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SUMMARY

Several research workers have recorded pilots' heart rates as a means of estimating levels of workload in flight. Such use of this physiological variable prompts a number of questions:

(1) What is the relationship between a pilot's heart rate and his workload?

(2) Is heart rate a valid and reliable indicator of workload?

(3) If it is - how should it be used?

(4) What are the likely neuro-physiological mechanisms involved?

These questions are discussed using examples of heart rate selected from more than 3000 plots recorded during flight trials at RAE Bedford.

It is concluded that:

(1) There is good evidence that heart rate increases with increased workload.

(2) Differences in heart rate values appear to indicate relative differences in workload.

(3) Heart rate is best used in conjunction with a good workload rating scale.

(4) A reasonable hypothesis can be constructed around the concept of arousal.

Paper presented at AFFTC/NASA Dryden/AIAA Workshop on flight testing to identify pilot workload and pilot dynamics, Edwards AFB California, January 1982

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1 INTRODUCTION

Monitoring heart rate in flight is a relatively simple procedure; the technique is not intrusive, it does not compromise flight safety, the signals are easy to record, and the discrete nature of the data make them amenable to various forms of analysis. It is not surprising, therefore, that a large number of experiments have been reported in which this physiological variable has been recorded in flight. Although most of these experiments were designed primarily to examine the effects of various physical and mental stressors on pilots a small number was aimed specifically at estimating levels of workload[1-3]. There is now unequivocal evidence that pilots' heart rates tend to increase during flight and especially during such demanding manoeuvres as the take-off and the landing.

Using heart rate to estimate workload in this way prompts one to ask a number of questions:

(1) What is the relationship between a pilot's heart rate and his workload?

(2) Is heart rate a valid and reliable indicator of workload?

(3) If it is - how should it be used?

(4) What are the likely neuro-physiological mechanisms involved?

These questions will be discussed using examples of heart rate selected from more than 3000 plots recorded during flight trials at RAE Bedford. But first it is important to describe what is meant by the term pilot workload. There are many definitions of workload most of which appear to fall into two broad conceptual areas, those that relate to the task or to the demands of the task and those that are associated with the response or effort. In this Memorandum, workload is considered to be related to effort, an interpretation which is compatible with the use of physiological variables and which also lends itself readily to subjective assessment. In this context it is worth noting that some 80% of pilots view workload as being effort-related[4], a view which agrees well with the influence on the piloting task of such individual factors as natural ability, response to stress, physical fitness, age, training and experience.

2 THE RELATIONSHIP BETWEEN HEART RATE AND WORKLOAD

The most used and probably the most reliable methods of estimating workload in flight are those based on some form of subjective reporting by experienced test pilots. And so it is of interest to examine the relationship between pilots' assessments of workload and their heart rate responses.

Following a three year exploratory study, in which heart rates were recorded from pilots flying a wide variety of aircraft, it was decided in 1972 to monitor heart rate routinely during a series of flight trials to evaluate different types of reduced noise landing approaches[5,6].

The first flight trial used a twin turbo-prop HS Andover to compare a number of different approach profiles using a conventional 3° glide slope as a datum. Single-segment approaches with gradients of 6°, $7\frac{1}{2}^{\circ}$ and 9° and two-segment approaches with a $7\frac{1}{2}^{\circ}$ slope changing to 3° at 200 ft were studied in detail. Fig 1 shows the senior project pilot's 30 s heart rates for the single-segment profiles recorded during one of a group of four sorties. The experimenter used a Latin square design to allow a realistic comparison to be made. Overall mean heart rates for the four approach profiles are shown in Fig 2 for the same pilot. In this case there was exceptionally good agreement between heart rate levels and subjective estimates of workload; and also with expected levels of task difficulty - the workload being expected to increase with steeper approach paths and higher rates of descent.

Later, two-segment approach profiles, with a $7\frac{1}{2}^{\circ}$ slope changing to a 3° slope at 200 ft, were evaluated. Fig 3 compares mean heart rate values for these two-segment approaches and landings with those for 3° approaches and landings. Interestingly, despite their relatively low heart rate responses the project test pilots initially rated the workload for the two-segment approaches as high. It later transpired that these two pilots had instinctively disliked the idea of changing from a steep gradient - with the higher rate of descent - to a normal gradient at 200 ft. After the first sortie they modified their views and then consistently rated the $7\frac{1}{2}^{\circ}/3^{\circ}$ approach as being as easy as, if not easier than, the normal 3° approaches. This example highlights the possibility of subjective assessments of workload being biased by allowing instincts and misconceptions to influence judgement. It also illustrates the advantage of using heart rate to augment - or sometimes to question - subjective assessments of workload.

