for admitting a message or message channel into the internal system.

These rules may include system turn-on and turn-off schedules, or power-up on input lines.

Input select rules may operate at the information source to compose a message eligible for entry into the systems according to criteria of (1) format, (2) content.

Examples

1. Polling procedures for accepting from an input channel
2. Rejection of message lacking preestablished fields of information
3. Rejection of message containing illegal symbols
4. Composing of source message for entry to system
5. Selective response to patterns of auditory input signals
6. Rejection of a given signal-to-noise relationship

Variables in Designing Input Select Rules

1. Physical mode of sensing: auditory, optical, mechanical, electronic
2. The symbol set or vocabularies permissible for acceptance
3. The grammar or syntax variables that structure symbols into words,

fields, stimulus (data) or response (instruction) and other format characteristics
4. Channels to be made available from sensor to processor–memory
5. Size of chunk of information acceptable at one time, for example, symbol, word, sentence, information field length

Principles

1. The fewer alternatives in message form (symbol set, formats, and length of message), the cheaper and faster to decide to accept or reject. The penalty for limited, standard messages comes from increased limitations in range of message content and increased effort to compose messages within the constraints.
2. The smaller the alternatives allowed in message options, the greater the number of messages that may have to be stored and collated if a meaningful system action requires more information than a single message can carry.
3. The greater the rigidity of message structure, the fewer the users and the smaller the range of users.
4. In summary, there tends to be a tradeoff between the ease of accepting the processing messages by a system and the ease of generating and composing messages from the information source.

FILTER — Straining out what does not matter

Procedures for reducing or eliminating irrelevance and disturbance from signals and messages.

Principle

Signal or message elements that do not serve a system purpose are costly to transmit, process, store, and retrieve, and can interfere in carrying out system purposes.

Comment

Major sources of irrelevance (and inaccuracy) are usually at the human input to information-processing. For this reason, attention to a discipline for input formats (language terms, syntax, and user concept of purpose) is perhaps the most important type of filtering device for a processing system. Some degree of redundancy usually helps the human in composing and checking his own output (which is also a message to himself). This redundancy may be filtered out by the nonhuman portions of the system to which it is a nuisance.

QUEUE TO CHANNEL — Lining up to get through the gate

Rules to organize random arrivals at one or more entrance gates into a waiting line.

Purpose of Queuing Rules

1. To attempt to minimize extreme fluctuations in length of waiting lines
2. To minimize delay in assigning processing priority if the priority is not based on serial order of arrival
3. To minimize conflicts among those in the waiting line
4. To sample from waiting lines at a rate that optimizes between:
   a. arrival frequencies and average waiting times
   b. length of input messages
   c. system response capabilities (throughout time)
   d. number of channels required for given population of demand

Note: Queuing rules interact with INPUT SELECT rules for the formatting of messages into the system. They may interact with rules for the formatting of output in real time systems in which an input channel is also an output channel.

Principles

1. If no user ever has to wait at all, the system is probably more expensive than it needs to be, or is underutilized.
2. Human users can accommodate their expectations of delay and delay probability in getting attention.
3. Humans with different kinds of purpose will tolerate different kinds of delay in getting attention.
4. Where possible, message priority should be established without having to process all the messages, and ideally would occur immediately when the message (or sender) joined the queue.
5. Unused channels should be switchable to overcrowded queue lines, but without jeopardizing relative positions in the waiting line. Thus, diverting the tail of queue to a new ticket booth is unfair to those forward of the break.
6. Any evaluation of throughput speed of a system should include waiting line statistics.
7. Humans are probably less patient in waiting for attention than in any other context.
8. Unless constrained or trained to do so, humans will not spontaneously organize themselves or their inputs into a serial order according to arrival.
9. If more than one equally accessible entrance gate is available, newcomers should be directed so that all wait lines are of equal length.

10. Qualify item 9 above as follows: specialize queues for long and short inputs. A short input will endure a longer line if it is perceived to move quickly. Average waiting time for short (or fragmentary) messages should be less than for long (or complete) messages.

DETECT — Is something there?

Procedures and mechanisms for sensing the presence or absence of a cue or condition requiring that some form of action should be taken by the system.

Detection requires the discrimination of an action-stimulating cue from some background of stimulation.

