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DEVELOPMENT OF SACCADE LENGTH INDEX OF TASKLOAD
FOR BIOCYBERNETIC APPLICATION

Robert S. Kennedy, James G. May, Marshall B. Jones,
and Jennifer E. Fowlkes

FINAL TECHNICAL REPORT

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31 January 1989

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The idea which prompted the present research was that biological events may be predictive of the attentional and task demands of work. If these could be analyzed in real time and fed back to the machine (or operator), a truly biocybernetic system could be created. A nonintrusive reliable measure of individual differences such as attention during monitoring and control tasks has obvious biocybernetic relevance, particularly in dynamic environments and for design of equipment. In Phase I, two investigations were performed to assess the feasibility of using specific characteristics of eye movement saccades as unobtrusive indicants of mental workload. Eye movements were measured while subjects were differentially task loaded by simple, moderate, and complex auditory tone counting. The results indicated that the extent of saccadic eye movements varied inversely in subjects as tone counting complexity increased. Phase II experimentation involved a series of interlocking experiments and

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proof of concept demonstrations. In the studies performed in this series, reliable data were obtained with as few as three subjects, provided there were sufficient calibrations and stable baselines of performance measures. We found that saccade length index of taskload was related to the workload under which the operator performs and not with performance per se. That is, the predictive validity of SLIT is chiefly as an index of the objective information load to the operator, even when visual tasks are employed. This finding surfaced when the effects of practice were examined. Practice did not have as much effect on SLIT as did the objective index of task loading. Therefore, while performance improved when tasks of different difficulty were practiced for many sessions, it appeared that the chief determinant of saccade length was the number of channels which were monitored. The SLIT effect, which was originally demonstrated in the dark with an auditory task, was obtained in a lighted room while monitoring a visual signal, thus broadening potentially the applicability of the phenomenon. Also, in a simulated field test, SLIT was demonstrated to be robust even when a visual forcing function (optokinetic nystagmus) was present.

A literature review and meta-analysis was conducted to synthesize the literature on workload measures and was presented in a series of tables. In general, the number of performance-based measures appeared to be on the upsurge over the past decade and physiological measures not involving eye movements appeared to be on the downswing. The number of subjective measures of workload studies were stable. Investigations of ocular-based measures, particularly cortical-evoked potentials, were on the increase. The chief finding from a fully quantititative meta-analysis of the ocular-based measures found a sufficient predicate for continuing the directions of the Saccade Length Index of Taskload (Workload) (SLIT) research since predictive validities of eye movement research in general appeared to be robust (particularly eyeblink), and several types of studies which examined eye movement extent (like SLIT) were considered to hold promise. In the feasibility demonstrations, vertical and horizontal eye movements became resolved and left- and right-eye recordings were also separated. The former was a necessary condition for isolating blinks, and the latter was a first step in removing artifacts from the eye movement records which might be due to other oculomotor activities (e.g., vergence, convergence, and accommodation).

Software development occurred when the work, originally conducted in the more controlled environment of a university laboratory using stationary equipment (e.g., infrared, head-fixed, oculometer) and hand scoring, was transferred to a regular office. There the software and hardware development continued and a series of proof of concept and feasibility demonstrations were undertaken. A low-cost microprocessor was selected for the SLIT system and software was developed and customized to produce a quasi-portable system. The customized program has the ability to reject blinks and it is possible to integrate eye movement records and deliver analyses automatically, scored within 2.5 minutes. The software program possesses many scoring and integration features (viz., left vs. right eyes, vertical vs. horizontal, vergence/convergence differences, velocity, # eye movements), which will easily be accommodated by larger capacity, more permanently emplaced, laboratory systems.

19. Abstract (cont'd)

The possible commercial applications of SLIT for the private sector are considerable. SLIT may be used as an independent assessment of an individual's attention which may wane with time on task or due to other factors. Such a relationship might be of interest during quality control on assembly lines, or in remote emplacements where security displays are monitored. Since SLIT size appears to be proportional to workload, displays and workstations could be tested and evaluated objectively and compared for difficulty level. In addition, preliminary evidence suggests that individual differences in saccade length may be sufficiently reliable so that they could be studied for stability over time and then examined for relations to equipment and operator aptitude tradeoffs in systems designs.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

EXECUTIVE SUMMARY

Investigations of workload are the logical extension of the time and motion studies of Gilbert and Taylor, which are often used to date the formal beginnings of human engineering and systems research. We use the term workload to refer to the demands imposed on a given human operator by a given task. Workload measurement involves an attempt to characterize conditions under which task demands can or cannot be met by the performer. The problems in workload measurement are many. In a recent Congressional hearing, for example, human factors experts offered their opinions as to the cause of the downing of Iran Air Flight 655. Opinions differed depending on area of expertise, but there was consensus that an incorrect decision had been made from displayed information and the incident was due to the combined effects of high workload and combat stresses. Perhaps more importantly, these factors were not addressed in the design of the AEGIS tactical information displays. Better workload measurement is needed both from the standpoint of the independent variable (the workstation) and the dependent variable (how it affects the operator). If such information were available with sufficient precision, it would be possible to take the output of the individual's interactions with displayed information and modify the display so the system will better accommodate the individual's needs.

The present research presumes that biological events may be predictive of the attentional and task demands of work. If these could be analyzed in real time and fed back to the machine (or operator), a truly biocybernetic system could be created. For example, we know there may be little or no deterioration in operational performance until the point of failure is closely approached, but perhaps sensitive biological measures of workload could provide premonitory signs of impending failure.

In Phase I, two investigations assessed the feasibility of using specific characteristics of eye movement saccades as unobtrusive indicants of mental workload. Eye movements were measured while subjects were differentially task loaded by simple, moderate, and complex auditory tone counting. The extent of saccadic eye movements varied inversely in subjects as tone counting complexity increased.

The second Phase I experiment used the same equipment and explored further the relationship of eye movement measures (saccade length) to workload. We also incorporated experimental evidence of high arousal. To organize our activities we employed a 2X2 classification schema of workload measures to improve descriptive precision and permit improved communication of ideas.

To test the relationship between saccade length and arousal, subjects in the second Phase I experiment performed an auditory tone counting task at three levels of difficulty while saccadic eye movements were recorded. Performance varied inversely with difficulty level of the tone counting task suggesting that the different task conditions induced different levels of mental workload. Average length of saccadic eye movements was also reduced with increased task difficulty. Correlation coefficients between saccade length and performance for each subject ranged from $r = .37$ to $r = .99$ with a mean of r = .64. Results suggested that saccade length was a promising objective measure of task demands of a display and could serve as a useful measure of mental workload.

Phase II objectives were to develop further the Saccade Length Index of Taskload (Workload) or SLIT and cross-validate the results of Phase I. The ultimate outcome of Phase II would be prototype development of a transportable system to assess mental workload via the SLIT metric and other bioelectric measures as appropriate. A chief ingredient in initial development of such a system was a focus on rapid (i.e., seconds) evaluation of the bioelectric events so that, when properly identified and classified, such signals could be fed back to signal generators. This work is divided into three main thrusts: Meta-analysis, Experimentation, and Software Development. The meta-analysis section has two components -- a literature review as well as a quantitative meta-analysis. The sections on experimentation describe a series of studies which address various aspects of implementing and measuring SLIT. The software development section outlines procedure and implementation of the apparatus and scoring used.

A meta-analysis was conducted to synthesize the literature on workload measures and is presented in a series of tables. In general, the number of performance based measures is on the upsurge over the past decade, and physiological measures not involving eye movements are on the downswing. The use of subjective workload measures is stable. Investigations of ocular based measures, particularly cortical evoked potentials, were on the increase. The chief finding from the quantititative meta analysis of the ocular based measures was a sufficient predicate for continuing the directions of SLIT research, since predictive validities of eye movement research in general appeared to be robust.

Experimentation involved a series of interlocking experiments and proof of concept demonstrations. SLIT measures are related to the workload under which the operator performs, and not to performance *per se*. That is, the predictive validity of SLIT is chiefly as an index of the objective information load to the operator, even when visual tasks are employed. While performance improved when tasks of different difficulty were practiced for many sessions, the chief determinant of saccade length was the number of channels being monitored. The SLIT effect, which was originally demonstrated in the dark with an auditory task, was obtained in a lighted room while monitoring a visual signal, thus broadening potentially the applicability of the phenomenon. Also, in a simulated field test, SLIT was demonstrated to be robust even when a visual forcing function (optokinetic nystagmus) was present.

Finally, software development "automated" the scoring process and converted stationary equipment to a quasi portable system on a low cost microcomputer. The customized scoring program has the ability to reject blinks and it is possible to integrate eye movement records and deliver analyses, automatically scored, within 2.5 minutes. The software program possesses many scoring and integration features (viz., left vs. right eyes, vertical vs. horizontal, vergence/convergence differences can be separated, velocity), which will easily be accommodated by larger capacity, more permanently emplaced, laboratory systems.

INTRODUCTION

In the early days of aviation, the machine was often the limiting factor in system performance. Today, overstressed aviators may be more common than overstressed aircraft. In addition to the structural improvements that modern technology has provided, new systems permit more information to be presented in real- or fast-time to the operator than he or she can handle efficiently. Descriptive terms like "getting behind the system," information overload," and "noisy" abound in design conferences, and, poignantly, we have "declutter switches." In modern weapon systems the human sensory systems are often bombarded with stimuli with the consequence that analyses of displayed information are time constrained. These issues are not limited to military jobs. Civilian air traffic controllers are often retired for job-related workload stress (Hale, Williams, Smith, & Melton, 1971), and astronauts experience "time compression" in connection with their high workload periods upon reentry (Schmitt & Reid, 1985). As military equipment has been made more complex, the proportion of the available pool of personnel which possesses the mental capabilities to accommodate the system is becoming more limited (Tice, 1986; Merriman & Chatelier, 1981).

Investigations of workload are the logical extension of the time and motion studies of Gilbert and Taylor which are often used as the formal beginnings of human engineering and systems research. Therefore, we will not describe at any length what workload is and why we study it. These problems do not come as any surprise to those who grew up in the field of human factors engineering. Indeed, they were eloquently predicted by Chapanis, Garner, Morgan, and Sanford (1947) in one of the earliest works on systems research where they said, "...Let us look ahead about 50 years [it's only 42!] and imagine what kind of problem the air traffic control officer at LaGuardia Field will have when a heavy fog settles over the place and 100 planes converge on the field from Mexico, London, Paris, San Francisco, and Albuquerque. How are we going to get all that information to him [sic!]. How can we present this information to him so that he can see the total picture? There are, after all, only a few channels that we can use in getting this information into his brain" (p. 240). Relatedly, and more recently, in a Congressional hearing, several prominent human factors experts from different fields, inside and outside the Department of Defense, were invited to offer their opinions as to the cause of the downing of the Iran Air Flight 655. Granted that an incorrect decision had been made from displayed information in that case, the one issue about which the experts appeared concordant was that the incident was due to the combined effects of the high workload and combat stresses which were not accommodated in the human factors design of the tactical information displays for the AEGIS weapon system (House Armed Services Committee, 1988). We do need to do better at workload measurement, both from the standpoint of the independent variable (the workstation) and the dependent variable (how it affects the operator). This paper will argue that, if such information were available with sufficient precision, it would be possible to take the output of the individual's difficulty with displayed information and by some means feed this information back into the system so that the system will better accommodate the individual's needs. Following Weiner (1948), we think that something like this is what K.U. Smith (1966, 1967; Smith & Smith, 1966) had in mind when he began writing about biocybernetics some 25 years ago.

For the exposition of our ideas, we have used the term workload to refer to the demands imposed on a given human operator by a given task, and workload measurement involves an attempt to characterize conditions under which task demands can or cannot be met by the performer (Gopher & Braune, 1984). Later, we describe a 2X2 classification schema which we have employed to organize our present effort. We believe that the improved descriptive precision of this model will permit improved communication of ideas. The classification follows from statistical theory and its assumptions, and we believe that it should have heuristic use as well.

The idea which prompted the present research was that biological events may be predictive of the attentional and task demands of work. If these could be analyzed in real time and fed back to the machine (or operator), a truly biocybernetic system could be created. For example, we know there may be little or no deterioration in operational performance until the point of failure is closely approached (Gopher & Donchin, 1986; Schmidt, 1978), but perhaps sensitive biological measures of workload could provide premonitory signs of impending failure. There are two technical developments which must be accomplished to produce a workable system. One is traditionally a human factors effort, and in the case of bioelectric events, neurophysiological and biomedical. The other entails engineering development, including software and hardware. In this work we have set out to accomplish both, but the emphasis has always been on the former rather than the latter. To organize our present effort, we describe a 2X2 classification schema which we have employed to organize our present effort. We believe that the improved descriptive precision of this model will permit improved communication of ideas. The classification follows from statistical theory and its assumptions, and we believe that it should have heuristic use as well.

There are other applications for validated biocybernetic workload indices. To the extent that such workload measures also follow task demands, they could be employed to index workload characteristics of military systems during various stages in the human factors engineering design and subsequent evaluation. It is generally accepted that workload is a function of task, operator capabilities, and sequential characteristics (e.g., practice with task, previous workload history, etc.). Moreover, a general consensus is that workload is multidimensional and that the researcher should have a battery of workload metrics at his or her disposal (Bateman, 1979; Crabtree, Bateman, & Acton, 1984; Eggemeier, 1980; Eggemeier, Shingledecker, & Crabtree, 1985; Frazier & Crombie, 1982; Gopher & Donchin, 1986). Researchers are determining whether there are reliable indicants of individual differences in information processing skills (Benel, Coles, & Benel, 1979; Damos, 1984a,b,c; Damos & Smist, 1981; Wickens, Mountford, & Schreiner, 1981). By assessing workload's impact on individuals for tasks of constant difficulty, workload indices can be used to match systems according to the reliable individual differences of the user population. Then better decisions can be made selecting between design tradeoffs (e.g., customize for individual use, design in "aided" systems, or automate the function). Any attempt at creating a biocybernetic system will need to take into account the demand characteristics of the workload prior to being able to feedback such information so that the system produces less workload.

OVERVIEW

This project, which was conceived to be carried out in three phases, entails the investigation of a physiological output of the human organism to be employed as fedback information to systems in order reduce task loading to acceptable levels; specifically, an eye movement index of mental workload was studied. Phases I & II, funded by AFOSR, have been completed and a prototype is available. Future plans call for a Phase III which will combine Essex development funding with federal and private sector support in order to make a fully-up-and-running system available to the technological community.

In Phase I, two investigations were performed to assess the feasibility of using specific characteristics of eye movement saccades as unobtrusive indicants of mental workload. Eye movements were measured while subjects were differentially task loaded by simple, moderate, and complex auditory tone counting. The results indicated that the extent of saccadic eye movements varied inversely in subjects as tone counting complexity increased. Thus encouraged, the objective of the Phase II work was to further develop the SLIT. This was done through interlocking, and parallel research efforts involving meta-analytic literature reviews, and experiments and prototype development including customized software for data acquisition and analysis. We also offer a model which we use descriptively, but which has heuristic applications. In what follows we will take these issues in turn, but first we describe why we investigated characteristics of involuntary eye movements.

RATIONALE

Impetus for the present effort began with the finding that habituation of the fast-phase component of vestibular ocular response was attenuated in subjects who performed a vigilance task (Kennedy, 1972). This might be expected, it was argued, since the fast phase component of nystagmus is dependent on the integrity of the reticular formation which is also related to arousal and alertness (Cohen, Feldman, & Diamond, 1969; Darhoff & Hoyt, 1971; Yules, Krebs, & Gault, 1966). Given that other research related nystagmus to arousal (Collins, Crampton, & Posner, 1961; Collins & Posner, 1963), the idea was pursued to relate velocity and latency of saccades to performance on a task which could be varied in terms of the demands it placed on the operator.

Thus, Phase I (May, Kennedy, Williams, Dunlap, & Brannan, 1985) of the present effort set out to study primarily whether eye movement form was predictive of arousal measured as performance on a mental task. There were two studies in Phase I. Initially, subjects performed an auditory tone counting task at three levels of difficulty while the velocity and latency of saccades in the horizontal plane were recorded. The "velocity hypothesis" was not supported - saccade velocities obtained during the baseline condition of free viewing did not differ significantly from velocities obtained under tone counting conditions. However, in this study, another variable (saccade latency) appeared to vary with the task demands but practice effects and individual differences in performance masked the relationship. There was also the suggestion that the length of a saccade may provide information about task demands. It should also be mentioned that while we did not find support for our hypothesis in Phase I, we also did not have convincing evidence against it since there were known limitations in sampling rate and recording sensitivity of the technique employed.

The second Phase I experiment used the same equipment and explored further the relationship of eye movement measures (saccade length) to workload. At this point we also incorporated findings from the literature on eye movement extent where preliminary experimental evidence showed extent of eye movements might be reduced under conditions which induced high levels of arousal. For example, Malmstrom (with Reed, 1983; and with Reed & Randle, 1983) reported a restriction of pursuit eye movement range during a concurrent auditory task and, more pointedly, Crommelinck and Roucoux (1976) found that restriction in saccade length occurred in cats under conditions of high arousal induced by amphetamines.

Therefore, to test the relationship between saccade length and arousal, subjects in the second Phase I experiment performed an auditory tone counting task at three levels of difficulty while saccadic eye movements were recorded. The mean range of eye movements in the horizontal plane for each of the three workload conditions are presented in (Table 1) along with mean performance on the tone counting task. As seen in the table, performance varied inversely with difficulty level of the tone counting task suggesting that the different task conditions induced different levels of mental workload. This relationship was substantiated by a significant linear trend ($F(1,4) = 9.10$, $p = .0393$). Average extent of saccadic eye movements was also related to task difficulty so that saccade length was restricted with increased task difficulty level ($F(1,4) = 16.65$, $p = .02$). To further substantiate the relation of saccade length to workload, correlation coefficients between saccade length and performance were computed for each subject. The correlations ranged from $r = .37$ to $r = .99$ with a mean of $r = .64$. Thus, the results from this research suggested that saccade length could be a promising objective measure of the task demands of a display and thereby serve as a useful measure of mental workload.