In a later trial in this series a VC-10 four-jet transport was used to evaluate $5^{\circ}/3^{\circ}$ two-segment approaches - the transition from the steep to the normal gradient being increased to 500 ft for this larger aircraft. Fig 4 illustrates beat-to-beat heart rates recorded from the handling pilot and from the co-pilot during an early two-segment approach and landing. The introduction of beat-to-beat or instantaneous heart rate plots increased the value of this physiological measure by recording short term changes in rate which can be used to identify changes in levels of workload. For example, in Fig 4 'A' indicates the start of descent on the 5° glide slope - in this case at a greater height than usual. Points 'B' and 'C' indicate, respectively, the outer marker and the transition at 500 ft. This type of presentation also provides a bonus measure in the form of sinus arrhythmia.

Figs 5 and 6 compare overall mean 30 s heart rates for $5^{\circ}/3^{\circ}$ and 3° approaches and landings. These responses confirmed the pilots' subjective assessments that the two-segment profiles generated similar levels of workload to the conventional 3° profile.

These examples are typical of flight trials in which different experimental workload levels can be compared in a realistic way with a convenient datum or with each other. Throughout the series there was a substantial measure of agreement between relative workload levels as judged by pilots' subjective estimates and by their heart rate values. Such comments made in later discussion as "... the way in which my heart rate consistently increased at that point reflects exactly how I felt about the difficulty ..." and "... I was aware of beginning to work harder at that stage of the approach indicated by an appreciable increase in my heart beat ..." are typical.

A number of other flight trials at Bedford has resulted in similar levels of agreement between subjective estimates of workload and heart rates. For example, in trials to assess the value of a 'ski-jump' take-off technique for Harrier VSTOL aircraft heart rate responses agreed with pilot ratings that workload levels for these take-offs were probably less, and certainly no greater, than those for conventional short take-offs in this aircraft[7].

During a recent series of flights to evaluate economic category 3 landings - consisting of autopilot approaches to a 50 or 60 ft decision height and then a manual flare and touchdown[8] - pilots heart rates and workload ratings (using a 10-point scale) for the decision and landing were recorded. Fig 7 is a typical beat-to-beat heart rate plot showing the rapid increase in workload as decision height was neared and manual control was assumed for the landing. The scatter diagram (Fig 8) illustrates graphically the relationship between 32 heart rate responses and workload ratings in real fog for the senior project test pilot. These data varied more or less according to fog conditions and runway visual ranges (RVRs).

Unlike the noise abatement trials workload levels during fog approaches and landings could not be compared directly with a suitable standard. Nevertheless, heart rates recorded in fog could be compared indirectly with those recorded during approaches and landings in clear weather. Pilots' subjective estimates of workload in fog tended to be based partly on comparison with those in clear weather and - using the rating scale - on an awareness of the degree of spare capacity available for other tasks (Fig 9). There was also a tendency for pilots to compare workload levels on different approaches during the same sortie as fog conditions varied.

Flight trials such as these have appeared to provide strong evidence of a reasonably good relationship between a pilot's heart rate response and his estimate of the workload level associated with a well defined and demanding piloting task. And it is a relationship that appears to hold good both for comparative levels of workload and for short term changes in workload as indicated by changes in beat-to-beat heart rate.

Unfortunately, when dealing with human subjects - even with experienced test pilots - discrepancies and inconsistencies are bound to occur between their opinions and their heart rate responses. In most such instances at Bedford a plausible cause for the disagreement has been identified.

3 HEART RATE AS AN INDICATOR OF WORKLOAD

The use of physiological variables to indicate levels of workload has been viewed with suspicion by many people and the use of only one variable - such as heart rate - has been criticised in particular. However, many of these criticisms have been based on the results of laboratory and flight simulator experiments where often the task and levels of workload were unrealistic.

Experience at Bedford has shown that when the pilot is in the handling loop, or expecting to enter the loop, and when the flight task is reasonably demanding heart rate alone will usually identify meaningful changes and differences in workload. Of course, expected changes in workload may be more theoretical than practical; and so before deciding whether heart rate can differentiate between workload levels it is important to be sure that there is, in fact, a real difference[7].

When the flight task is relatively undemanding or when the pilot is in a purely monitoring role heart rate alone may not differentiate between small differences in workload. But often in these instances visual inspection of beat-to-beat plots will reveal changes in the degree of heart rate variability (sinus arrhythmia) which may well signify changes in workload[9].

4 USING HEART RATE TO ASSESS LEVELS OF PILOT WORKLOAD IN FLIGHT

When monitoring pilots in flight it is obviously desirable to obtain their active co-operation and it is even better to have their enthusiastic support for the technique. At Bedford, test pilots frequently apply their own electrodes before flight; and at some time afterwards it is quite usual for them to express a keen interest in the recorded data so that they can relate their subjective impressions of workload and task difficulty to changes in their heart rate.