What is detected may consist of normal work cues, or of *exceptions* (such as errors). The source of these cues may be inputs to the system, or feedback from the monitoring of outputs. The sensing function does not analyze or classify the cue.

Note: Detecting, as defined here, is confined to a *sensing* operation, which excludes interpreting activities. In human terms, detecting results in sensing a stimulus to which attention will be paid. In many practical situations, however, detecting and identifying are a single process. (See IDENTIFY.)

Scanning and Detecting

Unless the sensor is a part of a fixed channel, it must scan segments of its environment so that the sensor is exposed to signals. The sensor is preset to respond to certain kinds of change or discontinuity in the field being scanned.

Principles

1. The response lag of the detecting device must be less than the cycle time of the stimulus to be detected.
2. The greater the contrast between the stimulus to be detected and its background, the greater the reliability of detection.
3. For given kinds of signal patterns to be detected, some scan patterns and frequencies are better than others.
4. In human behavior, what will be detected is related to "set" or pre-established tendencies to respond. More simply, we tend to notice what we expect to see, what we are looking for, or what we are attending to. A number of principles in addition to Item 2 influence human detection, as well as other sensing and perceptual behavior.[3]

[3]See the chapter on perception in any general psychology text.

Comment

In digital processing activities detect and IDENTIFY cannot be separated. But in analog activities a sensor may detect a pattern of frequencies representing a speaking voice, but not be able to identify it or its content.

SEARCH — Looking for something

Rules for selecting a set of entities for inquiry, for sequencing an inquiry among members of the set to be searched, and rules for applying criteria of "same" or "different" between the objective (search image) for searching and the objects in the search set being examined.

Selecting a Set of Entities for Inquiry

The set of entities for inquiry make up the "universe" to be searched, like the file room or file drawer in which a document is sought. The search request must contain or embody a code that identifies and subdivides the physical or logical universe to be searched.

Sequencing an Inquiry

The rule or principle for selecting for examination each next member or element in the searchable set. For example, this may be done by serial order, binary techniques, probability, recency of insertion to the file set, index linkages, and others.

Matching Search Image and Object Examined

The search image is by definition the necessary and sufficient information for establishing either "yes, this is the object I want in this search set" or "no, I don't want this object in this search set." The process of making this decision will consist of a set of rules for sequencing a pattern of steps for trying to match successive attributes of the search image with the object examined. Matching may be a step-by-step comparing of each attribute of the search image with the object examined, or simultaneously on the principle of an optical mask. Undoubtedly both principles require the support of an indexing structure.

Comment

The identity that is searched may be coded by location, relative position, or category code. The identity also may be based on one or more physical characteristics if the information is analog.

IDENTIFY

What is it and what is its name?

Methods for characterizing a message by type or by source.
In ordinary usage, to identify is to recognize an object or entity and apply some label to it.

Thus: Identify a sender, a Type *I* instruction, a location, a previously received message.

Identification requires a referencing action. This action produces the name or similar symbolic response to attach to the sensed input.

(In human behavior, the content of this symbolic response may not always be explicit: you "recognize" an individual and treat him as a "recognized" individual even though you don't recall his name or other explicit reference in your experience with him.)

In information-processing, two sets of reference codes may be necessary. One reference structure may apply to the universe outside the processing system (for example, the name and address of the sender of the message). The other reference structure is to the physical (and/or functional) location of the message as an identity within the system. These two identity codes may require a set of cross-referencing rules or codes.

Principles

1. The identifying operation generally requires information in addition to that necessary for the detecting operation.
2. Once an identification is made, cues inconsistent with that identification tend to be ignored.
3. In human behavior, expectancies and recent experiences strongly influence how a set of cues will be "identified" even though inconsistent cues are present.
4. The labels making up an "identity" may consist of one or more of the following kinds of symbols:
   a. Arbitrary serial number (library accession number of books, street numbers on buildings, serial numbers starting from zero and progressing continuously).
   b. Individual or class name (George Washington, emergency code, shelf number of library book, title of book).
   c. Combination of class identity and individual identity (social security number, which contains region digits and individual's digits; changed part number consisting of original part numbers plus suffix).