TABLE 1. Normalized Spontaneous Saccade Length and Tone Counting Performance (Percent Correct) as a Function of Task Difficulty

		Task Difficulty		
		Low	Medium	High
Saccade Length	Mean	3.25	3.01	2.44
	(SD)	(2.30)	(3.08)	(2.32)
Performance	Mean	0.96	0.82	0.64
(Percent Correct)	(SD)	(0.09)	(0.19)	(0.23)

DESCRIPTION OF PROJECT GOALS

The purpose of Phase II is to develop further the SLIT and cross-validate the results of Phase I. The ultimate outcome of Phase II would be prototype development of a transportable system to assess mental workload via the SLIT metric and other bioelectric measures as appropriate. A chief ingredient in initial development of such a system would be a focus on rapid (i.e., seconds) evaluation of the bioelectric events so that, when properly identified and classified, such signals could be fed back to signal generators. There were several key technical issues which needed resolution (Table 2) and these were the focus of much of our endeavors. This work was divided into three main thrusts: Meta-analysis, Experimentation, and Software Development. These are outlined in the later sections.

TABLE 2. Key Technical Issues for Phase II SLIT Program

	Description
1	Establish the relationship between the saccade length index of taskload and task performance.
2	Determine the validity of SLIT procedures when visual tasks are employed.
3	Examine the effects of practice on SLIT.
4	Extend SLIT to include vertical as well as horizontal eye movements.
5	Modify SLIT to reject eyeblink artifacts using binocular recording.
6	Compare SLIT to other physiological indices of workload.

Meta-Analysis and Literature Catalogue

To help us plan experiments we went to the scientific literature on workload (e.g., Aasman, Mulder, & Mulder, 1987; Acosta & Dickman, 1984; Biers & Masline, 1987; Hart & Bortolussi, 1984; Mane & Wickens, 1986) as well as to conference proceedings, literature reviews and listings of research. We employed the work of Casalli and Wierwille and their colleagues as a model and followed their taxonomy. This had the advantage of permitting comparison of data collected using the same subjects, tasks, and procedures. First, we catalogued the literature, tabularized them, and then surfaced studies for the meta-analysis which we employed as a context in which to regard our experimental findings.

For the meta-analysis (Green & Hall, 1984), separate studies having similar objectives and data presentation formats were compared on a common metric. For this quantitative literature review, we were primarily interested in those biological events which emanated in the eye and were related to workload (narrowed visual field, pupillary dilation, eye movement extent, eyeblinks, fixation fraction, nystagmus, and event-related potentials).

In connection with the literature cataloguing two useful by-products emerged:

- In Tables 10-13, the majority of the experimental work done since 1970 is organized by the type of workload metric, authors, date, and publication. These tables may be used to discern general trends in this area.

- Because of the number of titles we scanned, we were able to create a computer-based workload bibliography containing over 600 entries. A hard copy of the bibliography appears as Appendix A. The bibliography is also on disk AND may be used with commercial software programs such as d-base. Copies of this disk are available from the Principal Investigator (Robert S. Kennedy, Ph.D., Essex Corporation, 1040 Woodcock Road, Orlando, FL, 32803). We believe that quite apart from the written report, of which it is a part, a computer-based bibliography in this format offers significant advantages over hard copy in that sorting may be done by author, key words, date, etc., at the investigator's choice. A computer-based bibliography may then become part of the next investigator's data base and be updated, added to, annotated, etc., with little difficulty.

EXPERIMENTAL EFFORT

We performed a series of experiments in which the Phase I finding of restricted saccade length during higher workload was replicated. We also studied its applicability to new situations and extended our knowledge of the SLIT metric. Specifically, we examined the effects of practice on SLIT and demonstrated the generality of the SLIT techniques. The results show that the SLIT phenomenon is robust and the metric is stable. Even though large improvements in performance occurred with practice, the validity of SLIT as a workload metric did not change. Second, SLIT is not limited to auditory performances which occur in the dark - the metric appears to be appropriate while tasks which require visual monitoring are performed. Additionally, when moving visual environments which induce reflexive eye movements were created, the SLIT responses were still measureable. Below in our development section we address the independence of SLIT and eyeblink; at least the two metrics do not appear to covary. The question of overlap and which may be the better metric will take considerable exploration, but a provocative design question can be framed using the descriptive model of workload explained below.

SOFTWARE DEVELOPMENT EFFORT

In this part of the work we used analyses, demonstrations, and software to produce a customized scoring technique which permitted nearly immediate (10 seconds) analysis and reporting of data. Additionally, we demonstrated proof of concept in the recording of both eyes as well as vertical and horizontal movements. By software techniques we were able to isolate the SLIT metric from eyeblinks, saccadic frequencies, velocities and other measures. In feasibility studies three subjects were employed and the examination of the relationships between eyeblink and SLIT measures implied independence. Graphic and numerical printouts of the data are also available. This technique is easily adaptable to most laboratory-based PC systems and is as portable as the computer used for analysis.

MODEL OF WORKLOAD

Like the field of stress, and partly for the same reasons, we believe there are logical inconsistencies in the workload literature. For example: (a) workload measures are often dichotomized into objective and subjective measures; but (b) most measurement of mental workload can also be divisibile into two other primary categories -- Operator DEPENDENT and Operator INDEPENDENT. These two classification schemata are neither synonomous nor mutually exclusive, although the literature search nowhere appears to make this point. For example, there are subjective metrics which are operator dependent (e.g., like Cooper/Harper scales [1969]) and there are some which are (or are intended to be) operator independent (like the Subjective Workload Assessment Technique). We believe that by application of this 2X2 model, different outcomes can be predicted to occur depending on the cell from which a particular metric is selected. On this view, logically some analyses may be unwarranted when metrics arise from different sets of assumptions. Therefore, we believe that this descriptive model also has heuristic value.

META ANALYSIS AND LITERATURE CATALOGUE

This section of the report outlines a quantitative meta-analysis organized by a 2X2 classification model and based on an application of the point biserial correlation coefficient. The meta analysis is followed by an in-depth literature catalogue of relevant studies available in the open literature since 1970.

THE PROBLEM

Workload is a hypothetical construct which relates to the attentional demands of a task and is considered to be one of the many determinants of human performance. O'Donnell and Eggemeier (1986) propose that initially, at low levels, increasing workload has little effect on performance. With moderate to high workloads, however, performance begins to deteriorate, slowly at first and then more steeply. Other conditions enter into the determination of workload for a given person at a given time. Experience or practice, for example, reduces workload. The same task requirements impose a lighter burden on a skilled person than on a less skilled one. Time-on-task also affects workload. There are also major group differences in how much workload the same task imposes. Sex, age, and various aptitude categories are all relevant in this connection. Finally, of course, workload varies from one individual to another.

The complexity of this situation has made it more desirable than usual to have adequate, objective measures of workload. An operator, of course, can be asked to report how onerous a task is and, in fact, subjective judgments of workload are probably the best behaved measures of workload available (Gopher & Braune, 1984). Nevertheless, they are still subjective, and scientific bias favors objective measures; at the very least, one should try to develop such measures.

A DISTINCTION

We take the position that the literature on workload indicants has been somewhat clouded by ambiguous usage of the word "subjective." To address this ambiguity, we propose that the dichotomy of operator DEPENDENT measures versus operator INDEPENDENT measures be added to the usual distinction between SUBJECTIVE versus OBJECTIVE measures. For example, on the one hand, workload has been used to mean self-report or any measure derivative from self-report (Boff & Lincoln, 1988; e.g., pp. 1640, 1642). On the other hand, it includes measures which systematically vary within an individual, which we refer to as operator-dependent measures. To clarify the distinction, consider eyeblinks. The number of eyeblinks an operator makes in a standard interval of time is a strictly objective measure; it does not depend in any way with self-report by the operator. One can count eyeblinks without benefit of any communication whatsoever from the operator. Neverthelsss, number of eyeblinks is also operator dependent; it varies widely from one operator to another under the same conditions.

Table 3 presents a classification of workload measures, according as they are subjective or objective and operator-dependent or operator-independent. The upper row includes all operator-dependent measures. Self report by the operator is subjective. Objective (operator dependent) measures include variations in eye movements, pupillary dilation, evoked response potentials, eyeblinks, heart rate, and of course, much else.

In Table 3, the lower row includes operator independent measures. In most experiments, workload is specified by fixing the properties of a task. The properties fixed are usually the amount of information the operator must process, its complexity, or intervals of time between presentation of the material and allowable response (mnemonic demands). These specifications of workload are strictly objective. They do not depend on self report from anyone. However, operator-independent specification may also be subjective. It may involve self-report or judgment, if you like, but the self or judge is not the operator but, rather, the investigator or some other expert. The Subjective Workload Assessment Technique (SWAT) (Reid, Shingledecker, & Eggemeier, 1981) is a case in point. In this approach a trained expert evaluates a task, using a standardized technique, and assigns it a rating. SWAT is a subjective, albeit formalized procedure that does not depend on self report by the operator. Hence, it falls into the lower left-hand corner of the 2X2 table.

TABLE 3. A Classification of Workload Measures

	Examples: Subjective	Examples: Objective
Operator Dependent	Cooper-Harper	Eye Blinks Heart Rate Errors Latencies
Operator Independent	Subjective Workload Assessment Scale (SWAT)	Informational Demand or Complexity

Entries in the cells are examples of the four kinds of workload measures.

Operator INDEPENDENT techniques are based primarily on task descriptions such as time between presentation of stimuli, information bits, and number of information sources. Use of task descriptions to quantify workload is common to most research in which the intent is to assess workload measurement techniques. Often, and appropriately, task difficulty is independently verified prior to its use to validate measures of workload (Bortolussi, Kantowitz & Hart, 1985; Hart, Childress, & Bortolussi, 1981).

Operator DEPENDENT techniques include workload definitions based on the operator response. These include: (a) subjective indices, (b) task performance, and (c) physiological measures.

Subjective indices are operator ratings of task difficulty and task attentional demands obtained via debriefing interviews and questionnaires. For example, the Multi-descriptor Scale used by Casali (1982) requires that operators rate task demands according to each of six descriptors (i.e., attentional demand, error level, difficulty, task complexity, mental workload, and stress). The average of these six ratings is used as a measure of mental workload. Gopher and Braune (1984) argue that a psychophysical scaling approach can be adapted to the measurement of workload based on subjective estimates. As indicated in Table 11, subjective methods of workload assessment are, apart from performance measures, the most commonly employed workload assessment tool, most likely because that are easily administered, low in cost, and require minimal to no instrumentation. Disadvantages include interruption of task to obtain ratings, operator bias, and low or at least poorly understood correlation with measures of performance (Gopher & Braune, 1984; Gopher, Chillag, & Arzi, 1985; Vidulich & Wickens, 1984, 1985; Wickens & Yeh, 1983; Yeh & Wickens, 1984, 1985).

Task performance indices are based upon the assumption that decreasing performance results from increasing workload. Examples of performance measures include number of errors, percent correct, response time, and deviation from an optimal flight path. A common performance measure technique is to measure operator performance on a secondary task (Wickens, 1984). For example, Wierwille and Connor (1983) assigned a primary task to subjects (i.e., straight and level simulated flight) simultaneously with secondary tasks (e.g., mental arithmetic). Given a constant level of workload on the primary task, the performance on the secondary task is thought to represent "residual resources" or "spare mental capacity" (Kantowitz & Sorkin, 1983). Performance variations on the secondary task are thus presumed to measure workload imposed by the primary task which are not reflected by performance on the primary task. Disadvantages of performance measures include the uncertain relationship between performance and workload. Moreover, when secondary tasks are employed, it is essential that the primary task remains primary, a problem not always handled satisfactorily (Damos, Bittner, Kennedy, & Harbeson, 1981; Kantowitz & Weldon, 1985).

Finally, physiological measures have been extensively utilized to measure capability to perform physical workloads. As a logical extension, and in view of the working assumption that cognitive functions have an underlying physiological basis, measures of physiological responses have been extensively employed as an indices of mental workload. Examples include measures of cardiovascular, brain, respiratory, and visual functions. While physiological measures have potential in providing a proxy (Lane, Kennedy, & Jones, 1986) index for mental workload (Donchin & Kramer, 1986; Donchin, Wickens, & Cole, 1983; Frazier, 1966; Kennedy, 1978; Lewis, 1983 a,b; McCloskey, 1987; O'Donnell, 1981; O'Donnell & Shingledecker, 1986; O'Hanlon, 1971; Wilson, O'Donnell, & Wilson, 1982; Wilson, Purvis, Skelly, Fullenkamp, & Davis, 1987; Yolton, Wilson, Davis, & McCloskey, 1987), they may reflect stress rather than cognitive load (Shingledecker, 1982), and rarely account for a large proportion of the variance in the criterion.

It is clear that from the available scientific literature no single subjective, task, or response measure has allowed mental workload to be reliably and objectively quantified. Persistent barriers to satisfactory measure of mental workload include: (1) inadequate conceptualization of mental workload (e.g., Aunon, Kantowitz, McGillem, & Plonski, 1987; Kantowitz & Sorkin, 1983), (2) task dependent nature of many workload techniques (e.g., McCloskey, 1987; Wierwille, Rahimi, & Casali, 1985), (3) and lack of methodologies to handle human differences in task demands such as extent of practice on task, previous workload, ability or skill level (e.g., Matthews, 1986).

This distinction between operator-dependent and operator-independent measures is not artificial. It corresponds closely to the more familiar one between random and fixed factors in experimental design. A typical experiment on workload indicants uses operator-independent specifications as treatment conditions. Thus, the tasks that subjects are asked to perform may be characterized (usually according to objective parameters) as light, moderate, or heavy. In the experimental design these three specifications are levels of a treatment factor called "workload." The factor, moreover, is fixed. The analysis proceeds on the assumption that the experiment could be replicated using the same specifications for the workload factor without error or, more accurately, without sampling error.

The subjects in this typical experiment are studied with respect to their responses while performing the tasks assigned them. These responses, whether subjective or objective, are operator-dependent. In the experimental design the operator response (or indicant) appears as a random factor, either nested within treatment conditions (as in a factorial experiment) or crossing them (as in a repeated-measures design).

Failure to draw these distinctions can lead to serious confusion. It is possible and sometimes useful to correlate, in the sense of the Pearson Product-Moment Correlation Coefficient, two operator-dependent measures of workload. The unit of analysis in such a correlation is the individual operator. One might want to know, for example, how well an objective, operator-dependent indicant of workload on one task predicts operator reported workload on another. One might want to intercorrelate operator-dependent indicants with a view to determining their dimensionality, as in factor analysis. All such analyses take place within the upper row in Table 3.

It is also possible to correlate operator-dependent and operator-independent measures. In any such case, however, one of the two variables being correlated is fixed (the operator-dependent treatment condition) and the other random, whereas two operator-dependent measures are both random. Any text on correlational analysis points out the difference between these two situations. At the sample level, the calculations are much the same, but the models used to analyze these calculations and to test the significance of the results are fundamentally different. Any quantitative review of this field must take this into account. Stated differently, when the experimental design looks at relationships <u>between</u> elements of different classes expectedly these should be lower than those <u>within</u> classes.

In a typical experiment, workload treatment conditions are specified in objective, operator-independent terms. Operator-independent indicants may be either subjective or objective but the focus in the present report will be primarily on objective (visual) indicants. The goal of the experimental work reported here is a biocybernetic indicator of workload. The studies, therefore, that we will be examining involve the two cells of the right hand column of Table 3. The question at issue will be how well the operator-dependent visual (or other) indicants differentiate between the equally objective workload treatment conditions. If subjects (operators) respond very differently under the several workload conditions, it may be possible to infer from the subject's response which treatment condition he or she is in. Of course, it may also be that the operator response in different treatment conditions overlap heavily, in which case it is not possible to infer the treatment condition from the operator's response with much assurance.

The design just described is called in other areas of research a "biological assay." An organism's response is used to grade or rate the objective conditions under which the response is made. A precondition of successful biological assay is that subject responses be well separated under substantially different treatment conditions. The approach to workload by looking at objective, operator-dependent indicants is thoroughly orthodox, but it does not necessarily succeed. Everything depends on how well the indicants "follow" or are correlated with imposed workload conditions. If the correlation between indicant and workload conditions is "sufficiently high" it may make sense to grade the workload conditions according to the mean operator response. But what precisely are we to use in order to index this "correlation"? The next step in the anlaysis must be to settle on a measure of correlation appropriate to the task at hand. In the terminology of meta-analysis (Green & Hall, 1984) we need to specify a measure of effect size.

EFFECT SIZE

The measure of effect size used in this report will be the point biserial correlation coefficient. This measure applies to the relationship between a dichotomous variable and a fully quantitative one. It is obtained by scoring the dichotomy 0 and 1 (or any other two, distinct values) and calculating the Pearson product-moment correlation coefficient. In short, the point biserial is a variant of the Pearson $\underline{r}$ in which, on one variable, many subjects all have the same score (0) and the rest all have another same score (1).

In an experimental context the number of subjects assigned to two treatment conditions is usually the same. This is true for the papers which were analyzed in this report, but even if the sample sizes varied, it would still be correct procedure to treat the two sample sizes as the same, provided that the pooled within-group variance took account of the different sample sizes. Sample size is arbitrary in an experiment. Hence, when sample sizes are not the same, they could have been set to be the same and the means and variances would not change systematically with variable sample size.

Given that the two sample sizes are the same, the most useful form of the point biserial is the following:

$$\underline{r}_{pb} = ((\bar{Y}_1 - \bar{Y}_0)/2)/[((\bar{Y}_1 - \bar{Y}_0)/2) + s^2{}_w]^{1/2}$$

If we know the means under the same two treatment conditions ($\bar{Y}_1$ and $\bar{Y}_0$, and the pool within-group variances ($s^2{}_w$), $\underline{r}_{pb}$ is simply calculated. The square of the point biserial is easily shown to equal the ratio of the between-group to the total sum of squares.

There are two main reasons for choosing the point biserial. The first has already been mentioned, namely, its relationship to the product-moment $\underline{r}$. The Pearson coefficient is a familiar and widely understood statistic, and most psychologists have at least a few "pegs" by which to gauge the magnitude of a given value. They know, for example, that $\underline{r} = .90$ is an acceptable test-retest reliability coefficient or that $\underline{r} = .40$ is a good predictive validity for on-the-job performance.