Heart rate indicates only relative differences in workload and so it is helpful to have some form of datum for purposes of comparison. In practice assessment of workload is usually associated with the introduction of a new aircraft system or operating technique and so one can often compare the new with the old. Although it is not always possible to compare heart rate responses for different experimental variables during the same sortie, or even under similar flight conditions, the advantages of doing so are obvious.

The individual nature of heart rate responses make it almost essential, especially when dealing with small numbers of pilots, for each pilot to be considered as his own control.

A pilot may compensate for an easier task by improving his performance or, conversely, he may allow his performance to deteriorate rather than exert more effort to meet the demands of a more difficult task. In each case his workload - and thus his heart rate - may remain unchanged; and so it must be axiomatic that when assessing workload performance criteria are clearly defined and monitored.

As mentioned earlier, differences in workload are more likely to be detected by heart rate and probably by subjective assessment when the task is realistically demanding. And so the technique is particularly appropriate for estimating workload during the approach and landing. In this instance the task is well defined and performance can usually be monitored by on-board instrumentation and by airfield-sited kinetheodolites or radar.

The high cost of operating research aircraft usually makes it impossible to obtain enough data for worthwhile statistical analysis. Nevertheless, obvious trends in heart rate changes can be used in conjunction with pilot ratings to provide valuable and reliable indications of differences in workload levels. Surprisingly, despite being more used to obtaining precise measurements from mechanical and electronic devices, trials scientists at Bedford have found pilots' heart rate levels and subjective ratings to be of definite value for assessing or comparing levels of workload in flight.

5 POSSIBLE NEURO-PHYSIOLOGICAL MECHANISMS

There is a substantial amount of evidence in favour of workload being the main determinant of heart rate levels in experienced pilots during demanding flight manoeuvres. It is interesting to speculate on possible neuro-physiological mechanisms that would explain this relationship. Certainly, it is rarely due to physical activity - which during normal flight is very low. Although the fact that heart rates are higher for pilots in the handling loop does suggest that increased neuromuscular activity of some form must play a part.

Piloting an aeroplane, especially during the more difficult manoeuvres, requires the brain to collect, filter and process information quickly; to exercise judgement and make decisions; and to initiate rapid and appropriate actions. This neurological activity - which must have been essential for the survival of primitive man - is associated with a state of preparedness sometimes known as arousal. Furthermore there is experimental evidence that increased arousal - up to a moderate level - enhances a person's capacity for complex skills and thus improves performance[10]. For instance, Duffy[11] reported that the degree of arousal "... appears to affect the speed, intensity and co-ordination of responses and thus to affect the quality of performance". She also observed that in general the optimum level of arousal appears to be a moderate level with the curve expressing the relationship between performance and arousal taking the form of an inverted 'U'. Other authors have also referred to such a relationship though there is only meagre experimental evidence to support it[12]. Nevertheless, a theoretical relationship of this type has a particular attraction in the context of flying aeroplanes as there is evidence that both under- and over-arousal have preceded landing accidents where pilot performance was clearly below an acceptable level.

There is some experimental evidence that a similar inverted 'U' shaped function describes the relationship between performance and task demands[13]. And it has been suggested that levels of arousal are determined by task characteristics or demands, by how the individual perceives the situation, and by how he responds to his environment[14,15]. And so one can speculate that a pilot, by matching his level of arousal to the perceived difficulty of a flight task, is more likely to produce an adequate - if not optimum - level of performance. The result will depend largely on his training and experience, although if the task is a novel one, as frequently happens in test flying, a significant element of empiricism must be involved. Clearly, the level of arousal should be high enough for the task *per se* and also high enough to allow for the unexpected. For example, an engine failure on take-off may require extremely rapid and appropriate actions.

On occasions at Bedford it has been obvious from the sudden increase in heart rate after the start of a manoeuvre that a pilot had failed to anticipate the difficulty of the task and 'tune' his arousal accordingly. Converseley, high heart rates have been recorded - both before and during a manoeuvre - when there was an element of uncertainty about the task. This was particularly noticeable for the novel 'ski-jump' take-offs and for a pilot's first approach and manual landing in fog. The probability of a near optimum level of arousal being generated must be greater if a pilot has recently experienced the demands of a particular flight task. Heart rates recorded from several pilots during sorties of approaches and landings in fog became lower and reasonably consistent after the first or second run. Zwaga[16] in describing an 'adjustment period' during which physiological responses to specific stimuli were moderated related the phenomenon to the concept of arousal.