Note: the most efficient and unambiguous labeling or identity coding, from the standpoint of symbols required in an open-ended acquisition series, is by ordinal number. The code name given to each new acquisition is one increment larger in the symbol series than the previous acquisition, as 1, 2, 3, . . . *n*.

An object or message may have two cross-referenced identifications: an accession code (which is unambiguous) and a content or attribute code based on its attributes. The latter has high probability of ambiguity, but may simplify preliminary phases of search in a file.

CODE

Translating the same thing from one form to another

Encoding and decoding: rules for translating messages in one symbolic form to another symbolic form, presumably without loss of information content.

Example: The decimal number 12 coded as the binary number 1100.

Recording of messages standardizes their symbolic format so that they can be processed by a standard device and a standard instruction set.

Properties

1. Symbols are more readily (cheaply) checked and corrected automatically in some codes than in others.
2. A small variety of symbols may be compensated by a large number of symbol positions. Thus, there are 10 different decimal symbols, but only two binary symbols. On the other hand, the decimal *12* is expressed in two symbol positions (the tens position and the units position), whereas the binary expression of the decimal number 12 requires four positions.
3. Coding may apply to a symbol (m), a word (MILE), an expression (the miles from New York to Chicago), or a statement (the message went from New York to Chicago). Position information may be coded (18° latitude, 42° longitude), but always requires a position reference to be explicitly or implicity identified.
4. Recoding is often necessary when changing from one type of transmission medium to another.
5. Recoding can eliminate redundancy from a set of symbols (or a language) and thereby increase system efficiency. These gains are somewhat reduced by the cost of logic for the recoding operations.

INTERPRET

What does it mean?

Rules for translating the symbolic context of a message into a reference or meaning, usually by addition of reference context from within the message itself, or reference context outside the message itself.

Examples

1. Automatic analysis and "recognition" of an English word as a pattern contained in the physical wave form of an utterance.
2. Human conclusion that the unannounced approach of foreign aircraft, detected and identified on radar screens, means invasion and war.
3. Human conclusion that a given pattern of symptoms signifies that a system failure must be caused by a programming error rather than a machine failure.
4. Language translation from Greek to English expressions.

Note: Interpreting requires response to a pattern of cues, and applies to events on conditions that go beyond the input data (or symbols) as such. The input data are only a part of the total information required to make the interpretation. This differentiates interpretation from decoding.

An interpretation is an inference about a condition, or state of affairs, or source of data.

Process Variables

1. Degree of statistical certainty of correctness required of the interpretation.
2. Amount of redundancy in the form of context available in the message.
3. Range of variability among elements in the pattern to be determined.
4. Proportion of irrelevant transients in the message that act as noise to interpretation.
5. Number of elements sufficient and necessary to make matches with a reference set (or "dictionary") of meanings or interpretations.
6. Number of alternative meanings or identifications in the reference set available for trying to make matches.
7. Opportunity for interpreter to query message source for additional information for testing hypotheses about an interpretation.

CATEGORIZE — Defining and naming a group of things

Rules for classifying data, information, or intelligence according to its source, format, purpose, or content in order to organize messages into meaningful groups, or in order to selectively retrieve them for decision making and control.

Examples

1. All messages about John Doe are categorized (labeled) "John Doe" and go into the "John Doe file."

2. Data describing the functions of a system are classified as "*input*," "*processing*," or "*output*."
3. "Age of applicant" data are entered in the third "field" in each applicant's record.

Categorical Structures

A set of categories may be in the form of a list where each member category is independent of every other member ("age, height, weight"). A set of categories may be arranged in trees or hierarchies: "safe drivers under 25 years of age, safe drivers over 25 years of age."

Ambiguity in Classifying

Classification rules are unambiguous only when the classification is based on some arbitrary counting of discrete units (e.g. men with 5 children) or natural dichotomies (e.g., males or females) or physical location (e.g., cell 121). Rules for classifying by attribute (blond vs. brunet) are always ambiguous in application.

Design Principle for Category Structure

An efficient category structure is one which permits the largest number of purposes for using an information file to be performed with the fewest decision operations in (1) classifying incoming messages for the file and (2) in searching the file for messages relevant to purposes.

This principle suggests that a classification scheme for information coming into a system should be designed around the categories of purpose and the options of control available in the system or subsystem. In short, develop categories around the ways you will use the information, not on the ways in which messages may differ from each other. Control options tend to be fewer than the variety of input conditions requiring a control decision that selects a control option.