The second reason has also been alluded to, namely, the relative ease of extracting a point biserial from a published paper. No measure of effect size can be extracted from every scientific paper or, usually, even most papers; but means and standard deviations are the most commonly reported of all statistics and a measure like the point biserial that requires no additional information is as likely to be calculable from available information as any measure of effect size. Sometimes, moreover, the point biserial can be extracted even when means and standard deviations are not reported. It can, for example, be extracted from a t-statistic or an ANOVA table with one degree of freedom for the workload treatment factor. It can even be calculated from proportions of "successful" subjects under two conditions.

There are, of course, some drawbacks also. The point biserial applies to dichotomies. If an investigator imposes three workload conditions (light, moderate, and heavy), all three cannot be evaluated with a single point biserial. Instead, one needs three point biserials, one for each of the three possible pairwise comparisons. These three comparisons, moreover, are not themselves fully comparable. The light/heavy comparison should yield a substantially higher value than the two comparisons between adjacent levels.

Conventionally, it is not recommended that one use a point biserial excluding a middle category. The reason is that the resulting r_{pb} seriously overestimates the population r. In the context of a meta-analysis, however, r_{pb} is not used to estimate a population r but, rather, to gauge the extent of differentiation between two treatment conditions. It is, of course, necessary to bear in mind "how far apart" two treatment conditions are when quoting an r_{pb}.

This question, however, of how far apart two conditions are has to be faced in any event. Even if the dichotomous variable were fully quantitative, and we were using a conventional product-moment correlation, it would still be necessary to consider how far apart the values were over which the workload factor or variable ranged. In short, the necessity of considering the distance between two levels of a workload factor does not oblige us to do anything we would not have to do anyway, albeit in a subtler form and one that might quite probably be missed altogether.

THE CASALI-WIERWILLE EXPERIMENTS

From 1983-85, Casali and Wierwille published four studies on indicants of workload which together constitute a landmark in the field. All four studies used similar methodologies and multiple operator dependent indicants of workload, both subjective and objective. Since these various indicants were all studied under the same imposed conditions of operator-independent workload, the resulting point biserials are comparable in a way that r_{pb} from different studies with differentially specified workload conditions cannot be. Since the indicants were also quite diverse, the Casali-Wierwille studies provide an excellent framework within which to locate the visual indicants which are our primary concern.

Table 4 presents the findings from the Casali-Wierwille studies, where the indicants have been classified into four groups: judgment, vision, other physiological, and task (primary or secondary). The judgment indicants were subjective, a modified Cooper-Harper or Multi-descriptor scale; the visual indicants were eyeblinks and fixation fraction; other physiological measures were heart rate; and the task indicants were control movements, error rates, and reaction times. Table 4, it should be pointed out, includes only those indicants that showed a significant overall ANOVA. Table 4, therefore, presents the best indicants in these four categories. What we see is not a representative figure but the most that can be expected of the indicants that Casali and Wierwille studied in these four categories. Table 4 gives the maximum biserial observed in a category, the average r_{pb} in that category, and (on the left) the number of r_{pb} on which that average is based.

TABLE 4. Effect Size by Category of Indicant

Category	N	Point Biserial r Maximum	Point Biserial r Average
Judgment	18	.816	.499
Vision	9	.696	.298
Other Psychological*	3	.215	.145
Task	27	.854	.552

* Heart rate

From these results it appears that subjective and task indicants are better than visual indicants, which in turn are better than heart rate (other physiological). The relatively high values for subjective indicants was to have been expected. As noted earlier, subjectives are usually better behaved than other indicants. However, as was also noted earlier, the whole thrust of this report and of most of the literature on workload indicants is to get away from subjective indicants.

The $\underline{r}_{pb}$ for task indicants are unexpectedly high. Judging from the O'Donnell and Eggemeier account of the workload performance relationship, one would have expected lower values. Even, however, if task indicants are as strongly related to operator-independent workload conditions as they appear to be in Table 4, they are still seriously flawed on other counts. Biological assays for workload are intended to provide a means of grading or rating a large variety of real-world tasks. If, however, task indicants were to be used to register operator responses, then different tasks would frequently or usually involve different indicants. This fact would entail two crippling difficulties, one theoretical and one pragmatic. The theoretical difficulty is that different task indicants would involve different units and, therefore, be noncommensurate. The pragmatic difficulty is that multiple indicants would make the work of standardization many times more difficult than it might otherwise be.

Despite their high values, neither subjective nor task indicants meet the requirements we have set ourselves. That leaves us with visual and other physiological indicants. Judging from the heart rate results in Table 4, other physiological indicants held little promise.

We are left with visual indicants. Accordingly, the literature on visual indicants of workload was surveyed and culled for papers which seemed appropriate for our purposes. A total of 25 papers were located and analyzed, where possible, using the point biserial metric.

SURVEY OF VISUAL INDICANTS

Candidates for a Visually Based Eye Movement Indicant of Mental Workload

Of particular interest to this report is the potential of monitoring activity of the visual system to quantify mental workload. In view of the central role of eye movements in visual, cognitive, and refined motor activities (cf., Table 13), it is not surprising that numerous studies have related various quantitative aspects of eye movements to attention, cognitive performance, mental effort, fatigue, drug state, and the integrity of the underlying neural mechanisms (Ditchburn, 1973; Hall, 1976; Kim, Zangemeister, & Stark, 1984; Krivohlavy, Kodat, & Cizek, 1969; Monty, Hall, & Rosenberger, 1975). Visual activities which have been monitored for these purposes include visual evoked brain potentials, eyeblink frequency, pupil diameter, visual nystagmus, pursuit eye movements, percent time that eyes are closed, and saccadic eye movement (e.g., velocity, amplitude, and duration).

Our plan in what follows is to describe the various visually based measures and then to conduct the quantitative meta-analysis of these methods.

Functional Field of View. One visually-based approach to the assessment of workload involves the measurement of an observer's functional field of view (Sanders, 1970). Mackworth (1963) has described the functional field of view as an area around central fixation from which information is actively processed during performance of a visual task. The functional field of view has been found to be sensitive to cognitive load in that it changes in size according to processing demands. As processing demands increase, a shrinkage of the functional field of view is typically observed. Mackworth (1963) has referred to this constriction as "tunnel vision," and has proposed that it serves to prevent an overloading of the processing system when more information is available than can be processed. Others (Bursil, 1958; Teichner, 1968) have also discussed a shrinking of attentional fields as greater processing demands are imposed. Such modulation of the functional field of view with task demands has been reported in single task paradigms such as visual search (Edwards & Goolkasian, 1974), and matching (Williams & Lefton, 1981), as well as in dual-task paradigms where attention is divided between a foveal and peripheral task (Acosta & Dickman, 1984; Holmes, Cohen, Haith, & Morreson, 1977; Williams, 1982, 1985).

Pupil Size. Pupil dilation is induced by sympathetic nervous system activation and, therefore, it has been used as a measure of workload because it may reflect a general state of arousal in the organism (Bradshaw, 1968; Poock, 1972). This is also a disadvantage of the technique in that, coupled with its major function of regulating the amount of light that enters the eye, the sensitivity of pupil diameter to emotional stress may limit its usefulness in operational situations. However, under laboratory conditions, pupil dilation has been very tightly tied to task stimulus conditions (Beatty 1976, 1979, 1982). For example, Kahneman and Beatty (1966) showed that, in a task requiring subjects to memorize and then repeat digit strings, pupil dilation increased with presentation of the digits, and then decreased as the letters were repeated. In addition, the magnitude of the peak was related to the size of the digit string to be memorized. Systematic variations in pupil size have also been associated with performance changes in a secondary task (Kahneman, Beatty, & Pollack, 1967), rehearsal strategies that improve memory (Kahneman, Onuska, & Wolman (1968), language processing (Ahern & Beatty, 1981; Beatty & Wagoner, 1978; Wright & Kahneman, 1971), mathematical reasoning (Ahern & Beatty, 1979, 1981; Bradshaw, 1968; Hess & Polt, 1964; Payne, Parry, & Harasymiw, 1968), sensory perception (Hakerem & Sutton, 1966) and discrimination (Kahneman & Beatty, 1967). Beatty (1982) presents evidence that pupillometry may be used to index between-task variations in workload. Pupil dilation varied as a function of loaded flight task (Anderson & Chiou, 1977).

Eye Scanning/Dwell Times. Harris, Tole, Ephrath, & Stephens, (1982) found that increases in dwell times were associated with increased workload during a piloting task under simulated instruments conditions. Other investigators have performed eye scan analyses to measure visual workload (Krebs & Wingert, 1977; Simmons & Kimball, 1977, 1979; Simmons, Kimball, & Diaz, 1976; Simmons Lees, & Kimball, 1978a,b; Simmons, Sanders, & Kimball, 1979; Waller, 1976), evaluate the usefulness of instruments during landing (Dick & Bailey, 1976; Dick & Bailey, 1976; Spady, 1978; Waller, Harris, & Salmirs, 1979; Weir & Klein, 1970), and to evaluate the workload of displays and instrument configurations (Barnes, 1977; Clement, 1976; Harris, Tole, Ephrath, & Stephens, 1982).

Eye Blink Analysis. Stern and Skelly (1984) assessed eyeblink, blink rate, and blink duration in two simulated bomber missions. Differing task demands were reflected by blink rate and, in addition, blink duration appeared to be affected by time on task. In other research, Bauer, Goldstein, & Stern (1987) found that, in an encoding and retention task, blink rate was depressed following the presentation of task cues, memory set, and test stimulus.

Eye Movement Extent. Malmstrom and colleagues (Malmstrom & Reed, 1983; Malmstrom, Reed, & Randle, 1983) reported a restriction of pursuit eye movement range during a concurrent auditory task. Ceder (1977) found that frequency of large amplitude of eye movements was reduced under driving conditions presumed to induce high levels of workload. In addition, restriction in saccade length was measured in cats under conditions of high arousal induced by amphetamines (Crommelinck & Roucoux, 1976). Hall (1976) who appears to be the first (cf., also Hall & Cusack, 1972) to have identified this phenomenon, provides the clearest explanation of how this relation may reflect a gating process in the oculomotor system.

Results of Quantitative Meta-Analysis

Table 5 presents the results, using the same format as was used in Table 4. The indicants are organized into seven categories: narrowed visual field, pupillary dilation, eye movement extent, eyeblink frequency, fixation fraction, nystagmus, and event related potentials. At the bottom of the table the sample size, maximum and average r_{pb} are given for all seven categories combined.

The maximum r_{pb} in Table 5 (.801) is higher than for visual indicants in Table 4 (.696). This, however, is entirely to be expected. The larger a sample is the larger the largest value in the sample is expected to be. If the larger sample includes the smaller, the maximum r_{pb} must be at least as large in the larger as in the smaller sample. The average r_{pb} in Table 5 is somewhat but not a great deal larger than the average r_{pb} for visual indicants in Table 4. Altogether, therefore, the results in Table 5 agree substantially with those for visual indicants in Table 4. Hence, the first result of the survey is to confirm the general position of visual relative to other indicants of operator independent workload.

The second major result in Table 5 is the prominent position of pupillary dilation and eye-movement extent among visual indicants. This result is especially heartening inasmuch as eye-movement extent is much the same as saccade length. This implies, but does not prove, that in studying saccade length as an indicant of workload we may be "barking up the right tree."

TABLE 5. Effect Size by Subcategory of Visual Indicant

Visual Indicant	N	Point Biserial r Maximum	Average
Narrowed visual field	24	.569	.275
Pupillary dilation	10	.801	.535
Eye-movement extent	12	.788	.486
Eyeblink frequency	8	.640	.411
Fixation fraction	3	.696	.504
Nystagmus	4	.445	.300
Event-related potentials	12	.578	.310
All indicants	73	.801	.377

Table 6 presents effect size for pupillary dilation and eye-movement extent broken down by "how far apart" the two operator-independent treatment conditions are. The left column contains the average value of r_{pb} for the lightest contrasted with the heaviest workload used in the study (for example, light/heavy in a 3-condition (light-moderate-heavy design). The right column contains the average value of r_{pb} for adjacent levels (light/moderate or moderate/heavy in a 3-condition design). It is not possible, of course, to say in other terms how far apart the lightest and heaviest conditions really are, since there is no common metric; but clearly the high values in the left column ought not to be overemphasized. To be able to discriminate between top and bottom does not seem a sufficient credential for successful biological assay. The right column is more to the point and, also, more problematic. Neither pupillary dilation nor eye-movement extent, and they appear to be the best visual indicants available (with the possible exception of saccade length), do an especially good job of discriminating between adjacent levels of operator-independent workload. The between-group sums of squares in these adjacent-level r_{pb} account for less than 20 percent of the whole. Hence, while the outlook for visual indicants of workload seems to be hopeful, much remains to be done by way of locating better indicants and perfecting them. Judging from this survey, however, saccade length could well be such a "better indicant."

TABLE 6. Effect Size for Maximally Distant and Adjacent Workload Levels: Pupillary Dilation and Eye-Movement Extent

Measure	Point-biserial r: Maximally Distant	Point-biserial r: Adjacent
Pupillary dilation	.801	.354
Eye-movement extent	.679	.434

LITERATURE CATALOGUE

The literature was culled for work relating to workload. This resulted in the preparation of a bibliography containing over 600 items (Appendix A). In addition, to discern general trends in the literature, empirical-experimental work since 1970 was catalogued by workload metric category: that is, by whether the workload metric was physiological, subjective, performance-based, or vision/eye movement. Three hundred and twenty-eight papers were so characterized and and are presented in Tables 10-13. In each table, the publication year, workload indice, and setting for data collection are given, along with the author(s) and publication. Entries are listed alphabetically by author. Literature chosen for the tables include studies conducted to validate workload metrics and those in which the mental load imposed by task, system, or subject variables is assessed. Unpublished papers and manuscripts and foreign literature were not included.

Table 7 summarizes the primary publication areas. It can be seen that 85 percent of this sample of literature is contained in eight publication types. The primary publication avenues are technical reports and Proceedings of the Human Factors Society meetings. Less than 34 percent of this literature is published in referenced journals.

TABLE 7. Major Publication Areas for Workload Literature (Sample Size = 328)

Publication	Percentage
Technical Reports, Contractor Reports	25
Proc. Human Factors Society	23
Proc. Conf. Manual Control/NASA Univ. Conf. Manual	10
Human Factors	10
AGARD Conference Proceedings	7
Aerospace Med./Aviat. Space, and Environ. Med.	5
Ergonomics	5
Other	15

Table 8 summarizes the proportion of the literature that includes each of the workload categories for two time periods: 1970-1979 and 1980--1988. The table shows that the proportion of the literature, including physiological, performance, and vision/eye movement-based metrics, appears more or less stable from the 1970s to 1980s. Notable, though, is the increase in the proportion of studies including subjective measures of workload.

TABLE 8. Percentage of Workload Sample Including Each Workload Class

Workload Class	Year 1970-79	1980-88
Physiological	27%	27%
Subjective	33%	80%
Performance	66%	68%
Eye Movement	17%	14%
Sample Sizes	215	113

Table 9 summarizes the proportion of experimental effort including physiological and vision/eye movement based measures. Among the physiological indices, evoked cortical potentials are notable for the increased focus on them in the 1980s, compared to the 1970s. This is perhaps because of their potential role in the testing of limited capacity processing models of workload and information processing. Studies which include electrocardiogram and body fluid analysis were not represented in the 1980s sample suggesting the declining interest in these measures as workload metrics. Measures of heart rate were well represented in the 1970s and 1980s sample.

Among the eye movement based measures, it is notable that blink rate was included in half of the 16 studies in the 1980 decade, but in only 5% of the 1970s decade sample. Literature including eye movement/scan/extent measures appear to have declined from the 1970s to 1980s. The experimental results in this report suggest, though, that eye movement extent is potentially valuable in the assessment of mental workload. In addition, preliminary evidence is that blink rate and eye movement extent are independent, suggesting that future research should include both in the assessment of workload. Finally, Tables 10-13 summarize the majority of the experimental work done since 1970, organized by type of workload metric, author(s), date, and publication.