Anticipatory increases in heart rate seen before the start of manoeuvres such as the take-off presumably indicate an increased level of preparedness in the pilot's neurophysiological system for the demanding task to follow. It seems clear that increasing the level of arousal in this way must be an advantage in the same way that sportsmen 'warm up' before competitive events. In other words, a task requiring a high level of psychomotor skill should not be started from cold.

Support for these speculations is provided by experimental evidence showing that appropriate pathways in the brain and central nervous system do exist. Stimulation of the reticular activating system (RAS) results in increased alertness, improved information processing, and shorter reaction times. This state of increased arousal is apparently sustained by reciprocal feedback mechanisms between the cortex, the RAS and the hypothalamus. The hypothalamus, in addition to regulating autonomic nervous system activity, which includes heart rate, also contains integrating and organising centres concerned with arousal.

Although the concept of arousal is an oversimplification of complex neurophysiological mechanisms it is functional and, providing it is not confused with emotion, it conveniently explains the relationship between a pilot's workload and his heart rate.

A final example from Bedford may confirm - in a practical way - the importance of an adequate level of arousal during the approach and landing. Fig 10 shows two beat-to-beat heart rate plots for the same pilot during a sortie of 6° approaches using direct lift control (DLC) in a BAC 1-11. The upper trace was recorded during the ninth approach which ended in a particularly heavy landing when the pilot failed to arrest the rate of descent. Damage to the aeroplane necessitated grounding for 3 weeks. Uncharacteristically the heart rate did not increase as the runway threshold was neared - although it increased rapidly after the hard touchdown! (The temporary interference in the trace was caused by the jolt on landing affecting the on-board monitoring equipment.) The lower trace, of a typical response for a 6° approach and roller landing, is shown for comparison.

6 CONCLUSIONS

The questions posed at the beginning of this Memorandum cannot be answered with any degree of scientific certainty. Nevertheless, it is possible from the discussions above to arrive at the following conclusions:

(1) There is good evidence that heart rate responses increase with increased workload.

(2) Differences in heart rate values appear to indicate relative differences in workload.

(3) Heart rate monitoring is best used in conjunction with a rating scale for workload.

(4) Although the exact nature of the neuro-physiological mechanisms involved is not known it is possible to construct a reasonable hypothesis using the concept of arousal.

Reference was made earlier to the difficulty of defining workload - perhaps in the interest of clear thinking one should avoid using this term altogether and refer instead to pilot activity, effort, task demands and so on.

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REFERENCES

No.	Author	Title, etc
1	J. Roman *et al*	Flight research program VI: heart rate and landing error in restricted fields of vision landings. Aerospace Med 38, 128-132 (1967)
2	H.P. Ruffell Smith	Heart rate of pilots flying aircraft on scheduled airline routes. Aerospace Med 38, 1117-1119 (1967)
3	A.H. Hasbrook P.G. Rasmussen	Pilot heart rate during in-flight simulated instrument approaches in a general aviation aircraft. Aerospace Med 41, 1148-1152 (1970)
4	G. Ellis A.H. Roscoe	The airline pilot's view of flight deck workload: a preliminary study using a questionnaire. RAE Technical Memorandum FS(B) 465 (1982)
5	A.H. Roscoe	Heart rate monitoring of pilots during steep gradient approaches. Aviat Space Environ Med 46, 1410-1415 (1975)
6	A.H. Roscoe	Pilot workload during steep gradient approaches. In: Conference Proceedings No.212 Aircraft Operational Experience and its impact on safety and survivability. AGARD, Paris, 1976
7	A.H. Roscoe	Handling qualities, workload and heart rate. In: Eds Hartman B.O. and McKenzie R.E., Survey of methods to assess workload. AGARDograph No.246 (1979)
8	A.H. Roscoe	Pilot workload and economic category 3 landings. In: Conference pre-prints. Aerospace Medical Association Annual Scientific Meeting, 1980
9	A.H. Roscoe	Heart rate changes in test pilots. In: Eds Kitney R.I. and Rompelman O., The study of heart rate variability. Clarendon Press Oxford, 1980
10	R.B. Malmo	Activation: A neuro-physiological dimension. Psychological Rev 66, 367-386 (1959)
11	E. Duffy	Activation and behaviour. J. Wiley and Sons, New York, 1962
12	A.T. Welford	Arousal, channel capacity and decision. Nature 194, 365-366 (1962)
13	A.T. Welford	Stress and performance. Ergonomics 16, 567-580 (1973)

REFERENCES (concluded)