Example

A given control switch can be set in either position A or position B. No matter what varieties of information come into this mechanism, there are *only two* valid and useful categories for this information: Category A that sets it in Position A and Category B that sets it in Position B. (The argument that a category exists which is information that interferes with these choices is irrelevant.)

Comment

The central design issue in any information-retrieval system is category structure, and the interaction between filing categories and searching categories.

TRANSMIT — Moving something from one place to another

Rules and conditions for transmitting a message from one location to another.

Serial versus Parallel Transmission

In serial transmission, message elements are transmitted one after another, such as the dots and dashes of Morse code. In parallel transmission, the message as a whole, or chunks of it, is transmitted at the same time, such as the optical projection of an entire image through a lens. In wire facilities, parallel transmission is faster but costs more in hardware.

Bandwidth

This is the rate at which discriminably different elements at the receiver can be transmitted through a medium. Bandwidth is a measure of channel capacity to transmit signals. (It is also a term sometimes used to describe a processing throughput rate.) Greater bandwidth usually requires higher dollar cost.

Open versus Closed Transmission Lines

An open line (also called "dial-up") is one which is continuously open to a message source for transmission. A closed line requires the sender to request to be switched to an open path, or to wait until a path is periodically opened to him.

Coding and Buffering

Long distance transmission often requires changes in the physical form of the message, and in transmission rate. These changes require coding and decoding logic and physical changes in the signal carrying the message.

Tradeoffs

1. Speed of transmitting input messages in segments of all-at-once is a tradeoff against facility costs.
2. Reduction in mean waiting time to send a message is bought at higher cost whenever there are queues.
3. Local processing with fewer and shorter messages to transmit versus centralized processing with heavy communication traffic and facilities.
4. Error detection and correction operations impose redundancy in message content and delay in transmission throughput.
5. Identification of message (and message segments) by physical or logical location of source versus by code identification transmitted with the message or message parts.
6. Time slicing with fixed message length and predictable time of transmission versus total message transmission regardless of length but unpredictable time of initiating transmission of any given message from an origin.
7. Polling each of multiple source channels in sequence in order to determine if a source message awaits transmission versus demand for attention signals to the message link and queuing lines.

STORE — Keeping something intact for future use

Rules for where and how to hold messages for retrieval, including rules for filing and retrieval search. The contents of storage are data, programs, or combinations of both.

Essential Operations

1. Labeling the stored content by code or physical position
2. Determining units of physical store required by the stored content
3. Locating the physical place of available storage space
4. Loading the content into the physical storage
5. Safeguarding from physical deterioration
6. Identification of the stored content
7. Selective unloading of the stored content

Tradeoffs

1. In nonassociative memories, as memory size increases, the information required for identification of a storage cell (or content) may become greater than the information content of the cell.
2. *Serial* access to stored information (e.g., magnetic tape) is cheaper in storage cost per message, but more costly in search time than *random* access (e.g., magnetic core).
3. The savings in processing gained from tables of precalculated answers is offset by time to search the table and by the filling up of physical storage space.
4. Simplicity and reliability in filing a message or message content (such as by serial access number) is counterbalanced by complexity and unreliability in searching for the message content.

Associative and Nonassociative Memory

In a nonassociative memory, the *label* or name attached to a message for filing or retrieval has no meaningful relevance to the content of the message. The label may be an arbitrary cell number or position (e.g., "message number 1101").

In associative memory, the content of the message is, in part or in whole, the symbolic basis for filing and/or retrieving the message, (e.g., "message containing 'winning horse'").

In nonassociative memory, selection logic in search applies only to message labels. In associative memory, selection logic in search applies to message content.

SHORT-TERM MEMORY — Holding something temporarily

Rules for holding in temporary storage a message or parts of a message for use at a later time during a task cycle, or for combining with other information during the cycle.

Examples

1. A human typist reading a sentence and holding it in mind while her fingers key the symbols.
2. A register in a computer.
3. The retention of symbols or messages in a buffering device for translating into a different transmittal rate or frequency.

Operations

These are equivalent in principle to those in STORE.