TABLE 9. Preparation of Workload Sample Including Major Physiological and Vision/Eye Movement Measures

	Year 1970-79	Year 1980-88
Physiological		
Heart Rate	65%	53%
Electrocardiogram	33%	0
Blood Pressure	5%	3%
Electromyogram	12%	3%
Respiration Rate	26%	17%
Skin Resistance	16%	7%
Body Fluid Analysis	22%	0
Evoked Cortical Potentials	10%	53%
Vision/Eye Movements		
Blink Rate	5%	50%
Pupil Dilation	25%	31%
Eye Movement/Scan/Extent	53%	19%
Field of View	3%	19%
Sample Sizes	40	16

TABLE 10. Physiological Indicants

Year	Measure	Setting	Authors	Publication
1987	HR	Lab	Aasman et al.	Human Factors
1988	BP,ECP, EMG,HR	Lab	Albery et al.	Proc. Human Factors Society
1984	HR	Lab	Antin & Wierwille	Proc. Human Factors Society
1987	ECP	HR	Bauer et al.	Human Factors
1979	SR	Lab	Benel et al.	Proc. Human Factors Society
1985	ECP	Lab	Biferno	Report
1974	BP,HR	Flight	Blyx et al.	Aerospace Medicine
1974	EOG,HR,	Lab	Boyce	Ergonomics
1974	BF	Flight	Brictson et al.	AGARD Conference Proceedings
1979	HR,SR	Sim	Buckley & O'Connor	AGARD Conference Proceedings
1975	HR	Field	Caplan & Jones	J. Applied Psychology
1983	HR,RR	Sim	Casali & Wierwille	Human Factors
1984	HR,RR	Sim	Casali & Wierwille	Ergonomics
1977	BF,HR	Flight	Clark & Armstrong	Report
1971	BP,HR RR	Lab	Ettema & Zielhuis	Ergonomics
1976	BF,HR	Lab	Frankenhaeuser & Johansson	J. Human Stress
1977	EEG	Lab	Gale et al.	Ergonomics
1975	BP,RR,SR	Lab	Gaume & White	Report
1983	ECP	Lab	Gill & Wickens	Proc. Conf. Manual Control
1984	ECP	Lab	Gopher	Proc. Conf. Manual Control
1982	HR,RR	Flight	Graaff	Proc. Flight Test Workshop
1971	BF	Flight	Hale et al.	Aerospace Medicine
1984	HR	Flight	Hart et al.	Proc. Human Factors Society
1975	HR	Field	Helander	Report
1972	HR	Lab	Hicks & Soliday	Proc. Human Factors Society
1979	HR	Sim	Hicks & Wierwille	Human Factors
1984	ECP	Lab	Horst et al.	Proc. Human Factors Society
1978	EEG,ECG	Flight	Howitt et al.	Aviat. Space & Env. Med.
1977	HR	Lab	Inomata	J. Human Ergology
1980 1	ECP	Lab	Isreal et al.	Psychophysiology
1980 1	ECP	Lab	Isreal et al.	Human Factors
1979	ECP	Lab	Isreal et al.	Proc. Human Factors Society
1972	HR	Lab	Jenney et al.	Report
1970	ECG,EKG, HR,RR,SR	Lab	Jex & Allen	Proc. NASA Conf. Manual Ctrl
1977	BF	Flight	Krahenbuhl et al.	Report
1985	ECP	Lab	Kramer & Wickens	Proc. Human Factors Society
1987	ECP	Sim	Kramer et al.	Human Factors
1983	ECP	Lab	Kramer et al.	Human Factors
1988	ECP	Lab	Lalehzarian	Proc. Human Factors Society
1988	HR	Flight	Linde & Shively	Proc. Human Factors Society

1981	ECP,HR,SR	Sim	Lindholm et al.	Report
1984	ECP,HR,SR	Sim	Lindholm et al.	Report
1976	EEG,HR,SR	Lab	Lorens & Darrow	Electroenceph. & Clin.
1974	BF	Flight	McHugh et al.	AGARD Conference Proceedings
1979	HR,SR	Sim	McKenzie et al.	AGARD Conference Proceedings
1979	BF	Field	Melton	AGARD Conference Proceedings
1976	BF,HR	Field	Melton et al.	Aviat., Space & Env. Med.
1977	BF,ECG	Field	Melton et al.	Report
1970	BF,HR	Flight	Miller & Rubin	Report
1971	ECG,HR,RR	Lab	Mobbs et al.	Report
1973	ECG,HR,RR	Lab	Mulder & van der Meulen	Ergonomics
1988	ECP	Lab	Nataupsky et al.	Proc. Human Factors Society
1973	ECG,MT	Flight	Nicholson et al.	Aerospace Medicine
1979	ECG,EMG HR	Sim	North & Graffunder	Proc. Human Factors Society
1973	HR,RR	Sim	Opmeer & Krol	Aerospace Medicine
1985	ECP	Lab	Parasuraman	Proc. Human Factors Society
1977a	RR	Flight	Pettyjohn et al.	AGARD Conference Proceedings
1977b	RR	Flight	Pettyjohn et al.	Report
1982	RR	Sim	Rahimi & Wierwille	IEEE Conf. Cyber. & Society
1976	ECG,EMG, HR,RR	Flight, Sim	Rault	Book
1984	HR	Lab	Robertson	Proc. Human Factors Society
1985	HR	Lab	Robertson & Meshkati	Proc. Human Factors Society
1978	HR	Flight	Roscoe	Aviat., Space & Env. Med.
1976	HR	Flight	Roscoe	Aviat., Space & Env. Med.
1975	HR	Flight	Roscoe	Aviat., Space & Env. Med.
1973	HR	Sim	Roscoe & Goodman	Report
1973	HR,RR	Field, Lab	Sayers	Ergonomics
1978	HR	Lab,Sim	Sekiguchi et al.	Aviat., Space & Env. Med.
1987	HR	Flight	Shively et al	Proc. Symp. Aviat. Psychology
1975	ECG,HR	Lab	Simonov et al.	Aviat., Space & Env. Med.
1979	HR	Sim	Smith	Report
1977	ECG,ECP, HR	Sim	Soede	Proc. NASA Conf. Manual Ctrl.
1977	BF,ECG, ECP	Lab	Soutendam	AGARD Conference Proceedings
1971	ECG,EEG EMG,HR,RR SR	Lab	Spyker et al.	Report
1973	ECG,HR	Flight, Sim	Stackhouse	Report
1976	ECG,EMG RR	Sim	Stackhouse	Report
1976	BF	Flight	Storm et al.	Report
1977	HR	Lab	Strasser	AGARD Conference Proceedings
1973	ECP,HR	Lab	Strasser et al.	Aerospace Medicine
1970	BF	Lab	Street at al.	Human Factors
1976	ECG,EMG RR	Sim	Sun et al.	Proc. Aviat. Electronics Symp.

1987	HR	Lab	Vicente et al.	Human Factors
1975	ECG,HR, RR,SR	Lab	White & Gaume	Report
1977	ECP	Lab	Wickens et al.	Proc. Human Factors Society
1976	ECP	Lab	Wickens et al.	Proc. NASA Conf. Manual Ctrl.
1983	HR,RR	Sim	Wierwille & Connor	Human Factors
1978	ECG,EMG HR,RR	Sim	Wolfe	Report
1979	ECG,EMG HR,SR	Field	Zeier	Ergonomics

BF = Body Fluid Analysis, BP = Blood Pressure, ECP = Evoked Cortical Potentials, ECG = Electrocardiogram, EEG = Electroencephalogram, EMG = Electromyogram, HR = Heart Rate, MT = Muscle Tension, RR = Respiration Rate, SR = Skin Resistance

TABLE 11. Subjective Measures

Year			Authors	Publication
1983	R	Lab	Acton et al.	Proc. Human Factors Society
1984	R	Lab	Albery et al.	Proc. Human Factors Society
1970	I/Q	Sim	Anderson & Toivanen	Report
1984	I/Q	Lab	Antin & Wierwille	Proc. Human Factors Society
1979	R	Sim	Bateman	Proc. Human Factors Society
1984	I/Q,R	Ambig.	Bateman et al.	Proc. Human Factors Society
1988	R	Sim	Battiste & Bortolussi	Proc. Human Factors Society
1985	R	Lab	Battiste & Hart	Proc. Symp. Aviat. Psychology
1984	R	Sim	Berg & Sheridan	Proc. Conf. Manual Control
1985	R	Sim	Berg & Sheridan	Report
1986	R	Sim	Berg & Sheridan	Proc. Conf. Manual Control
1988	R	Lab	Biers et al.	Proc. Human Factors Society
1985	R	Lab	Biferno	Report
1985	R	Lab	Bloem & Damos	Psychological Reports
1985	R	Sim	Bortolussi et al.	Proc. Symp. Aviat. Psychology
1987	R	Sim	Bortolussi et al.	Proc. Symp. Aviat. Psychology
1983	R	Lab	Boyd	Proc. Human Factors Society
1976	I/Q	Sim	Bromberger	Report
1988	R	Field	Byers et al.	Proc. Human Factors Society
1983	R	Sim	Casali & Wierwille	Human Factors
1984	R	Sim	Casali & Wierwille	Ergonomics
1975	R	Field	Caplan & Jones	Journal of Applied Psychology
1982	R	Sim	Childress et al.	Proc. Human Factors Society
1977	I/Q	Flight	Clark & Armstrong	Report
1976	R	Sim	Clement	Proc. NASA Conf. Manual Ctrl.
1983	I/Q	Sim	Connor & Wierwille	Report
1974	I/Q	Sim	Corkindale	AGARD Conference Proceedings
1984	R	Field	Courtright & Kuperman	HFSC
1975	R	Sim	Crabtree	Report
1984	R	Lab	Crabtree et al.	Proc. Human Factors Society
1984a	R	Lab	Damos	Proc. Conf. Manual Control
1984b	R	Lab	Damos	Eng. Tech. Conf. Proc.
1984c	?	?	Damos	Report
1984d	R	Lab	Damos	Perceptual and Motor Skills
1985	R	Lab	Damos	Human Factors
1988	R	Lab	Deaton & Parasuraman	Proc. HUman Factors Society
1981	R	Lab	Derrick	Proc. Human Factors Society
1983	R	Lab	Derrick	Proc. Human Factors Society
1976	I/Q	Sim	Dick & Bailey	Report
1976	R	Sim	Dick et al.	Report
1983	R	Lab	Eckel & Crabtree	Proc. Symp. Aviat. Psychology
1984	R	Lab	Eggemeier & Quinn	Proc. Human Factors Society
1984	R	Lab	Eggemeier & Stadler	Proc. Human Factors Society
1983	R	Lab	Eggemeier et al.	Proc. Human Factors Society

1982	R	Lab	Eggemeier et al.	Proc. Human Factors Society
1984	R	Lab	Eggemeier et al.	Proc. Human Factors Society
1977	R	Lab	Fergenson & Gold	Proc. Human Factors Society
1977	I/Q	Flight	Geiselhart et al.	Report
1976	I/Q	Flight	Geiselhart et al.	Report
1977a	R	Lab	Goerres	AGARD Conference Proceedings
1977b	R	Lab	Goerres	Aviat., Space, & Env. Med.
1984	R	Lab	Gopher	Proc. Conf. Manual Control
1984	R	Lab	Gopher & Braune	Human Factors
1985a	R	Lab	Gopher et al.	Report
1985b	?	Lab	Gopher et al.	Proc. Human Factors Society
1982	R	Flight	Graaff, R. C. van de	Proc. Flight Test Workshop
1978	R	Sim	Gunning	Proc. Human Factors Society
1978	I/Q,R	Flight	Hagen et al.	Report
1988	R	Lab	Hancock et al.	Proc. Human Factors Society
1982	R	Sim	Harris et al.	Proc. Human Factors Society
1984	I/Q	Lab	Hart & Bortolussi	Human Factors
1983	R	Sim	Hart & Chappell	Proc. Conf. Manual Control
1977	R	Sim	Hart et al.	Report
1981	R	Lab	Hart et al.	Proc. Human Factors Society
1982	R	Lab	Hart et al.	Proc. Eighth Psy. in the DoD Symp.
1984a	R	Lab	Hart et al.	Proc. Conf. Manual Control
1984b	R	Flight	Hart et al.	Proc. Human Factors Society
1984c	R	Lab	Hart et al.	Proc. Human Factors Society
1983a	R	Lab	Hauser & Hart	Proc. Human Factors Society
1983b	R	Lab	Hauser & Hart	Proc. Conf. Manual Control
1983	R	Lab	Hauser et al.	Proc. Conf. Manual Control
1986	R	Sim	Haworth et al.	Proc. American Helicopter Society
1975	R	Flight	Helm	Report
1976b	R	Flight	Helm	Report
1979	R	Sim	Hicks & Wierwille	Human Factors
1988	R	Field	Hill et al.	Proc. Human Factors Society
1978	I/Q	Flight	Howitt et al.	Aviat. Space & Env. Med.
1978a	R	Field	Hurst & Rose	Ergonomics
1987b	R	Field	Hurst & Rose	Ergonomics
1972	R	Lab	Jenney et al.	Report
1976	R	Sim	Johannsen et al.	Book
1976	R	Sim	Johnston et al.	Report
1983	R	Sim	Kantowitz et al.	Proc. Human Factors Society
1984	R	Sim	Kantowitz et al.	Proc. Conf. Manual Control
1979	R	Sim	Kopala	Proc. Human Factors Society
1972	R	Sim	Kornstadt & Pfennigstorf	AGARD Conference Proceedings
1977	R	Field	Koym	Report
1987	R	Sim	Kramer et al.	Human Factors
1976	R	Sim	Krebs & Wingert	Report
1977	R	Sim	Krebs et al.	Report
1976	R	Sim	Kreifeldt et al.	Proc. NASA Conf. Manual Ctrl.
1972	?	?	Krzanowski	Aerospace Medicine
1976	R	Field	Kuhar et al.	Report

1975	R	Flight	Lebacqz & Aiken	Report
1988	R	Flight	Linde & Shively	Proc. Human Factors Society
1979	R,I/Q	Sim	Madero et al.	Report
1977	I/Q	Flight	Markeiwicz et al.	Report
1976	R	Field	Melton et al.	Aviat. Space & Env. Med.
1977	R	Field	Melton et al.	Report
1984	R	Lab	Miller & Hart	Proc. Conf. Manual Control
1986	R	Lab	Miller et al.	Aerospace Behav. Eng. Tech.
1977	R	Lab,Sim	Milord & Perry	J. General Psychology Conf.
1974	I/Q	Sim	Murphy et al.	Proc. NASA Conf. Manual Ctrl.
1970	I/Q	Flight	Murrell et al.	AGARD Conference Proceedings
1988	R	Lab	Nataupsky	Proc. Human Factors Society
1973	I/Q	Flight	Nicholson	Aeronautical Journal
1979	R	Sim	North & Graffunder	Proc. Human Factors Society
1984	R	Lab	Notestine	Proc. Human Factors Society
1973	R	Sim	Opmeer & Krol	Aerospace Medicine
1971	R	Field	Philipp et al.	Ergonomics
1982	I/Q	Sim	Rahimi & Wierwille	IEEE Conf. Cyber. & Society
1976	R	Field, Sim	Rault	Book
1983	R	Lab/Sim	Rehmann et al.	Human Factors
1981	R	Lab	Reid et al.	Proc. Human Factors Society
1976	R	Sim	Repa & Wierwille	SAE Paper
1982	R	Lab	Repperger et al.	Report
1985	R	Lab	Revesman & Rokicki	Proc. Human Factors Society
1984	R	Lab	Robertson	Proc. Human Factors Society
1985	R	Lab	Robertson & Meshkati	Proc. Human Factors Society
1974	R	Sim	Rolfe et al.	AGARD Conference Proceedings
1982	R	Lab	Rosenberg et al.	Report
1975	R	Flight	Roscoe	Aviat., Space & Env. Med.
1976	R	Flight	Roscoe	Aviat., Space & Env. Med.
1978	R	Flight	S[illegible]lers et al.	Report
1980	R	Flight	Schiflett	Report
1985	R	Lab	Schlegel & Shingledecker	Proc. Human Factors Society
1970	R	Sim	Schultz et al.	Proc. NASA Conf. Manual Ctrl.
1972	R,I/Q	Lab	Seifert et al.	AGARD Conference Proceedings
1987	R	Flight	Shively et al.	Proc. Symp. Aviat. Psychology
1984	R	Lab	Silverstein et al.	Report
1978	R	Flight	Simmons & Kimball	Report
1977	I/Q	Lab	Soutendam	AGARD Conference Proceedings
1978	R	Sim	Spady	Report
1971	R	Lab	Spyker et al.	Report
1973	R	Flight, Sim	Stackhouse	Report
1976	R	Lab	Stamford	Ergonomics
1985	R	Lab	Staveland et al.	Proc. Conf. Manual Control
1977	R/I/Q	Flight	Steininger	AGARD Conference Proceedings
1979	R	Flight	Stone et al.	Report
1978	I/Q	Sim	Streib	Report
1976	R	Flight	Strom et al.	Report
1987	R	Lab	Vicente et al.	Human Factors

1988	R	Sim	Vidulich & Bortolussi	Proc. Human Factors Society
1985	R	Lab	Vidulich & Wickens	Proc. Human Factors Society
1983	R	Lab	Vidulich & Wickens	Report
1984	R	Lab	Vidulich & Wickens	Proc. Conf. Manual Control
1985	R	Lab	Vidulich & Wickens	Proc. Symp. Aviat. Psychology
1976	R	Sim	Waller	Report
1976	R	Lab	Wewerinkle	Proc. NASA Conf. Manual Ctrl.
1977	R	Flight	Wewerinkle	Proc. NASA Conf. Manual Ctrl.
1974	R	Sim	Wewerinkle & Smit	AGARD Conference Proceedings
1975	R	Lab	White & Gaume	Report
1983	R	Lab	Wickens & Yeh	Proc. Human Factors Society
1988	R	Sim	Wickens et al.	Proc. Human Factors Society
1983	R	Sim	Wierwille & Connor	Human Factors
1985	R	Sim	Wierwille et al.	Human Factors
1984	R	Lab	Wierwille et al.	Proc. Conf. Manual Control
1978	R	Sim	Wolfe	Report
1984	R	Lab	Yeh & Wickens	Proc. Human Factors Society
1985	R	Lab	Yeh et al.	Proc. Human Factors Society

I/Q = Interviews and Questionnaires, R = Rating Scales, Ranking

TABLE 12. Performance Measures

Year			Authors	Publication
1987	P	Lab	Aasman et al.	Human Factors
1988	P,S	Lab	Albery	Proc. Human Factors Society
1971	P,S	Lab	Alluisi & Morgan	Perceptual & Motor Skills
1970	P,S	Sim	Anderson & Toivanen	Report
1984	P,S	Lab	Antin & Wierwille	Proc. Human Factors Society
1981	P	Field	Asiala et al.	Report
1984	P,S	Ambig.	Bateman et al.	Proc. Human Factors Society
1988	P	Sim	Battiste & Bortolussi	Proc. Human Factors Society
1985	P	Lab	Battiste & Hart	Proc. Symp. Aviat. Psychology
1978	P,S	Lab	Bell	Human Factors
1984	P	Lab	Bellenkes	Report
1979	S	Lab	Benel et al.	Proc. Human Factors Society
1979	P,S	Sim	Beringer	Proc. Human Factors Society
1984	P	Sim	Berg & Sheridan	Proc. Conf. Manual Control
1985	P	Sim	Berg & Sheridan	Report
1986	P	Sim	Berg & Sheridan	Proc. Conf. Manual Control
1979	P,S	Sim	Bermudez et al.	Proc. Human Factors Society
1988	P	Lab	Biers et al.	PHFC
1985	P	Lab	Biferno	Report
1985	P,S	Lab	Bloem & Damos	Psychological Reports
1985	P,S	Sim	Bortolussi et al.	Proc. Symp. Aviat. Psychology
1987	P,S	Sim	Bortolussi et al.	AP
1983	P	Lab	Braune & Wickens	Proc. Human Factors Society
1974	P	Flight	Brictson	AGARD Conference Proceedings
1976	P	Sim	Bromberger	Report
1979	P	Sim	Buckley & O'Connor	AGARD Conference Proceedings
1979	P,S	Lab	Burke	Report
1983	P,S	Sim	Casali & Wierwille	Human Factors
1984	P,S	Sim	Casali & Wierwille	Ergonomics
1983	P	Lab	Chechile & Sadoski	Human Factors
1979	P,S	Lab	Chiles et al.	Aviat., Space & Env. Med.
1982	P	Sim	Childress et al.	Proc. Human Factors Society
1977	P	Flight	Clark & Armstrong	Report
1976	P,S	Sim	Clement	Proc. NASA Conf. Manual Ctrl.
*1983	P,?	Sim	Connor & Wierwille	Report
1985	P	Flight	Cote et al.	Aviat., Space, and Env. Medicine
1975	P	Sim	Crabtree	Report
1984	P,S	Lab	Crabtree et al.	Proc. Human Factors Society
1972	P	Sim	Cross & Cavallero	AGARD Conference Proceedings
1978	S	Lab	Damos	Human Factors
1984a	P	Lab	Damos	Proc. Conf. Manual Control
1984b	P	Lab	Damos	Eng. Tech. Conf. Proc.
1984c	P	Lab	Damos	Report