No.	Author	Title, etc
14	R.T. Wilkinson S. El-Beheri C.C. Gieseking	Performance and arousal as a function of incentive, information load and task novelty. Psychophysiology 9, 589-599 (1972)
15	D. Kahneman	Attention and effort. Prentice-Hall Inc, Englewood Cliffe, 1973
16	H.J.G. Zwaga	Psychophysiological reaction to mental tasks - effort or stress. Ergonomics 16, 61-67 (1973)
17	G.E. Cooper R.P. Harper	The use of pilot rating in the evaluation of aircraft handling qualities. NASA Technical Note 5153, Washington DC (1969)

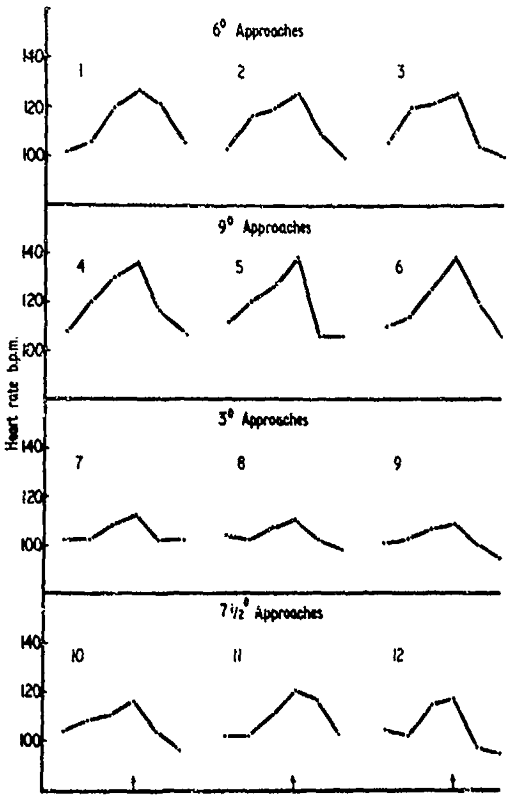

Fig 1 Mean 30 s heart rates for one sortie of experimental approaches (HS Andover)

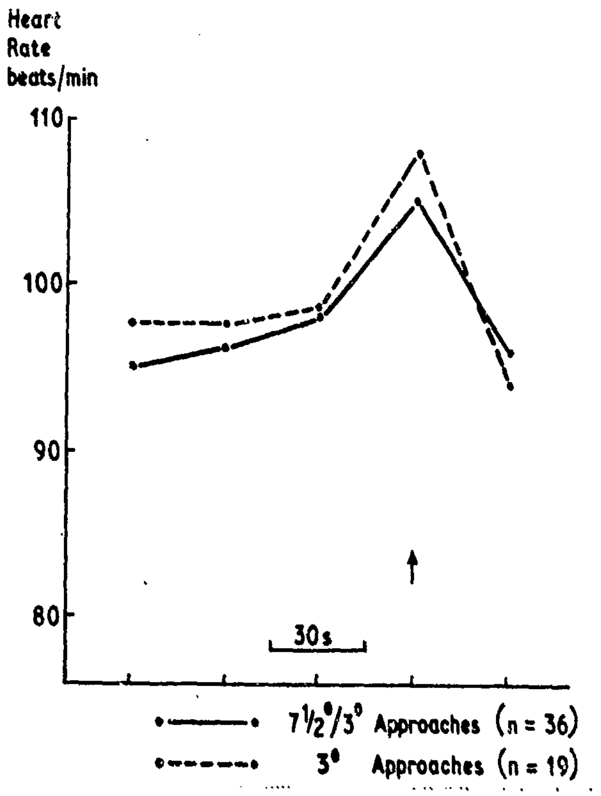

Fig 3 Overall mean heart rates for 7½°/3° and 3° approaches (HS Andover)

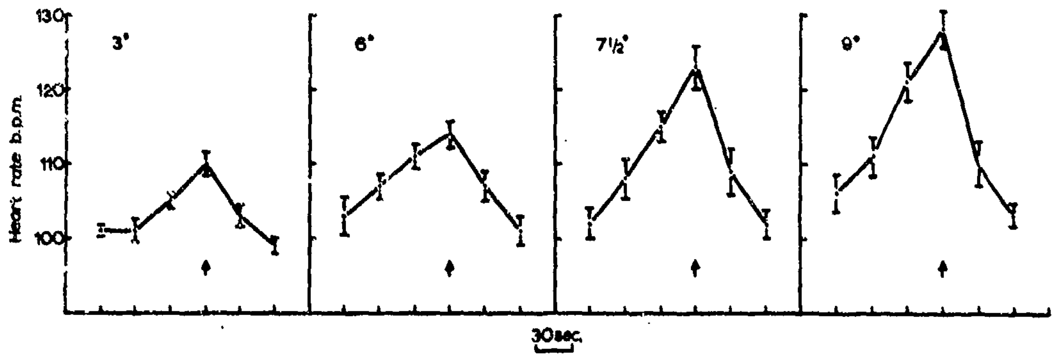

Fig 2 Overall mean 30 s heart rates (± SE) for four sorties of experimental approaches (HS Andover)