Comments

1. The greater the number of channels, variables, codes, and chunks of information input that must be integrated in order to reach a decision or select a response, the larger the short-term storage that is needed. Human short-term memory is limited, but can be functionally increased by practice and by regularizing or formatting the input, by mnemonic aids, and by map-like job aids.
2. The greater the variations among message sizes and message rates of transmitted and processing data, the more important the design of short-term storage facilities to the efficiency of the total system (e.g., time-shared, remote terminals).
3. Information elements in short-term storage must be addressable as parts to the decision to be reached or problem to be solved. These addresses use up system channel capacity (or bandwidth). Some address codes will be more efficient, than others in a given system. (For humans, standard spatial patterns—map-like or chart-like—are good as a matrix for displaying elements of information as they arrive.)
4. Short-term memory may store partial solutions in heuristic, semi-algorithmic problem solving, or in trying out strategies (e.g., troubleshooting and other diagnosis, or in game playing). If the human must make judgments and intervene in further steps, the codes and pattern in which partial solutions are displayed will be critical to human effectiveness in participation.
5. In human behavior, unaided short-term memory is flexible but unreliable.

Note: The concept of short-term storage is among the highest in importance to human problem-solving capability. The computer in conversational mode can be a great aid to the human in retaining and effectively displaying short-term task information in tasks such as information searching, diagnosing, decision making, and constructing.

COUNT — Keeping track of how many

Identifying an entity or unit of something and incrementing or decrementing a storage and readable device by a unit of magnitude.
The definition may be expanded as follows:

1. The counter must sense the presence of the entity to be counted. (This might include specialized detecting and identifying mechanisms.) The presence or absence of the entity or characteristic of the entity must be all-or-none.
2. Incrementing or decrementing some numerical value, which could be zero.
3. Storing the new count.
4. Displaying the count to a mechanism which reads it in order to fulfill some purpose of the system. The reading mechanism may be human or machine.
5. Resetting the counter when a new counting cycle is initiated. If the counter is not reset, a log must be kept of the count when a new cycle is entered.

COMPUTE — Figuring out a logical/mathematical answer to a defined problem

Rules for solving arithmetic and mathematical problems involving numerical data, or the logical reduction of logical statements (equations).

Comment

Any class of computation problems can be solved by a large variety of equally valid patterns of logical manipulation. The general tradeoff is space (number of channels holding and processing in parallel) versus time (number of operations performed in series). Computation requires both short-term memory (intermediate results) and long-term memory (sequence of logical instructions).

Operational Tradeoffs

1. Computing an answer by logical means versus obtaining the answer from a table in storage

2. Digital computation (counting) versus analog computation (adding or subtracting physically continuous properties, such as voltages)
3. Various specific mechanisms for given logical operations and few program instructions versus general purpose logical mechanisms and many program instructions
4. Parallel computing operations (with high speed but more facilities) versus serial computing operations (with lower speed and less facilities required)
5. Higher speed from local short-term storage of intermediate results (more facilities) versus lower speed by storing and retrieving intermediate results in long-term memory (fewer facilities)

PLAN — Matching resources in time to expectations

Rules for predicting what future sets of conditions will occur and what responses to make to them and in what order.

Planning is a subset of decision making.

Functions in Planning

1. Predicting the future, by using historical and present information to anticipate which of a set of alternative states will occur at some future moment or time interval
2. Exercising priority rules for determining which of several anticipated states to give priority of attention
3. Determining the set of response capabilities required for effective response to the expected condition or state
4. Scheduling the resource for making the response so that the resource is available when the expected condition occurs

Summary

The planner combines the functions of predictor, resource selector, and resource scheduler.

TEST — Is it what it should be?

Rules and procedures for deciding on the integrity of (1) a signal, (2) a message, (3) a mechanism.

A Signal Test is made as follows:

1. Sensing and measuring one or more attributes of the test signal
2. Comparing these measurements with a set of normative or reference values

3. Deciding whether the test signal fell within the prescribed tolerances for that signal
4. An indication of that decision

Note: A "mask" may be used to compare several variables in the signal set at one time.

A Message Test consists of:

1. Identifying the class of message
2. Deciding whether its contents do or do not match, according to:
   a. the reference set of symbol elements
   b. rules for combining symbol elements into words
   c. format rules for combining words into messages.