1984d	P	Lab	Damos	Perceptual and Motor Skills
1985	P?	Lab	Damos	Human Factors
1980	P	Lab	Damos & Lintern	Proc. Human Factors Society
1970	P	Sim	Daniels	AGARD Conference Proceedings
1988	P	Lab	Deaton & Parasuraman	Proc. Human Factors Society
1981	P	Lab	Derrick	Proc. Human Factors Society
1983	P,S	Lab	Derrick	Proc. Human Factors Society
1984	P,S	Lab	Derrick & McCloy	Proc. Human Factors Society
1976	P	Sim	Dick et al.	Report
1977	P	Sim	Drennen et al.	Report
1976	P,S	Sim	Dunn et al.	Proc. NASA Conf. Manual Ctrl.
1978	P	Sim	Edwards et al.	Report
1982	P	Lab	Eggemeier et al.	Proc. Human Factors Society
1984	P	Lab	Eggemeier & Stadler	Proc. Human Factors Society
1977	P	Sim	Ephrath & Curry	IEEE Trans. Sys., Man, & Cybernetics
1971	P	Lab	Ettema & Zielhuis	Ergonomics
1977	S	Flight	Geiselhart et al.	Report
1976	S	Flight	Geiselhart et al.	Report
1976	P	Lab,Sim	Gerathewohl	AGARD Conference Proceedings
1978	P,S	Lab	Gilson et al.	Proc. Human Factors Society
1985	P,S	Lab	Goettl	Proc. Human Factors Society
1978	P,S	Lab	Goldstein et al.	Human Factors
1979	P,S	Lab	Gopher & Navon	Proc. Conf. Manual Control
1977	P,S	Lab	Gopher et al.	Proc. Human Factors Society
1977	P,S	Lab	Gopher & North	Human Factors
1984	P	Lab	Gopher	Proc. Conf. Manual Control
1977	P,S	Lab	Gopher et al.	Report
1985a	P,S	Lab	Gopher et al.	Rept.
1985b	P	Lab	Gopher et al.	Proc. Human Factors Society
1982	P	Flight	Graaff, R. C. van de	Flt tst wrkshop
1977	P,S	Lab,Sim	Green & Flux	AGARD Conference Proceedings
1978	P,S	Sim	Gunning	Proc. Human Factors Society
1980	P,S	Flight	Gunning & Manning	Proc. Human Factors Society
1978	P	Flight	Hagen et al.	Report
1988	P	Lab	Hancock et al.	Proc. Human Factors Society
1975	S	Lab	Hart	Proc. Conf. Manual Control
1977	P,S	Sim	Hart et al.	Report
1976	S	Lab	Hart & Simpson	Proc. NASA Conf. Manual Ctrl.
1984a	P	Flight	Hart et al.	Proc. Human Factors Society
1986	P	Lab	Hart et al.	Proc. Conf. Manual Control
1983	P	Lab	Hauser et al.	Proc. Conf. Manual Control
1978	S	Sim	Hart et al.	Proc. Conf. Manual Control
1983a	P	Lab	Hauser & Hart	Proc. Human Factors Society
1983b	P	Lab	Hauser & Hart	Proc. Conf. Manual Control
1974	P,S	Lab	Hess & Teichgraber	IEEE Trans. Sys., Man, & Cybernetics
1979	P,S	Sim	Hicks & Wierwille	Human Factors
1988	P	Field	Hill et al.	Proc. Human Factors Society
1972	P	Lab	Holland & Tarlow	Psychological Reports
1974	P,S	Lab	Huddleston	Perceptual & Motor Skills
1971	P,S	Lab	Huddleston & Wilson	Ergonomics

1978a	P	Field	Hurst & Rose	Ergonomics
1978b	P	Field	Hurst & Rose	Ergonomics
1979	P,S	Lab	Isreal et al.	Proc. Human Factors Society
1972	P,S	Lab	Jenney et al.	Report
1972	P,S	Lab	Jex et al.	Proc. Conf. Manual Control
1976	S	Sim	Johannsen et al.	Book
1976	P	Sim	Johnston et al.	Report
1977	P,S	Lab	Kantowitz & Knight	Book
1984	P,S	Sim	Kantowitz et al.	Proc. Conf. Manual Control
1972	P,S	Lab	Klein & Cassidy	Proc. Human Factors Society
1979	P	Sim	Kopala	Proc. Human Factors Society
1972	P,S	Sim	Kornstadt & Pfennigstorf	AGARD Conference Proceedings
1987	P,S	Sim	Kramer et al.	Human Factors
1972	P,S	Sim	Krause & Roscoe	Proc. Human Factors Society
1976	P	Sim	Krebs & Wingert	Report
1977	P	Sim	Krebs et al.	1977
1976	P	Sim	Kreifeldt et al.	Proc. NASA Conf. Manual Ctrl.
1971	P,S	Flight	Krol	Ergonomics
1978	P,S	Field	Laurell & Lispar	Ergonomics
1975	P	Flight	Lebacqz & Aiken	Report
1988	P	Flight	Linde & Shively	Proc. Human Factors Society
1977	P	Flight	Lovesay	AGARD Conference Proceedings
1979	P,S	Sim	Madero et al.	Report
1975	P,S	Field	McDonald & Ellis	Proc. Human Factors Society
1979	P	Sim	McKenzie et al.	AGARD Conference Proceedings
1975	P	Field	McLean & Hoffman	Human Factors
1979	P	Field	Melton	AGARD Conference Proceedings
1977	P,S	Lab,Sim	Milord & Perry	J. General Psychology
1984	P	Lab	Miller & Hart	Proc. Conf. Manual Control
1986	P	Lab	Miller et al.	Aerospace Behav. Eng. Tech. Conf.
1971	S	Flight	Nagaraja Rao & Griffin	Report
1979	P,S	Sim	Nataupsky et al.	Proc. Human Factors Society
1977	S	Lab	North	Report
1976	P,S	Lab	North & Gopher	Human Factors
1979	P	Sim	North & Graffunder	Proc. Human Factors Society
1984	P	Lab	Notestine	Proc. Human Factors Society
1976	P,S	Sim	O'Donnell	AGARD Conference Proceedings
1976	P	Sim	Onstott	Proc. NASA Conf. Manual Ctrl.
1977	P,S	Sim	Onstott & Faulkner	Proc. NASA Conf. Manual Ctrl.
1978	P,S	Lab	Owens & Harris	Report
1979	P,S	Lab	Payne & Buck	Proc. Human Factors Society
1976	S	Lab	Phillips	Report
1975	P,S	Lab	Price	Human Factors
1982	P	Sim	Rahimi & Wierwille	IEEE Conf. Cyber. & Society
1976	P,S	Field, Sim	Rault	Book
1983	P	Lab,Sim	Rehmann et al.	Human Factors
1976	P	Sim	Repa & Wierwille	SAE Paper
1984	P	Lab	Robertson	Proc. Human Factors Society
1982	P	Lab	Rosenberg et al.	Report

1974	P	Sim	Rolfe et al.	AGARD Conference Proceedings
1978	P	Flight	Roscoe	Aviat., Space & Env. Med.
1978	P	Flight	Sanders et al.	Report
1977	S	Flight	Sanders et al.	Proc. Human Factors Society
1978	S	Lab	Savage et al.	Human Factors
1978	P,S	Flight	Schiffler et al.	Report
1976	P,S	Flight	Schiffler et al.	Report
1980	S	Flight	Schiflett	Report
1983	P	Sim	Schiflett	Report
1985	P	Lab	Schlegel & Shingledecker	Proc. Human Factors Society
1973	P,S	Lab	Schori	Ergonomics
1975	S	Lab	Schori & Jones	J. Motor Behavior
1970	P	Sim	Schultz et al.	Proc. NASA Conf. Manual Ctrl.
1972	P	Lab	Shiffrin & Gardner	J. Experimental Psychology
1987	P		Shively et al.	AP
1971	P,S	Lab,Sim	Shulman & Briggs	Report
1971	P	Lab	Shulman & Greenberg	Journal of Experimental Psychology
1976	P,S	Lab	Siegel et al.	Report
1977	P	Flight	Simmons & Kimball	AGARD Conference Proceedings
1979	S	Flight	Simmons & Kimball	Proc. HUman Factors Society
1978	P	Flight	Simmons et al.	Report
1979	P	Sim	Smith	Report
1977	P,S	Lab,Sim	Soede	Proc. NASA Conf. Manual Ctrl.
1978	P	Sim	Spady	Report
1971	P	Field	Sperandio	Ergonomics
1974	P,S	Sim	Spicuzza et al.	Report
1971	P,S	Lab	Spyker et al.	Report
1973	P,S	Flight, Sim	Stackhouse	Report
1976	P,S	Sim	Stackhouse	Report
1971	S	Lab	Stager & Muter	J. Experimental Psychology
1972	S	Lab	Stager & Zufelk	J. Experimental Psychology
1985	P	Lab	Staveland et al.	Proc. Conf. Manual Control
1979	P	Flight	Stone et al.	Report
1976	S	Flight	Storm et al.	Report
1977	P	Lab	Strasser	AGARD Conference Proceedings
1973	P	Lab	Strasser et al.	Aerospace Medicine
1978	P,S	Sim	Strieb et al.	Report
1976	P,S	Sim	Sun et al.	Proc. Aviat Electronics Symp.
1972	P,S	Lab	Trumbo & Noble	Org. Behav. & Human Perf.
1976	P	Sim	Verplank	Proc. NASA Conf. Manual Ctrl.
1977	P	Lab	Verplank	Proc. NASA Conf. Manual Ctrl.
1988	P,S	Sim	Vidulich & Bortolussi	Proc. Human Factors Society
1983	P	Lab	Vidulich & Wickens	Report
1984	P	Lab	Vidulich & Wickens	Proc. Conf. Manual Control
1985	P	Lab	Vidulich & Wickens	Proc. Symp. Aviat. Psychology
1987	P	Lab	Vicente et al.	Human Factors
1979	P	Lab	Waller et al.	Proc. Human Factors Society
1972	P,S	Lab	Watson	Report
1975	P	Sim	Waugh	Report

1976	P,S	Lab	Wewerinke	Proc. NASA Conf. Manual Ctrl.
1977	P	Flight	Wewerinke	Proc. NASA Conf. Manual Ctrl.
1974	P	Sim	Wewerinke & Smit	AGARD Conference Proceedings
1979	P,S	Lab	Whitaker	Acta Psychologica
1975	S	Lab	White	Report
1975	S	Lab	White & Gaume	Report
1974	P,S	Lab	Wickens	Report
1976	P,S	Lab	Wickens	J. Experimental Psychology
1977	P,S	Lab	Wickens & Gopher	Human Factors
1983	P	Lab	Wickens & Yeh	Proc. Human Factors Society
1988	P,S	Sim	Wickens et al.	Proc. Human Factors Society
1984	P	Lab	Wiener et al.	Human Factors
1983	P	Sim	Wierwille & Connor	Human Factors
1985	P,S	Sim	Wierwille et al.	Human Factors
1977	P	Lab	Wickens et al.	Proc. Human Factors Society
1976	S	Lab	Wickens et al.	Proc. NASA Conf. Manual Ctrl.
1977	P,S	Lab	Wickens & Kessel	Proc. NASA Conf. Manual Ctrl.
1979	P,S	Lab	Wickens & Kessel	IEEE Trans. Sys., Man, a & Cybernetics
1977	P,S	Lab	Wickens & Pierce	Report
1979	P,S	Lab	Wickens & Tsang	Report
1979	P,S	Lab	Wickens et al.	Proc. Human Factors Society
1978	P,S	Sim	Wierwille & Gutmann	Human Factors
1977	P,S	Sim	Wierwille et al.	Human Factors
1978	P,S	Sim	Wolfe	Report
1984	P	Lab	Yeh & Wickens	Proc. Human Factors Society
1985	P	Lab	Yeh et al.	Proc. Human Factors Society
1975	P,S	Lab	Zeitlin & Finkelman	Human Factors
1971	P,S	Lab	Zeitlin & Finkelman	Exp Pub. Systems

TABLE 13. Vision/Eye Movement

Year			Authors	Publication
1984	FOV	Lab	Acosta & Dickman	Proc. Human Factors Society
1979	PD	Lab	Ahern & Beatty	Science
1988	BR	Lab	Albery	Proc. Human Factors Society
1977	PD, BR	Lab	Anderson & Chiou	Report
1977	ES	Flight	Barnes	AGARD Conference Proceedings
1979	CFF	Lab	Baschera & Grandjean	Int'l Ergonomics Assoc.
1987	BR	Lab	Bauer et al.	Human Factors
1985	BR	Lab	Bauer et al.	Psychophysiology
1976	PD	Lab	Beatty	Proc. NASA Conf. Manual Ctrl.
1979	FOV	Sim	Bermudez et al.	Proc. Human Factors Society
1983	PD,EB,EF	Sim	Casali & Wierwille	Human Factors
1984	PD,EB	Sim	Casali & Wierwille	Ergonomics
1977	EME	Lab	Ceder	Human Factors
1976	ES	Sim	Clement	Proc. NASA Conf. Manual Ctrl.
1974	ES	Sim	Corkindale	AGARD Conference Proceedings
1976	ES	Sim	Dick & Bailey	Report
1976	ES	Sim	Dick et al.	Report
1980	ES	Sim	Ephrath et al.	Proc. Human Factors Society
1975	PD	Lab	Gardner et al.	Perceptual & Motor Skills
1973	EM	Lab	Gopher	Perception & Psychophysics
1982	ES	Sim	Harris et al.	Proc. Human Factors Society
1979	ES,PD	Sim	Harris & Mixon	Proc. Human Factors Society
1977	EM	Field	Hayashi & Ogawara	Jrnl. Human Ergology
1972	BR	Lab	Holland & Tarlow	Psychological Reports
1977	PD	Lab	Juris & Velden	Physiological Psychology
1984	BR	Lab	Kim et al.	Proc. Conf. Manual Control
1976	ES,PD	Sim	Krebs & Wingert	Report
1977	ES,PD	Sim	Krebs et al.	Report
1976	EM	Lab	Lorens & Darrow	Electroen. & Clin. Neuro.
1977	ES	Flight	Lovesay	AGARD Conference Proceedings
1983	EME	Lab	Malmstrom et al.	J. Applied Psychology
1970	ES	Field	Mourant & Rockwell	Human Factors
1979	EM,PD	Sim	North & Graffunder	Proc. Human Factors Society
1972	PD	?	Poock	Proc. Human Factors Society
1976	EM	Flight, Sim	Rault	Book
1979	ES	Flight	Sanders et al.	Human Factors
1977	ES	Flight	Sanders et al.	Proc. Human Factors Society
1979	ES	Flight, Sim	Simmons	Human Factors
1977	ES	Flight	Simmons & Kimball	AGARD Conference Proceedings
1979	ES	Flight	Simmons & Kimball	Proc. Human Factors Society
1978	ES	Flight	Simmons & Kimball	Report
1978	ES	Flight, Sim	Simmons et al.	AGARD Conference Proceedings
1985	BR	Lab	Simonov & Frolov	Aviat., Space, & Env. Med.

1977	ES	Sim	Spady	AGARD Conference Proceedings
1978	ES	Sim	Spady	Report
1974	EM	Sim	Spicuzza et al.	Report
1971	EM	Lab	Spyker et al.	Report
1984	BR	Sim	Stern & Skelly	Proc. Human Factors Society
1976	EM	Sim	Waller	Report
1979	EM	Lab	Waller et al.	Proc. Human Factors Society
1970	EM	Sim	Weir & Klein	Proc. NASA Conf. Manual Ctrl.
1983	PD, BR	Sim	Wierwille & Connor	Human Factors
1985	PD,BR,EF	Sim	Wierwille et al.	Human Factors
1982	FOV	Sim	Williams	Human Factors
1985	FOV	Sim	Williams	Human Factors
1978	EM, PD	Sim	Wolfe	Report

BR = Blink Rate, CFF = Critical Flicker Frequency, EM = Eye Movement Analysis, EME Eye Movement Extent, EF = Eye Fixations, ES = Eye Scan Analysis, FOV = Field of View, PD = Pupil Diameter

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EXPERIMENTAL EFFORT

In an effort to address issues concerning the reliability and validity of the SLIT technique, we proposed a series of experiments, demonstrations and proof of concept trials. We have attempted to preserve the numbering from the original proposal and from the Annual Report, although this is somewhat artificial since as the research and development unfolded, it was necessary to add experiments in some cases (e.g., 3B). In other cases where experiments were planned (e.g., blink exclusion, vertical eye movements) these were handled by software techniques and were merely demonstrated in a few subjects. These are listed below, more or less in the chronology that they were conducted.