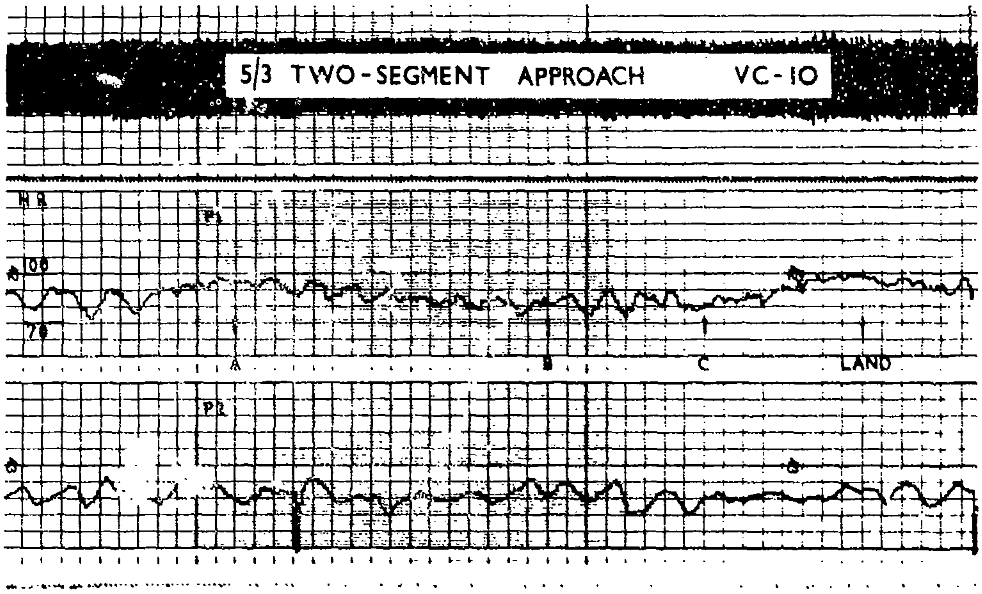

Fig 4 Beat-to-beat heart rate for two pilots during $5^{0}/3^{0}$ approach
A = start of descent; B = outer marker; C = transition

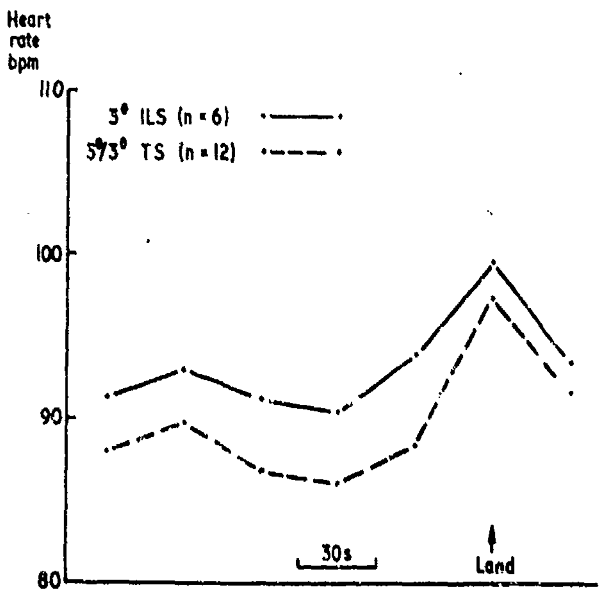

Fig 5 Pilot No.1

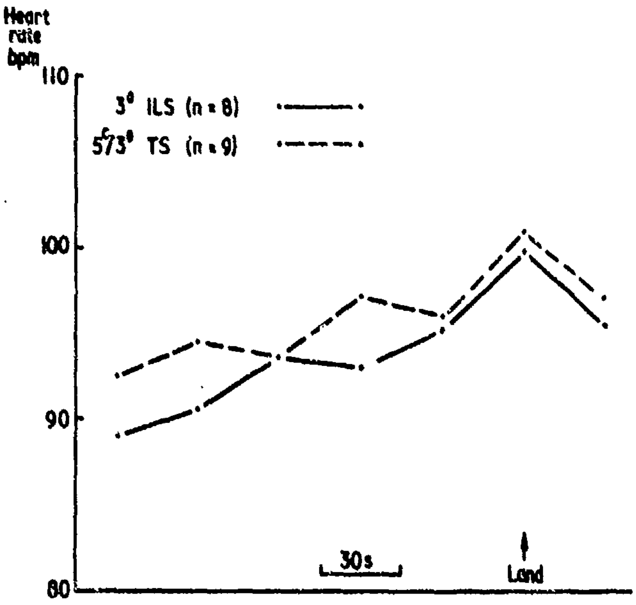

Fig 6 Pilot No.2

Figs 5&6 Overall mean 30 s heart rates for $5^{0}/3^{0}$ and 3^{0} approaches (VC-10)