Note: Tests for the validity of the "meaning" or content of a message must be made in a context of "meaning" references. Ordinarily this requires a redundant expression of the message. A check and confirmation with the source is an example of such redundancy.

A Test of a Mechanism requires:

1. A controlled or known signal or signal pattern as input to a mechanism
2. Measurement of relevant characteristics of the corresponding output of the mechanism
3. A comparison of the input–output relationship with a set of reference values prescribed for that relationship
4. A decision as to whether or not the actual output falls within the prescribed tolerance limits

Note: A test may also be a decision based on a comparison of outputs from redundant mechanisms that use the same input.

CONTROL — Changing an action according to plan

Physical Control

Changing the direction, rate, or magnitude of a physical force that may be acting on objects, processes, or symbols. The stimulus may be embedded in a fixed serial order, or it may consist of feedback Test Signals.

Physical control is observed in the human nerve and muscle that manipulates a tool, in the electromagnetic yoke which directs the electron beam in a cathode ray tub.

Symbolic Control

The source of instructions as to what will be done next with what facility.

Symbolic control appears when an instruction in a computer program reads and interprets an input message and, despite competing claims for a particular input channel, opens that channel to more messages from the source of that input message. Control resides in that instruction, in the location that holds that instruction, and in the physical mechanism that executes the command contained in that instruction.

Factors in the Process of Control

1. A signal of status based either an instruction count, or on test feedback
2. A decision or other selection mechanism for eliciting an instruction
3. The instruction that directs a change in some set of physical behaviors
4. The mechanism which converts the instruction into a physical action or initiates a train of physical actions
5. The jurisdiction (set) of physical actions which can be physically modified at some time by the instruction and its location

Note: The concept of control includes the function of coordination in time and space according to plan.

Feedback control implies both a monitoring–testing and an executive function.

EDIT — Arranging things according to rules

Rules for arranging information (or symbols) into a message according to prescribed formats.

Editing may have as its purpose the structuring of data or information for machine handling purposes or for human handling purposes.

Examples

1. Suppressing nonsignificant zeros
2. Breaking a chain of symbol elements into component strings
3. Arranging a listing of bookkeeping data into a display of rows and columns according to tabs and headings
4. Correcting a misspelled word or ungrammatical sentence

Note: Editing changes elements in the structure but not the operational content of a message, nor the symbol set by which the message is expressed.

DISPLAY — Showing something that makes sense

Arranging messages into a prescribed format and symbology for human perception and interpretation.

A convenient, but by no means exhaustive, distinction at a primitive level may be made between displays in symbolic forms such as:

1. Signals, such as a flashing light associated with a label or spatial position
2. Alphanumerics, such as words, phrases, and sentences in English
3. Graphics, such as pictures, maps, charts, and graphs

PURGE — Getting rid of the dead stuff

Rules for eliminating unwanted information from storage.

Example

All files except those marked with an asterisk, will be thrown out upon reaching their tenth year.

Requirement for Purging

As new messages arrive, storage space is used up and search time is increased. Methods for systematically clearing storage are therefore essential.

Purging Policy

Aside from the special case of legal requirements, files or messages are discarded when the probability of referring to them goes below some value, or when the importance of finding them shrinks to some value less than the cost of maintaining the message or file in a given medium.

Purging policy may specify how purged messages are to be abstracted and retained in condensed form, or statistically summarized and retained as a summary.

Purging policy may specify exceptions, and how exceptions to purging rules will be identified and treated.

Comment

Humans tend to be irrationally reluctant to discard their files except under conditions of space crisis or other pressure, and then they may be equally irrational in what they discard. Purging policy is a planned discipline against these tendencies.

RESET — Getting ready for some different action

Purging an old context of status and readiness in order to respond by substituting a new context of status and readiness.

Examples

A clock completes timing the runners in a foot race and is reset to zero in readiness for the next race. In another example, an English-speaking person is addressed in French and shifts his language context and speech patterns into French.

The reset operation is meaningless except as preparation for a new action context. It is therefore necessary for the system to identify the new context to which the reset is relevant. The mere return to zero of an indicator or control is irrelevant to a concluded action, but relevant to some next action.

Reset of Short-Term Memory

This is equivalent to turning the clock or indicator back to a zero setting in preparation for a new cycle or context of system action.