All experiments employ the complex counting task of Jerison (1956) modified for auditory presentation (Kennedy & Bittner, 1980) and which we have used for many years (Kennedy, 1971). Among the chief attributes for the present study were that the task stabilizes reasonably well within a short practice period (i.e., factor structure of the task does not change). The apparatus lends itself to inexpensive, simple data collection with a minimal data analysis time. The task can be varied (psychophysically scaled) almost infinitely from "too simple to pay attention to for a long time without becoming bored" to an "information overload" for all subjects. The task has been employed in over two dozen studies, and over 1000 subjects have been tested in one way or another (cf., Kennedy, 1971, 1975; Kennedy & Bittner, 1980; for reviews of the task and its metric properties). We have implemented the task to be self scoring on a portable computer and will "run" on NEC PC8201A and IBM compatible systems. Demonstration copies of the program are available on request from Robert S. Kennedy, PhD, Essex Corporation, 1040 Woodcock Road, Orlando, Florida, 32803. The counting task can present auditory (experiments 1, 3, 4, and 5), visual (experiment 2) stimuli and both.

EXPERIMENT 1: THE RELATIONSHIP BETWEEN SACCADE LENGTH AND TONE COUNTING PERFORMANCE

Rationale

The purpose of this experiment was to employ a difficult level of the counting task in order to precisely relate saccade length to performance measures. However, as we began the experiment with the first ten subjects, we found that 1) subjects were not able to perform the task, and 2) there was virtually no correlation between saccade length and performance. When these subjects were brought back for a second session of testing, it was found that tone counting performance improved for many of them. Thus, the importance of practice seemed evident and we opted to perform experiment 3 (listed below as 3A) as the initial research. The outcome of experiment 3 persuaded us that our originally proposed experiment 1 was illadvised and we therefore conducted a more promising alternative (experiment 7).

EXPERIMENT 3A: THE EFFECTS OF PRACTICE ON SACCADE LENGTH

Rationale

Practice of a difficult task results in more efficient performance and, possibly, the reduction of mental workload associated with that task. Our previous demonstration (Phase I, second experiment) that increased task complexity results in decreased saccade length was obtained with low levels of pretest practice. In the present experiment, we examined the effects of practice on saccade length. Our hypothesis was that saccade length would increase with increasing practice, reflecting the decrease in task load that derives from increasing automaticity. Such a result would provide evidence that SLIT is sensitive to an important factor (i.e., practice) in human performance.

Method

Ten volunteer subjects were employed in 10 eye movement recording sessions occurring over a period of 10 successive days. Each subject was paid $100.00 at the completion of the experiment.

Apparatus

An infrared eyetracking instrument was used to record eye movements from the left eye. These signals were applied to the modulation input of a voltage-controlled frequency generator (Wavetek, Model 148), the output of which was fed into a signal processor (Nicolet, Model 1072) which was programmed to accumulate a time-interval histogram. In this fashion, eye movement extent was coded in terms of frequency modulation.

The auditory version of the tone counting task was administered with a microprocessor (NEC, Model 8201A) which was programmed to present a random series of 36 low pitch tones, 28 medium pitch tones and 24 high pitch tones. Tone durations were .5 seconds and the same temporal distribution was repeated every 60 seconds, but the subjects did not recognize that a pattern was present. The task required that subjects hit one of three keys after each fourth low, medium, and high pitch tones. Three separate keys were used to indicate the three different tone counts. Scoring was always reset in the event of a miss or an incorrect response.

Procedure

Subjects participated in 10 sessions. In the first session, each subject performed the auditory tone counting task once prior to recording eye movements. The following control conditions were then performed for five minutes each while eye movements were recorded: (1) a fixation condition in which subjects fixated a small cross (subtending 10 min of visual angle), (2) an alternating fixation condition which required 20 degree saccades at an aperiodic rate (.2 Hz), and (3) a free-viewing condition in which subjects were permitted to freely move their eyes. Following the control conditions, eye movements were recorded while subjects performed the tone counting task for five minutes. The procedure was repeated in the subsequent nine sessions except that subjects were not given the pretest practice.

Results

Data reduction involved normalizing the range of saccades for fixation, free viewing and task related saccades by dividing these measures by the range for alternate fixation. These three measures and the performance scores (mean percent correct) for each session were submitted to an analysis of variance. For eye movement data, a condition by sessions design was employed. For the tone counting performance measure, a simple repeated measured design was employed.

Mean normalized saccade lengths across testing sessions are depicted in Figure 1 for each condition. The mean ranges for the fixation condition are consistently lowest across sessions, while those for free viewing are highest. The ranges obtained in the task condition fell between those obtained for the free viewing and fixation conditions. The analysis of variance revealed that none of the saccade length measures changed systematically with practice on the tone counting task. These conclusions are supported by the results of the analysis of variance which revealed a significant main effect for conditions ($F=10.1$; df = 18; $p < .01$ but no other significant main effects. Newman Keuls tests revealed significant differences between the fixation and free viewing conditions ($p < .001$), task and free viewing conditions ($p < .05$), but not between fixation and task conditions.

In Figure 2, mean saccadic ranges obtained during the task condition have been replotted along with mean tone counting performance as a function of practice sessions. It is apparent in the figure that performance increased considerably with practice. This is supported by the results of the analysis of variance which revealed a significant main effect for sessions ($F = 9.13$; df = 9, 18; $p < .01$).

Finally, an intercorrelation matrix between performance and saccade length, collapsed across trials, did not reveal any significant correlations.

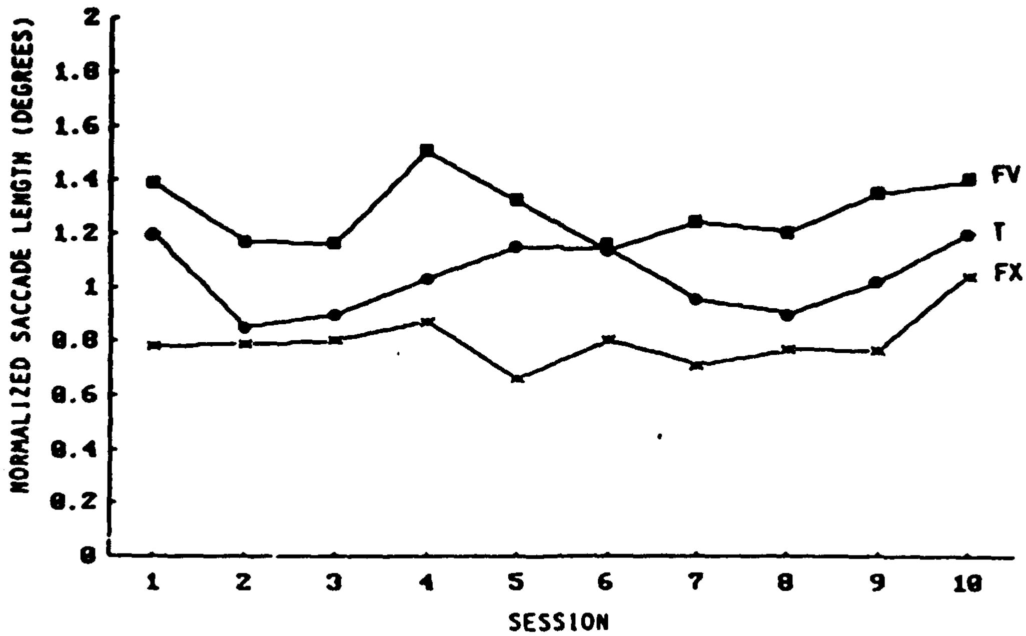

Fig. 1. Mean normalized saccade ranges for the free-viewing (FV), fixation (FX), and task (T) conditions across ten testing sessions.

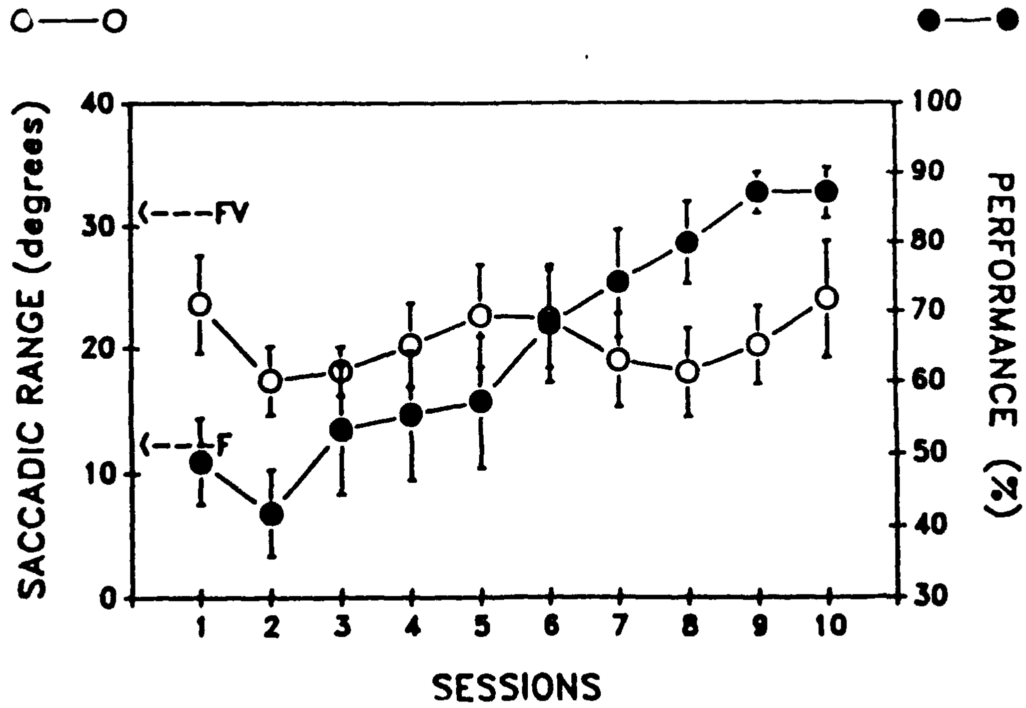

Fig. 2. Saccadic range in degrees obtained under task conditions and tone counting performance (percent correct) across testing sessions.

Discussion

The results show: (1) that the average saccade length obtained while subjects perform a difficult tone counting task is restricted compared to free-viewing conditions, and (2) that percent correct performance on the tone counting task continued to improve across ten testing sessions while saccade length was not modified as a function of practice. The first finding reinforces the contention that saccade length may be used to measure mental workload. The second finding runs contrary to the original expectation that the task would become automated with practice and that saccade length would increase. It may be hypothesized that, although subjects were getting better at the tone counting task, it remained a "high" workload condition which was reflected in saccade length which remained constant across sessions. If this hypothesis were true, then it could be expected that if these subjects were administered low and medium difficulty levels of the tone counting task, saccade length should reflect the decrease in workload but performance should remain high. This expectation was tested in an additional unplanned experiment (experiment 3B).

EXPERIMENT 3B: THE EFFECTS OF EXTENDED PRACTICE AT HIGH WORKLOAD ON SACCADE LENGTH OBTAINED UNDER LOW AND MEDIUM WORKLOADS

Rationale

Following the rationale outlined above, the subjects from Experiment 3A who had the best performance on the tone counting task were employed to replicate experiment 2 from Phase I.

Method

The same basic control conditions which were employed in experiment 3A were employed. Then then were required to perform a one tone counting task (depressing a key after every fourth low tone), a two tone counting task (depressing a key after every fourth low tone and another key after every fourth medium tone), and then a three tone counting task (depressing separate keys after every fourth low, medium, and high pitch tones). Each of the tone counting tasks were performed for five minutes under free viewing conditions while eye movements were recorded.

Results

The data were reduced and analyzed as in experiment 3A. The mean performance scores (percent correct) and the individual differences in saccade lengths were normalized and are presented in Figure 3 for each tone counting condition. As is apparent in the figure, tone counting PERFORMANCE did not vary significantly with task load, as expected. In contrast, saccade length (SLIT) decreased with increased task difficulty, also as expected. Finally, the correlation between saccade length and tone counting performance scores was not statistically significant.

Discussion

Saccade length measured in subjects who performed tasks of low, medium, and high difficulty reflected changes in mental workload after they had extensive practice on the high difficulty level of the task. This finding supports the hypothesis that workload remained constant across testing sessions in experiment 3A. The combined results of experiments 3A and 3B suggest two important findings. First, the saccade length measure is not affected by extended practice under difficult task conditions. Thus, under extended practice on a task that induces high workload, saccade length reflected workload while performance did not. This finding is important given the use of performance indices to measure workload. Moreover, it is a partial answer to the question posed for experiment 1; namely, the relationship between SLIT and performance. Second, these results suggest that saccade length remains a valid measure of the mental effort required under low and medium task demand levels even after extended performance at high task difficulty level. This finding is important given the increasing concern with temporal factors involved in workload (e.g., Matthews, 1986) and the possible effects of practice on workload indices reported in other research (May, Kennedy, Williams, Dunlap, & Brannan, 1985; Wilson, McCloskey, & Davis, 1986).

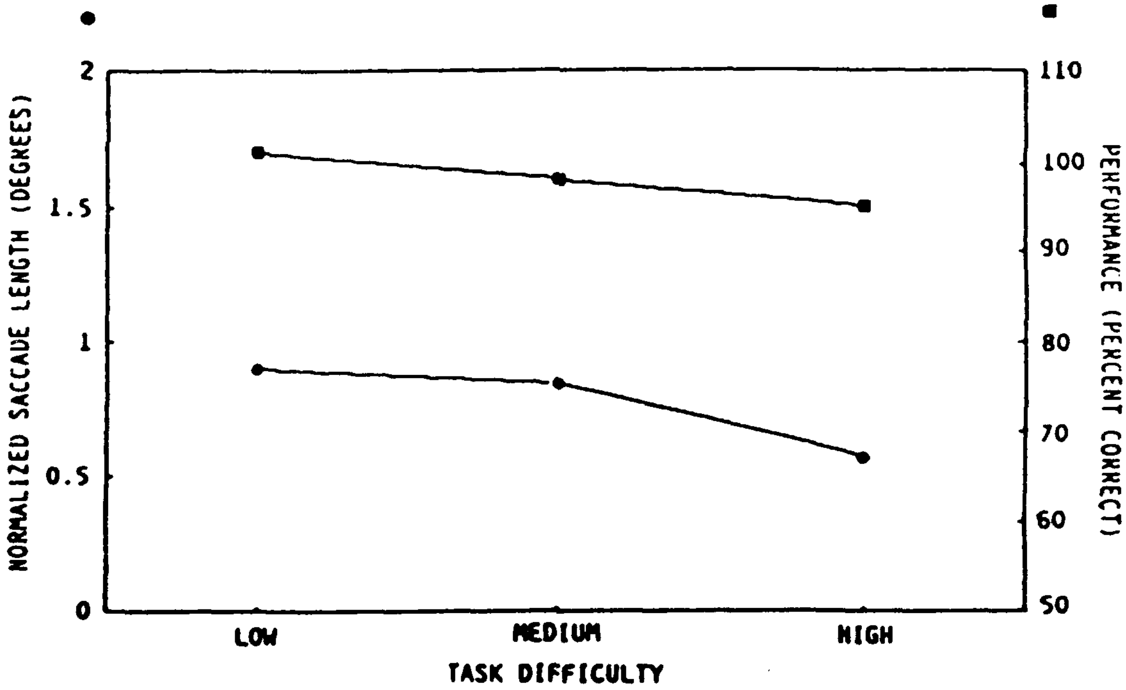

Fig. 3. Mean normalized saccade length and tone counting performance (percent correct) under low, medium, and high task difficulty levels

EXPERIMENT 2: THE EFFECTS OF VISUAL TASKLOAD ON THE EXTENT OF SACCADIC EYE MOVEMENT.

Rationale

Previously (Phase I experiments and Experiments 3A & 3B) we demonstrated that the extent of visual saccades decreased as task complexity increased using a three channel auditory tone counting task. In this experiment, we attempted to replicate these findings while using an analogous visual task which did not require precise visual fixation or tracking but did require visual monitoring and the same type of cognitive effort (i.e., counting). Thus, this experiment addresses the issue of generalization and the practical issue of whether the SLIT technique can be employed while operators perform visual work. Obviously if visual stimuli interfere with SLIT measures (or were necessary for triggering it) usefulness would be limited.

Method

Ten subjects who were paid $10 for their participation were instructed to perform low, medium, and high difficulty levels of a visual counting task while eye movements were recorded using the same methodology reported previously in experiment 3A. In addition, the same microcomputer was used to administer the task, but the microprocessor was reprogrammed to present a series of three dark rectangles (1 cm X 2 cm) on the face of a LCD screen. The rectangles were arrayed horizontally in three channels (left, center, and right) with the left and right rectangles located 10 degrees to each side of the central one. The screen was located 18 inches in front of the subject's bite bar. Each rectangle was presented for one second and their order of occurrence was aperiodic with the average rate of occurrence being .2 Hz. Under the three counting conditions the subjects (1) counted each occurrence of the left rectangle and depressed a key after each fourth occurrence, (2) counted the occurrence of each left and middle rectangle and depressed different keys after the fourth occurrence of each one, and (3) counted the occurrence of each left, middle, and right rectangle and depressed different keys after the fourth occurrence of each. Fixation, alternating fixation, and free-viewing control conditions were run as described previously in experiment 3A.

Results

Measures of rectangle counting performance and normalized saccade length were computed for each condition. The mean saccadic range and counting performance scores have been presented in Figure 4 for each counting condition. The performance decrements with increasing task load declined, but overall performance was quite high relative to that for tone counting in experiment 1. Decreasing saccade length was, again, associated with increases in task difficulty. Analysis of variance revealed significant main effects for performance (F = 7.11; df 2,18; $p < 0.005$) and saccade length (F = 16.07; df 2,18; $p < 0.0001$). Subsequent Newman-Keuls tests revealed that performance under high task difficulty was significantly lower than the other two conditions ($p < .008$) and the mean saccadic ranges under all conditions were significantly different from each other ($p < 0.02$ or less).

Discussion

These data indicate that the saccade length index of taskload is valid under conditions of visual channel monitoring. Thus, it appears that SLIT may be generalized to other visual performance tasks which do not require precise fixation or tracking.