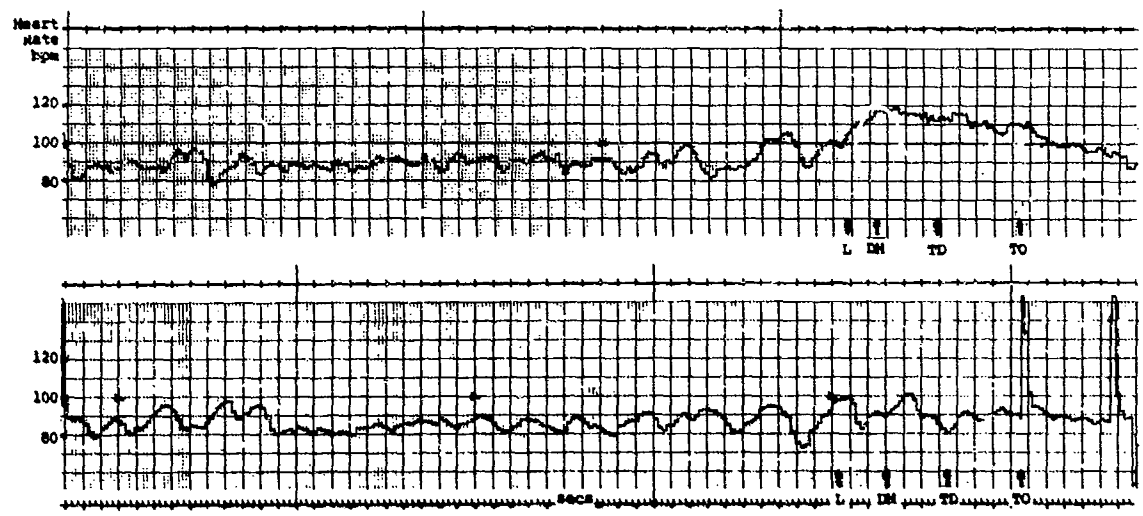

Fig 7 Heart rates during approaches and landings in fog (BAC 1-11)
Upper trace - Economic Category 3 with manual landing
Lower trace - Category 3 autopilot approach and landing