Reset of Instruction Readiness

A reset may include any changed readiness of a mechanism to respond. Thus, a new instruction set loaded into active memory and controls is a reset operation by this definition. The human who shifts from speaking English to speaking French has had a reset operation.

Note: The concept of reset makes the term "set" unnecessary. After the first occasion on which a mechanism is set, it can only be reset. Note that the expression set is used in the sense of "prepare."

DECIDE/SELECT — Choosing a response to fit the situation

Rules for selecting a response alternative to given states of affairs. Conceptually, the simplest decision mechanism is a two-way switch in which the input may be in one of two relevant states, each of which selects a response alternative.

In symbolic behavior, an operation implicit in a hardware mechanism must be a "compare" action. The decision results from the comparison of one or a set of input states, with reference criteria for each of a set of response alternatives. When a match is found between the input conditions and the criteria for a response alternative, that response is selected and the alternatives rejected.

Human decision making requires an extended analysis.

The variables of the "input state" consist of

+ goal variables and priorities
+ situation variables and their data content

The output variables are characterized by

+ the set of response alternatives and their respective implications

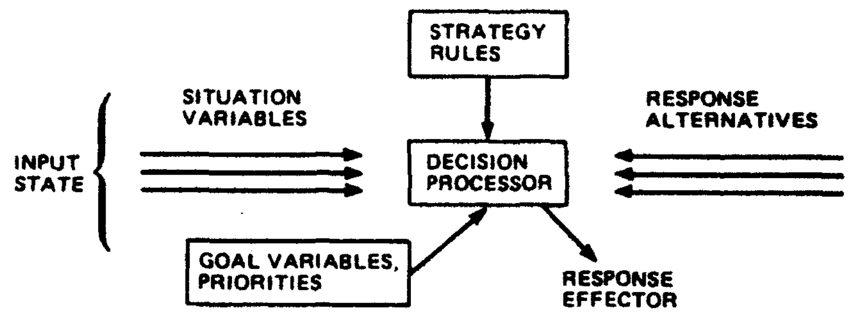
Another kind of information in probabilistic or ambiguous situations consists of

+ strategy rules for selecting a response alternative from any given input state

A strategy rule seeks the best fit between a "profile" of needs expressed in a problem statement and the "profile" of capabilities of each of the response alternatives.

Note: The term SELECT has the same operational meaning as DECIDE, although its connotation emphasizes the executive action implied by the choice reached in a decision.

DIAGRAM OF HUMAN DECISION-MAKING VARIABLES



DIFFICULTIES IN HUMAN DECISION MAKING

Input State

1. Input variables are incomplete or include irrelevant variables.
2. Classification structure of input variables is inappropriate to this problem (potentially relevant information cannot be labeled properly).
3. Information is absent on one or more variables.
4. Information on various input variables arrives out of time phase.
5. Input noise disturbs the perception of relevant signals.
6. The meaning of the situation is not adequately interpreted (failure to organize data about the situation variables as a whole or pattern).

Goal Variables, Priorities

1. Goal variables are inadequately defined.
2. Incompatible priorities exist among goal variables.

Response Alternatives

1. The set of alternatives recognized is inadequate.
2. The definition and classification of alternatives is inadequate.
3. The premises for combining or compromising alternatives are inappropriate.
4. The data on consequences of respective response alternatives in this kind of situation are inadequate.

Strategy Rules

1. Processor is unable to identify and select appropriate strategy rule.
2. Strategy rules conflict.
3. No strategy rule is available for this combination of situation and recognized response alternatives.

Decision Processor

1. Short-term memory (buffer) is insufficient.
2. Logical capability to process all the data is inadequate.

Response Effector

1. No channel exists for transmitting or executing the chosen response.
2. There is no appropriate message code for converting output response into control behavior.

ADAPT/LEARN — Making and remembering new responses to a repeated situation

Structural modification of the behavior of a system as the result of experience, where the behavior change carries over from one cycle of operation to another.

A learned act requires that: Response B becomes substituted for Response A to Situation X, and that when Situation X recurs, Response B will tend to recur rather than the old Response A. The information handling process must account both for the acquisition and substitution of Response B for A when Situation X occurs, and also for its retention and recurrence when Situation X recurs.