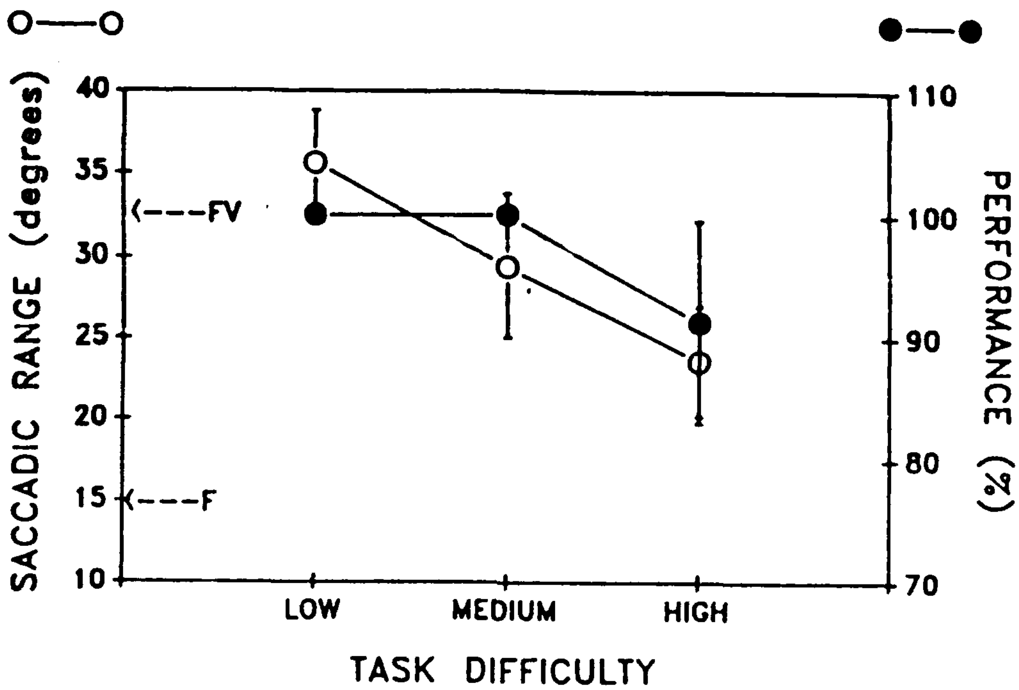

Fig. 4. Saccadic range in degrees and visual counting performance scores (percent correct) under low, medium, and high task difficulty levels.

EXPERIMENT 7: MEASUREMENT OF SLIT WITH A VISUAL FORCING FUNCTION

Rationale

The experiments carried out to date indicate that the eye movements are restricted in range when subjects are performing tasks involving high degrees of mental workload. The present study examines the relationship between saccade length and workload while subjects are exposed to a visual forcing function which was designed to simulate the dynamic features which might be viewed from an aircraft cockpit. To simulate this we employed a series of stripes which normally produces optokinetic nystagmus (OKN) - related to railroad nystagmus. One of two outcomes was hypothesized for this situation: 1) OKN would be unaffected during the task and saccade length will no longer be related to the level of task complexity, or 2) OKN would be inhibited and the degree of inhibition will increase with workload. If the first hypothesis were confirmed it would imply that the SLIT technique is not useful in situations which require reflexive eye movements. If the second hypothesis were confirmed, it would imply that the cognitive load results in a reduction of saccade length even in the presence of provocative stimulation.

Method

Ten subjects were paid $10.00 each to participate. Optokinetic stimulation was provided by a 20 degree field of vertical stripes displayed on a color monitor (Tektronix, Model 690SR). The stripes were red and green and had spatial frequency of 1.2 c/d. The stripes appeared to drift to the right for 10 seconds and then to drift to the left for 10 seconds. This duty cycle (.1 Hz) was repeated for five minutes.

Subjects were required to participate in the control conditions as in experiment 1 (fixation and alternate fixation), and to undergo five minutes of optokinetic stimulation while eye movements were recorded. Next, they were required to perform a one-tone counting task (depressing a key after every fourth low tone), a two-tone counting task (depressing a key after each fourth low tone, and another key after every fourth medium tone), and then a three tone-counting task (depressing separate keys after every fourth, low, medium, and high pitch tones). Each of the tone counting tasks were performed for five minutes under conditions of optokinetic stimulation while eye movements were recorded.

Results

The data were reduced and analyzed as in experiment 1. The mean performance scores (percent correct) and the mean saccadic ranges are presented in Figure 5 for each tone counting condition. As is apparent in the figure, tone counting performance declined significantly with task load, as expected. Interestingly, saccade length decreased with increased task difficulty, even when optokinetic stimulation was used. Finally, the correlation between saccade length and tone counting performance scores was not statistically significant.

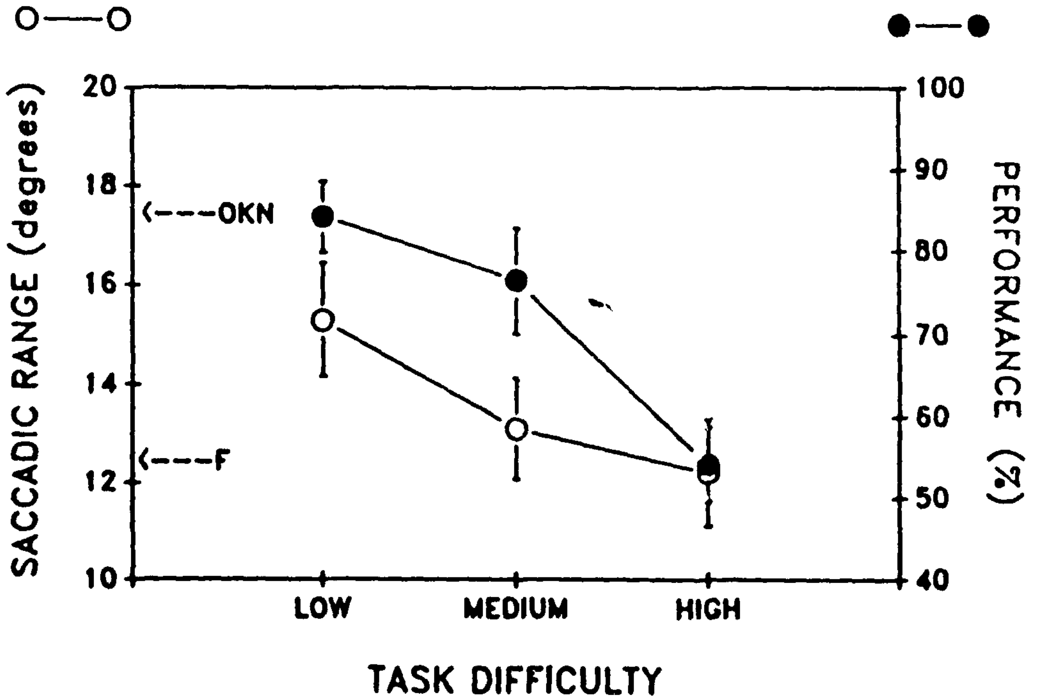

Fig. 5. Saccadic range in degrees under optokinetic stimulation and performance scores (percent correct) under low, medium, and high task difficulty levels.

Discussion

Saccade length measured in subjects who performed tasks of low, medium, and high difficulty reflected changes in mental workload even under conditions of optokinetic nystagmus. This finding indicates that the saccade length index of workload is a valid measure even when a reflexive visual forcing function is employed.

EXPERIMENT 4, 5 & 6: EXCLUSION OF BLINK, VERTICAL EYE MOVEMENT RECORDING AND CORRELATION OF PHYSIOLOGICAL MEASURES.

During the last year our effort turned to the software development as the key focus of our effort. As we moved deeper into a careful development and subsequent debugging of the software and scoring protocols, the successful conduct of this work in some cases precluded the need for experimental work since it was possible to demonstrate the requirements once the software package was completed. Recordings were made with the newly developed automatically scored system (described below under hardware and software development) from three subjects over 30 epochs each and the five "different" physiological variables were cast into a correlation matrix. Left and right eye measures were accomplished separately. In general there was a bias within a subject indicating a directional preponderance but these differences, while reliable, were small. It is important however to have this capability for some measurement purposes (e.g., when diplopia or disconjugate eye movements are suspected) and when vergence/convergence issues can surface (e.g., with night vision goggles or visually coupled systems are in use). Table 14 provides correlational data for the five "different" physiological variables which are used in our standard package. It may be seen that eyeblinks correlate r =0.40 ($p<.001$) with SLIT but this correlation would only imply a 16 percent overlap between the two measures. It would seem that while these two indicants are related, the relationship is weak. The case for velocity and SLIT is much stronger, and this is not surprising since similar metrics (displacement, speed, duration) are employed in calculating both measures. These reveal a 50 percent overlap a relationship which is rational. The other measures (saccade frequency, and duration of saccades) may turn out to be useful measures in future studies.

TABLE 14. Intercorrelations of Saccade Frequency, Duration, Length, Blink Rate, and Velocity

	Frequency	Duration	Blinks	Velocity	SLIT
Frequency	1.00				
Duration	0.23	1.00			
Blinks	0.40**	0.12	1.00		
Velocity	-0.20	-0.74**	0.23	1.00	
SLIT	0.04	-0.12	0.09	0.71**	1.00

**p < .001
N = 90

GENERAL DISCUSSION

The major finding of these investigations is that the range of extent of spontaneous eye movements decreases as cognitive workload demands increase. This is the case when an auditory counting task is used and also when a visual counting task, which does not involve fixation or tracking, is employed. The results of experiment 3 indicated that the saccade length measure is not affected by extended practice under difficult task conditions. Thus, under extended practice on a task that induces high workload, saccade length indexed objective conditions of workload while performance increased. This finding is important given the previous use of performance indices to measure workload because it implies that the method may be very stable and relatively independent of practice effects. Finally, the results of experiment seven suggest that saccade length remains a valid measure of the mental effort required under low, medium, and high task difficulty even in the presence of a reflexive visual forcing function. This finding is important given the increasing concern with temporal factors involved in workload (e.g., Matthews, 1986) and the possible effects of practice on workload indices reported in other research (Wilson, McCloskey, & Davis, 1986). Moreover, this finding makes SLIT, along with blink and other nontriggered events very important adjuncts for use in real world situations where it is not necessary to have to "see through" stimuli which are required by other metrics.

These findings raise interesting questions regarding previous reports of attentional constriction during conditions of high levels of mental workload. If this phenomenon is associated with an attempt to restrict information processing to a limited portion of the central visual field, then it stands to reason that a concommitant restriction of eye movements would facilitate such a process. Future research aimed at assessing attentional constriction and eye movement extent under varying levels of cognitive workload would further elucidate th.' relationship.

HARDWARE AND SOFTWARE DEVELOPMENT EFFORT

GENERAL ANALYSES

The techniques employed in the present investigation included two serious limitations which we set out to rectify in the development portion of the present effort. First, the eye tracking apparatus was insensitive to eye movements in non-horizontal meridians. It may be possible to use similar techniques with instruments which track vertical as well as horizontal eye movement signals. Second, the apparatus employed did not allow for the exclusion of eyeblinks. As Stern & Skelly (1984) have shown, eyeblinks change under conditions of cognitive workload and it may well be that a system which measures both frequency of eyeblinks and saccadic range uncontaminated by the former would offer a more sensitive index of taskload. A final caveat concerns the applicability of this technique to real world settings. Although the apparatus used in the present study required a chin block for head stabilization, other less restrictive methods are available and need only involve head mounted eye monitoring equipment. In what follows we employ a system where the head is fixed for calibration and then held stationary by a chin block which is less restrictive than a bite board. If additional channels of information were available for recording of head position, there would be no technical reasons why eye movement recordings could take place while the head were unrestricted.

Relatedly, we considered the possible artifacts in eye movement recording which could result from oculomotor system interactions (e.g., accommodation, vergence and convergence). These issues were surfaced during equipment hardware and software design conferences. They were considered to be important issues throughout this effort but of less importance when compared to problems which occur due to the intrusion of blinks. Moreover, by recording vertical and horizontal eye movements separately and excluding eyeblinks through our software programs, we believed some of the problems with vergence would either be removed through the separate recording or could be. More expensive data analytic systems (i.e., more channels and more storage) could have eliminated these artifacts further but we did not consider the additional expense warranted at this stage of development of SLIT.

Since we are able satisfactorily to measure the movement of both eyes separately, we see no important technical issues in addressing this issue in future versions of this system provided that there are sufficient channels and computer storage capability. Likewise, we know that accommodation can be measured in real time (Fowlkes, Kennedy & Hennessy, 1987) and have done so. Accomodation can be removed, but because measurement and recording of this information also adds considerable to the cost (and thereby limits future portability) we have only reckoned with this issue in our scientific meetings and discussions. The relationship of accommodation and arousal (i.e., emotion) has been addressed in another context (Fowlkes, Kennedy & Hennessy, 1987). We believe these two techniques (dark focus and SLIT) should be merged when both are developed further. At the present time incorporating the two would complicate and (more importantly) retard the development of both. These oculomotor effects when compared to those of other concerns were small and have therefore employed this form of analysis to address these potential artifacts.

In summary, we have attempted to answer, either by provocative test or analysis, those problems which we considered to be significant. We defined significant to be those which were necessary and sufficient for ultimate use of the biocybernetic system. We have relegated problems believed to be less critical to the successful functioning, particularly when they represented high cost items, to a lower level of importance and dealt with them through consensus.

Therefore, in parallel with the experimental effort we conducted a formal hardware and software development effort to produce a prototype of a quasi-portable, and versatile SLIT system. Development took cognizance of the experimental results and, where practical, incorporated features found beneficial (e.g., two-dimensional eye movement recording, eyeblink rejection). Experimental demonstrations of these features were accomplished in this effort and are described more fully below. Development was concerned with key technical issues which did not lend themselves easily to experimental solution, or which required customized software programs to effect outcomes which were deemed necessary from the experimental effort (viz., computer selection, interfaces, and software).

COMPUTER SELECTION

We purchased a PC's LIMITED® 12 MHz 286 microcomputer as the main processor of the SLIT system. The computer has 640 kilobyte main memory, 1.92 megabytes of expanded memory, (giving a total of 2.5 megabytes of addressable memory), a 72 megabyte hard disk configured as three 23 megabyte hard drives, a 1.2 megabyte and 360 kilobyte floppy disk drives, an Intel 80287 math co-processor; and thus has sufficient computational power for the SLIT system. The video interface was an EGA compatible display controller with a Mitsubishi RGB EGA monitor. A comparably equipped IBM PC-AT (TM) would have cost almost 75 percent more, yet would not have delivered the necessary processor speed and disk storage to handle the amount of data collected.

In year two, we would have purchased a portable microcomputer [e.g., COMPAQ 386 (TM)] which would have enabled SLIT to be transportable and used for field testing. However, with the introduction of the IBM MicroChannel (TM), along with a shortage of 256K CMOS DRAM chips; the price of the portable computers capable of performing this task proved to be prohibitive to this effort.

INTERFACES

Interface issues concerned the development of a head mounted recording system, easily applied surface electrodes, reliable amplification, and an analog to digital converter.

We have experimented with both silver/silver chloride and gold surface electrodes and with different methods of attaching them. Currently, we favor 4 mm silver/silver chloride electrodes for EOG recordings. Subjects were instructed to thoroughly wash their face and left inner wrist. After a complete scrub down, subjects were instructed to lightly buff with sandpaper the seven locations where the electrodes would be applied (see Figure [illegible]). The seven sites were then cleaned with an alcohol swab, and the electrodes were applied.

Subject impedance was then checked by connecting the ground electrode (i.e., the one attached to the subject's wrist) to the common of an Ohm meter, connecting a reference electrode to the positive pin, and setting the meter to Rx1000. It was determined that a good, clean signal could be obtained if the measured resistance of each of the surface electrodes measured less than 15,000 ohms. If this test passed our maximum impedance, the surface electrodes were then connected to the three amplifiers.

We used three reliable amplifiers featuring characteristics suitable for EOG recording. The three amplifiers (2 vertical channels, 1 horizontal) were EOG amplifiers obtained on loan from the U.S. Navy, and were powered by Hewlett Packard HP6217A Power supplies, also on loan from the U.S. Navy.

We purchased a MetroByte Corporation DAS 16F 8 channel (bipolar) analog to digital converter capable of sampling up to 100,000 samples per second to serve as the SLIT interface to the microprocessor. The DAS 16F also provides 2 D/A channels, and 8 Digital I/O Channels. The interface provides for 9 different voltage selections, plus a user option is available for customizing your own voltage ranges. Connecting to the DAS 16F via a 37 pin ribbon cable, we purchased an STA 16 Screw Terminal Board which enable us to easily modify our cabling requirements.

Fig. 6. Placement of Electrodes for Eye Movement Recordings

In all our experiments, we selected ± 2.5 volts for signal gain, giving us a resolution of 1.22 millivolts. For the later experiments, we sampled three different channels (1 horizontal, 2 vertical) at 256 samples per second each (i.e., 256 samples per second (SPS) for the horizontal channel, 256 SPS for the left eye vertical movement, 256 SPS for the right eye vertical movement).

We designed and built our own calibration board which doubled as the visual version of the counting task. This board, (Figure 7), contains 8 red LEDs imbedded in a four foot square panel which was painted black. The LEDs are controlled via software using the 8 digital I/O channels provided by the DAS-16F. With the subject seated 6 feet from the center of the board, and at eye level, 40 degrees of vertical and 40 degrees of horizontal distance separate the top/bottom, left/right LEDs, with 10 degrees of separation between each LED.

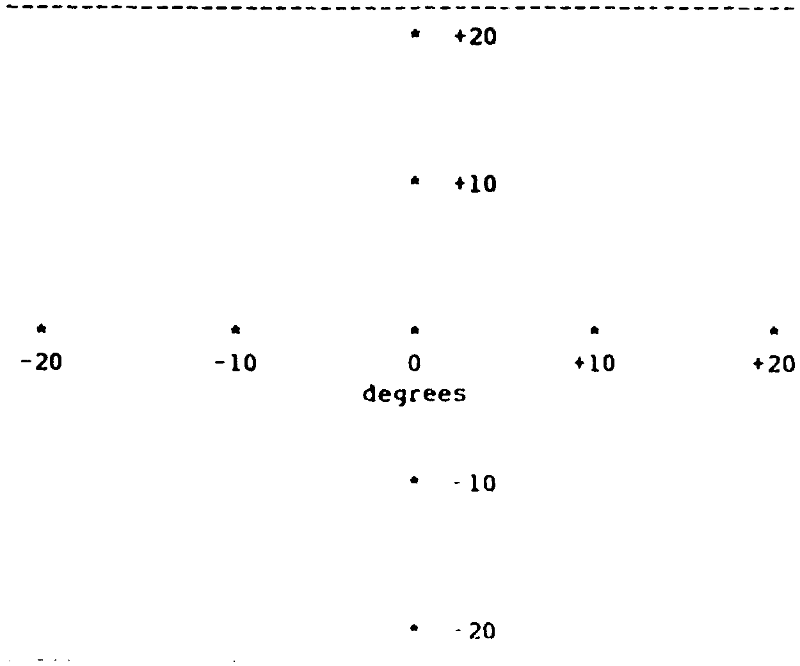

Fig. 7. Calibration/Visual Counting Board

SOFTWARE OVERVIEW

With the purchase of the DAS 16F, we also acquired FORTRAN IV object modules to aid in the sampling of Analog to Digital channels, the programming of the on board Real Time Clock, and programming of the Digital I/O channels. This library is used extensively in each of the software programs described below.