L = lights; DH = decision height; TD = touchdown; TO = take-off

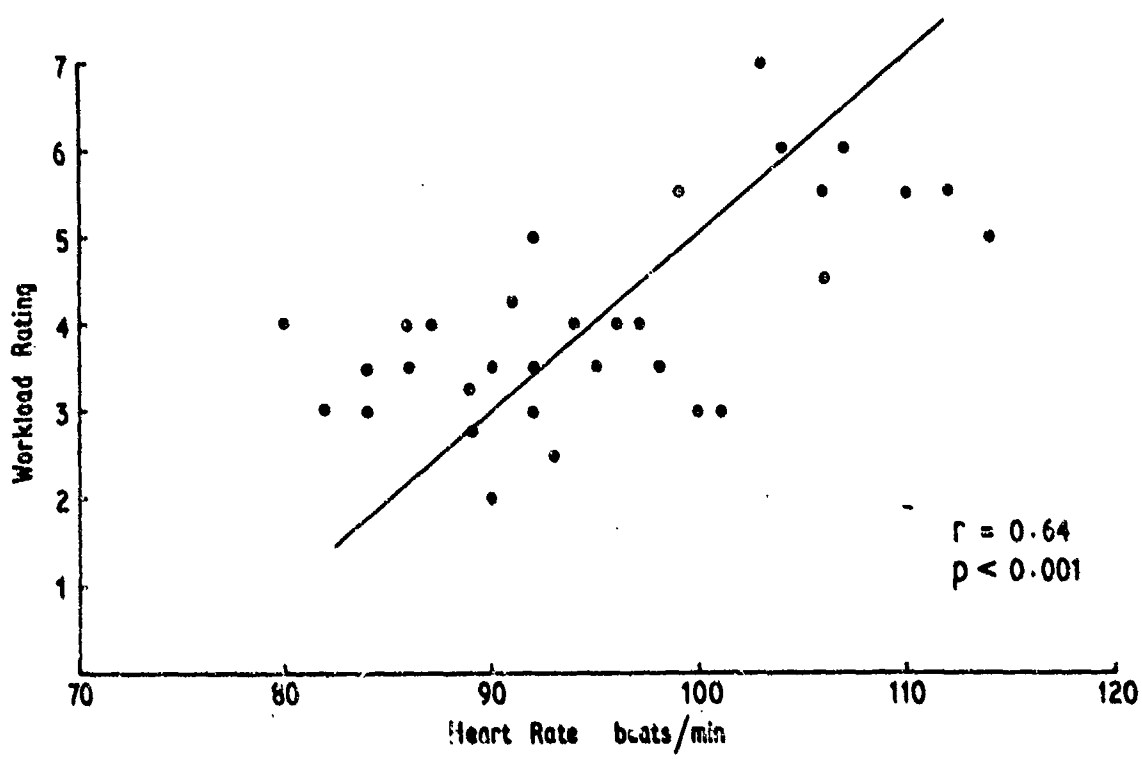

Fig 8 One pilot's workload ratings and heart rate levels for manual landings in fog

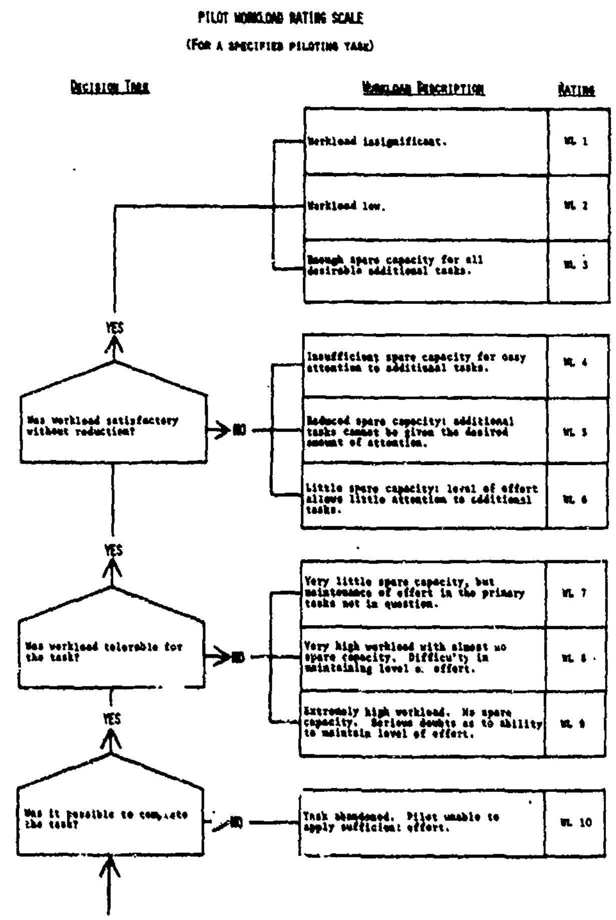

Fig 9 Pilot workload rating scale (based on the Cooper-Harper handling qualities rating scale (Ref 17))

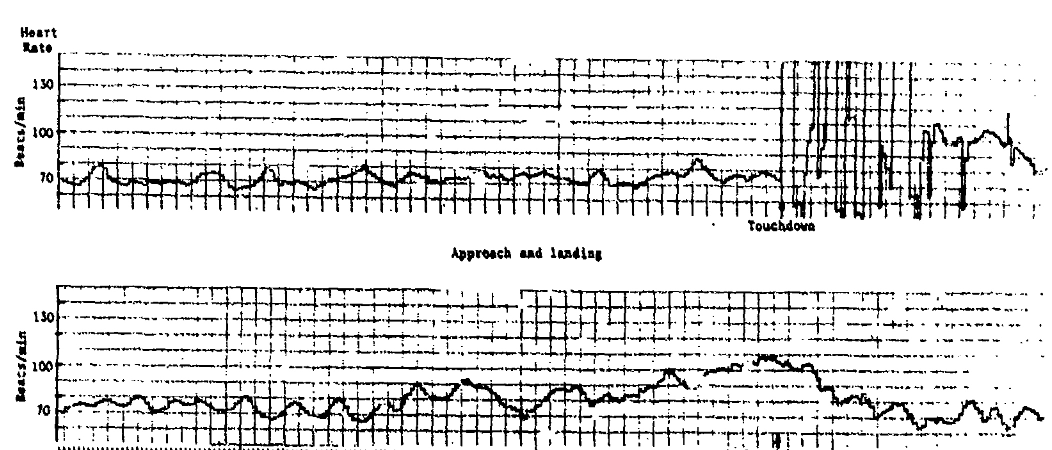

Fig 10 Heart rates recorded during a sortie of experimental 6° approaches using DLC (BAC 1-11)

Upper trace - Approach ending in a heavy landing
Lower trace - Typical response for approach and 'roller' landing