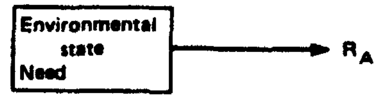
Information Handling Requirements

1. A transcript of the effective stimulus in the situation
2. A transcript of the goal sought or intent realized in the situation
3. A transcript of the original response that was made
4. A record of the consequence of that response

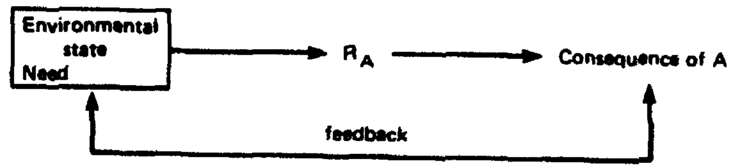
5. Some record of a "corrective" response or hypothesis for a corrective response
6. An associative link between (1) a mechanism for recognizing the old stimulus in a new operational cycle and (2) the "corrected" response—i.e., a mechanism for superseding the old maladaptive response to the stimulus and goal

Process Paradigm of Structural Adaptation or Learning

1. A combination of need and environmental state elicit R_A (R_A has been previously "learned" to this situation).



2. The consequence of R_A fails to satisfy the need.



3. Response A is extinguished and Response B in the *device's repertory* is substituted. The consequence of Response B does reduce the need.
4. The adaptive device substitutes the linkage or Response B to this need and environmental state in its memory.
5. The environmental state and need recur on a later occasion. The device *identifies* the recurrence of the old stimulus and the old need. Assume the linkage or R_B has been effectively stored. Response B is emitted. Learned behavior is demonstrated.

GOAL IMAGE — A picture of a task well done

The operator's goal image embodies criteria for terminating a task or segment of work or mission with an experience of some degree of success or failure. The goal image is a mental picture of the conditions that should obtain when a task cycle is completed. Different goal images may apply to different levels of work activity. The goal image serves as both a steering and power reference for moving from a present state of affairs into and through a projected route of action. Goal information is meaningful operationally insofar as the behavior of the system is not rigidly programmed, that is, when the system has options for activity in mind and amount.

Behavior tendencies include the following. The student initially may be preoccupied by learning procedures and operations, rather than goals and goal variables. With increasing degrees of practice, what may once have been a clear goal image deteriorates, especially under stress and fatigue and from repetition. A high degree of routinization induces the emitting of chains of behavior in an automatic fashion.

When loss of goal image may be maladaptive, the operator car postpone deterioration by maintaining a continuously higher level of aspiration than his performance level. Training strategy obviously should emphasize and test the student's acquisition of goal variables and images of goal states that are realistic and reasonable for aspiration. The training situation also may demonstrate concrete instances of goal states that barely are acceptable (for given sets of circumstances), as well as goal states that barely are unacceptable. It is insufficient to limit these demonstrations merely to the orientation stages of training; they must be frequently reintroduced even into the mastery stages of student skill.

If the student is instructed in the tolerance ranges of goal variables, and if he is in the cognitively active mode, he can interpret task feedback and, thus instruct himself. But requires direction, opportunity, and encouragement. Ideally, the student will continue this activity after he terminates formal training.

To the extent that the operator has a clear picture of goal states, and is guided and driven by them, he has a basis for rational control over his own emotional impulses and his own tendencies for the expedience of the moment. The active control of a powerful goal image may enable the operator better to withstand the stress, including periods of boredom. The indoctrination and refurbishing of the subjective goal image, therefore, has a continuing strategic value for operator performance.

Although these comments about goal image are self-evident, generally they seem not to be put into serious practice by managers or by specialists in the training and educational arts. Mechanized training procedures especially are prone to skip adequate training in purpose, goal image, and goal criteria, perhaps because they assume that the student, as a passive mechanism, can acquire these implicitly when he learns procedures and task formats.

In conclusion, the strategic objective for training the student in goal images and goal criteria is to make him cognitively active and aggressive as an operator. Otherwise, he might be limited to passively emitting chains of responses that have been programmed into him. The operational "liability" is that he may be less docile to arbitrary external control. This liability will be counterbalanced by his more effective capability for behavioral change that will be required either because of new operational goals or because of new operational conditions.