We have written software for the SLIT system to permit storage of analog to digital conversions of eye movement signals (including two-dimensional recording), data archiving, and immediate play-back. In addition, software has been written to take a novice SLIT system user through calibration techniques and actual use of the system.

While it would have been desirable to have immediate on line scoring of saccade lengths, eyeblinks, and saccade durations, it was found that with the computations involved, (even with the high speed processor in use), it was not feasible without an increased expenditure for more expensive and faster hardware.

Currently, we are able to analyze a two and a half minute session and have the results stored in an intermediate file in less than two minutes. With the price of fast DRAM chips coming down to a reasonable figure, and with increased availability, most 80386 machines are now within the price range of the system we originally purchased; and we would anticipate that concurrent processing of the data collected during a session is now a fiscally prudent possibility.

DESCRIPTION OF THE SOFTWARE MODULES

All of the executable modules are kept on a single partitioned drive of the computer, in our case in directory BIOC. The source code for the Essex developed modules are located in a sub-directory as are the libraries used for linkage. Data are collected in the main directory, and after an experimental run, are 'squashed', archived, and stored in a DAT sub-directory.

There are four modules which need be executed to cycle through an experimental run: LIVESHOW, BIOC, SQUASH and SCORE.

LIVESHOW is run prior to beginning the data recording, and after the electrodes have been tested. Because there tends to be a slight drift in the signals, from the beginning of a session to the end, it is necessary to ensure that all signals start on the zero line. LIVESHOW enables to experimenter to center each signal prior to the execution of the experiment by displaying the incoming signals from the subject on the EGA monitor.

Once the hardware has been calibrated, the run-time data recording task, BIOC, is executed. Upon execution, the experimenter is prompted for a three letter subject identifier, most often the first letter of the subjects first, middle and last name. The experimenter then enters the order of the tasks to be performed by the subject, (i.e., high, middle, or low demand).

Each workload level is broken down into two 2.5 minute sessions. A software calibration period precedes and follows each 2.5 minute session. It was decided to place a calibration section at the end of a session due to the slight drift that occasionally occurs. With a calibration period at the beginning and the end of each session, automatic compensation can take place in the scoring module. The software calibration routine successively illuminates the calibration LEDs in the following order: 20 degree vertical, 10 degrees vertical, +10 degrees vertical, +20 degrees vertical, 20 degrees horizontal, 10 degrees horizontal, +10 degrees horizontal, +20 degrees horizontal and 0 degrees (center LED). The subject is instructed to fixate on the illuminated LED and one second's worth of data is collected and stored in the data file.

The next 150 seconds worth of data consist of the actual eye movement data, followed by 9 seconds of calibration data and, finally, the performance scores for the trial session. Data are stored as 2's complement two byte integer values, using the upper 12 bits of the word. The first word of the file is data for A/D channel 0, the second is channel 1 and the third word is channel 2. Data are stored in the above order for each sample taken during the run. Since we sampled at 256Hz, one second worth of data takes 1536 bytes.

After the last workload level is completed, (when the experimental run is over), the SQUASH module is executed to compress the file. Due to the timing of writing to the disk, sometimes zero data is transferred into the file. SQUASH removes this non data and effectively cuts file size by approximately 23 percent. Since a complete testing session generates over 2.5 megabytes of data, SQUASH effectively reduces this amount to nearly 2 megabytes. After scoring the data, we further compressed the data using PKARC, an archiving program, which reduced the size of the data files to about 1.25 megabytes, and then we moved the archive to the DAT subdirectory.

The SCORE module prompts the experimenter for the three letter subject ID, and asks whether or not a visual display of the data is desired. The data for each testing session is then read, scored, and results are printed in file SACCADE.DAT, and is also displayed on the EGA monitor. If a visual display of the data was requested, the vertical channels are displayed in blue, and the horizontal channel is displayed in green. Two seconds worth of data is display on the monitor at a time. The next frame of data is displayed by pressing any key on the keyboard. Saccades are identified by vertical green lines, and eyeblinks are identified with a vertical blue line. A sample report generated by the SCORE module can be seen in Figure 8. As can be seen from the figure, each session is broken down into five 30 second epochs. Results reported for each epoch are saccades per second, average duration of a saccade, average duration of a left going saccade, average duration of a right-going saccade, number blinks, average estimated saccade velocity, average SLIT per epoch, average left-going SLIT per epoch and average right-going SLIT per epoch. Also reported are average durations of saccades for the session, average SLIT score per session, the number of saccades per minute, and number of blinks per minute. The final listing displays subject performance on the counting task.

Saccade identification is comprised of three stages: the first identifies saccade initiation, the second saccade termination, and the third computes the voltage delimited by these points to arrive at the size of the saccade. To identify saccade initiation, the program calculates the absolute difference in amplitude between five successive samples (19.5 ms) from the horizontal channel. If all five differences exceed 3.66 millivolts AND are in the same direction, a tentative saccade initiation is flagged. Saccade termination is determined by searching for five successive samples whose differences are less than 3.66 millivolts. If saccade termination criteria is not met within 100 ms, the tentative saccade is flagged as a false saccade, and not included in the data analysis.

The size of the saccade, SLIT, is computed by taking the absolute difference in amplitude of the end of the saccade from the beginning of the saccade. This results, in millivolts, is then multiplied by the scale factor obtained from the calibration routines to arrive at the number of degrees the eye moved. Duration of the saccade is computed by simply subtracting the number of the data point which began the saccade, from the ending data point number and multiplying by the known sample rate, which in this case, is 256Hz. For example, if a saccade began at data point number 1432, and ended at data point number 1466, the duration of the saccade would be 34 x .0039063, giving a result of 132.8 milliseconds. Velocity of the saccade, in degrees per second, is estimated from dividing the SLIT score obtained above by the duration of the saccade.

Eye blinks are relatively easier to detect. The vertical channels are monitored for quick, positive successive slopes. If five successive samples show this trend, a tentative blink flag is set. The termination of a blink is detected by checking for five successive samples with quick, negative slopes.

Epoch #	sac./sec.	ave.dur.	lf ave.	rt ave.	# blinks	deg/second
1	.667	43.555	46.441	41.193	1.000	192.387
2	.333	40.625	43.945	38.411	1.000	185.505
3	.500	46.875	49.665	44.434	1.000	194.056
4	.800	45.410	47.585	43.570	1.000	175.613
5	.533	59.082	56.152	62.012	2.000	165.545
Epoch #	sac./min	ave.dur.	lf ave.	rt ave.	blinks/min	ave/deg/sec
0	34.000	47.243	49.079	45.686	2.400	182.083

Epoch #	ave. SLIT / epoch	ave. left SLIT	ave. right SLIT
1	8.260	7.742	8.892
2	7.566	6.765	8.767
3	8.992	8.109	10.001
4	7.996	7.282	8.840
5	9.233	8.992	9.474
	Overall ave. SLIT	ave. left SLIT	ave. right SLIT
	8.416	7.766	9.183

	lows	middles	highs
series	6	5	4
missed	0	0	0
correct	5	4	0
incorrect	1	1	0

Filename: dbb3.dat

Epoch #	sac./sec.	ave.dur.	lf ave.	rt ave.	# blinks	deg/second
1	.667	41.602	42.969	40.483	1.000	160.216
2	.367	49.006	54.688	45.759	1.000	137.684
3	.267	43.945	35.156	58.594	1.000	166.677
4	.433	42.067	39.714	44.085	2.000	173.153
5	.500	45.573	42.480	49.107	3.000	173.994
Epoch #	sac./min	ave.dur.	lf ave.	rt ave.	blinks/min	ave/deg/sec
0	26.800	44.076	42.480	45.536	3.200	162.883

Epoch #	ave. SLIT / epoch	ave. left SLIT	ave. right SLIT
1	6.602	6.421	6.823
2	6.534	5.481	8.377
3	7.303	9.550	5.954
4	7.263	7.599	6.872
5	7.491	6.905	8.003
	Overall ave. SLIT	ave. left SLIT	ave. right SLIT
	7.002	6.833	7.186

	lows	middles	highs
series	6	5	4
missed	0	0	0
correct	6	4	0
incorrect	1	2	0

Figure 8. Sample print out from module SCORE

SUMMARY/APPLICATIONS

The idea which prompted the present research was that biological events may be predictive of the attentional and task demands of work. If these could be analyzed in real time and fed back to the machine (or operator), a truly biocybernetic system could be created. For example, we know there may be little or no deterioration in operational performance until the point of failure is closely approached, but perhaps sensitive biological measures of workload could provide premonitory signs of impending failure. There are two technical developments which must be accomplished to produce a workable system. One is traditionally a human factors effort, and in the case of bioelectric events, neurophysiological and biomedical as well. The other entails engineering development, including software and hardware. In this work we have set out to accomplish both.

This project, which was conceived to be carried out in three phases, entails the investigation of a physiological output of the human organism to be employed as feedback information to systems in order reduce task loading to acceptable levels; specifically, an eye movement index of mental workload was studied. Phases I & II, funded by AFOSR, have been completed and a prototype is available. Future plans call for a Phase III which will combine Essex development funding with federal and private sector support in order to make a fully up and running system available to the technological community.

In Phase I, two investigations were performed to assess the feasibility of using specific characteristics of eye movement saccades as unobtrusive indicants of mental workload. Eye movements were measured while subjects were differentially task loaded by simple, moderate, and complex auditory tone counting. The results indicated that the extent of saccadic eye movements varied inversely in subjects as tone counting complexity increased.

The second Phase I experiment used the same equipment and explored further the relationship of eye movement measures (saccade length) to workload. At this point we also incorporated findings from the literature on eye movement extent where preliminary experimental evidence showed extent of eye movements might be reduced under conditions which induced high levels of arousal. For example, others reported a restriction of pursuit eye movement range during a concurrent auditory task and, more pointedly, found that restriction in saccade length occurred in cats under conditions of high arousal induced by amphetamines. To organize our activities we employed a 2X2 classification schema which we believe will improve descriptive precision and permit improved communication of ideas. The classification follows from statistical theory, and we believe that it should have heuristic use as well.

Therefore, to test the relationship between saccade length and arousal, subjects in the second Phase I experiment performed an auditory tone counting task at three levels of difficulty while saccadic eye movements were recorded. Performance varied inversely with difficulty level of the tone counting task suggesting that the different task conditions induced different levels of mental workload. This relationship was substantiated by a significant linear trend ($F(1,4) = 9.10$, $p = .04$). Average extent of saccadic eye movements was also related to task difficulty so that saccade length was restricted with increased task difficulty level ($F(1,4) = 16.65$, $p = .02$). To further substantiate the relation of saccade length to workload, correlation coefficients between saccade length and performance were computed for each subject. The correlations ranged from $r = .37$ to $r = .99$ with a mean of $\underline{r} = .64$. Thus, the results from this research suggested that saccade length could be a promising objective measure of the task demands of a display and thereby serve as a useful measure of mental workload.

The purpose of Phase II was to develop further the Saccade Length Index of Taskload (Workload) or SLIT and cross-validate the results of Phase I. The ultimate outcome of Phase II would be prototype development of a transportable system to assess mental workload via the SLIT metric and other bioelectric measures as appropriate. A chief ingredient in initial development of such a system would be a focus on rapid (i.e., seconds) evaluation of the bioelectric events so that, when properly identified and classified, such signals could be fed back to signal generators.

This work was divided into three main thrusts: Meta-analysis, Experimentation, and Software Development. The meta-analysis section has two components -- a literature review as well as a quantitative meta-analysis. The sections on experimentation describe a series of studies which address various aspects of implementing and measuring SLIT. The software development section outlines the procedure and implementation of the apparatus and scoring used.

In summary, *experimentation* involved a series of interlocking experiments and proof of concept demonstrations. In the studies performed in this series, reliable data were obtained with as few as three subjects, provided there were sufficient calibrations and stable baselines of performance measures. We found that saccade length index of taskload was related to the workload under which the operator performs and not with performance *per se*. That is, the predictive validity of SLIT is chiefly as an index of the objective information load to the operator, even when visual tasks are employed. This finding surfaced when the effects of practice were examined. Practice did not have as much effect on SLIT as did the objective index of task loading. Therefore, while performance improved when tasks of different difficulty were practiced for many sessions, it appeared that the chief determinant of saccade length was the number of channels which were monitored. The SLIT effect, which was originally demonstrated in the dark with an auditory task, was obtained in a lighted room while monitoring a visual signal, thus broadening potentially the applicability of the phenomenon. Also, in a simulated field test, SLIT was demonstrated to be robust even when a visual forcing function (optokinetic nystagmus) was present. In the feasibility demonstrations, vertical and horizontal eye movements became resolved and left and right eye recordings were also separated. The former was a necessary condition for isolating blinks, and the latter was a first step in removing artifacts from the eye movement records which might be due to other oculomotor activities (e.g., vergence, convergence, and accommodation).

A preliminary meta-analysis was conducted to synthesize the literature on workload measures and was presented in a series of tables. In general, the number of performance based measures appeared to be on the upsurge over the past decade and physiological measures not involving eye movements appeared to be on the downswing. The number of subjective measures of workload studies were stable. Investigations of ocular-based measures, particularly cortical-evoked potentials, were on the increase. The chief finding from a fully quantititative meta-analysis of the ocular-based measures found a sufficient predicate for continuing the directions of the Saccade Length Index of Taskload (Workload) (SLIT) research since predictive validities of eye movement research in general appeared to be robust (particularly eyeblink), and several types of studies which examined eye movement extent (like SLIT) were considered to hold promise.

Software development occurred when the work, originally conducted in the more controlled environment of a university laboratory using stationary equipment (e.g., infrared, head-fixed, oculometer) and hand scoring, was transferred to the the contractor's Orlando field offices. There the software and hardware development continued and a series of proof of concept and feasibility demonstrations were undertaken. A low-cost microprocessor was selected for the SLIT system and software was developed and customized to produce a quasi-portable system. The customized program has the ability to reject blinks and it is possible to integrate eye movement records and deliver analyses, automatically scored, within 2.5 minutes. The software program possesses many scoring and integration features (viz., left vs. right eyes, vertical vs. horizontal, vergence/convergence differences can be separated, velocity, # eye movements), which will easily be accommodated by larger capacity, more permanently emplaced, laboratory systems.

A nonintrusive reliable measure of individual differences such as attention during monitoring and control tasks has obvious biocybernetic relevance, particularly in dynamic environments. Such a technique could also be employed to measure pilot performance and, through feedback, permit improved weapon systems operations. The possible commercial applications of SLIT for the private sector are considerable. SLIT may be used as an independent assessment of an individual's attention which may wane with time on task or due to other factors. Such a relationship might be of interest during quality control on assembly lines, or in remote emplacements where security displays are monitored. Since SLIT size appears to be proportional to workload, displays and workstations could be evaluated objectively and compared for difficulty level. In addition, preliminary evidence suggests that individual differences in saccade length may be sufficiently reliable so that they could be studied for stability over time and then examined for relations to equipment and operator aptitude tradeoffs in systems designs.

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APPENDIX A

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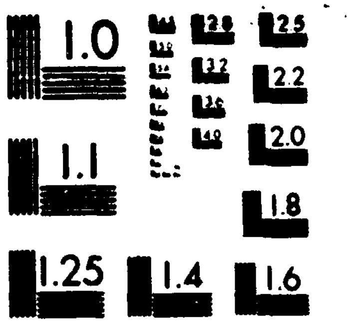
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APPENDIX B
LIST OF PROFESSIONAL PERSONNEL ASSOCIATED WITH THE RESEARCH EFFORT
(in alphabetical order)

BRUNO BREITMEYER

Ph.D.	Psychology, Stanford University, Palo Alto, CA, 1971
B.A.	Mathematics, University of Illinois, Urbana, IL, 1968

JENNIFER E. FOWLKES

Ph.D.	Experimental Psychology, University of Georgia, Athens, GA Expected May 1988
M.S.	By-Passed, University of Georgia, 1985
B.A.	Psychology, Appalachian State University, Boone, NC

MARSHALL B. JONES

Ph.D.	Psychology, University of California at Los Angeles, 1953
B.A.	Philosophy, Yale University, 1949

ROBERT S. KENNEDY

Ph.D.	Experimental Psychology, University of Rochester, Rochester, New York, 1972.
M.A.	Experimental Psychology, Fordham University, New York, New York, 1959.
B.A.	English & Philosophy, Iona College, New Rochelle, New York, 1957.

JAMES E. MAY

Ph.D.	Psychology, University of Houston, Texas, 1969
M.S.	Psychology, University of Southern Mississippi, 1966
B.A.	Psychology, Louisiana State University, 1965

KEVIN SCHNITZIUS

B.S.	Computer Science, University of Central Florida, Expected May 1988.

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B.A.	Psychology, University of Central Florida, 1975

APPENDIX C

MANUSCRIPTS PLANNED FOR LATER SUBMISSION

Kennedy, R. S., May, J. G, Jones, M. B., & Fowlkes, J. E. (1989). Review of eye movement indicants of mental workload. Manuscript to be prepared and submitted to Human Factors.

Kennedy, R. S., May, J. G., Smith, M. G., Schnitzius, K., & Fowlkes, J. E. (1988). Saccade length as an index of mental workload. Manuscript to be prepared and submitted to Human Factors.