HUMAN MENTAL WORKLOAD & PERFORMANCE IN SPACE:
ENGINEERING DEVELOPMENT AND POLICY ASPECTS

by

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Abstract

This thesis details the technical development and political pathways associated with the Mental Workload and Performance Experiment (MWPE). The engineering development of workload and performance measurements for a human executing a cursor control task on a microcomputer using graphic input devices in microgravity is assessed. Reaction time, movement time, and subjective ratings are measured for subjects executing the MWPE. Both technical and political choices shape space experiments; a policy analysis complements the engineering aspects of MWPE.

Ground-based results validate the MWPE protocol and establish a data base for upright and supine postural orientations. The reaction time and movement time results are presented for comparison with classical Sternberg and Fitts' models. The complex interactions between experimental variables suggests that reaction time depends not only on the size of the memory set, but also on the direction of target alignment and postural orientation. It is suggested that movement time depends not only on index of difficulty, but also on direction of target alignment and postural orientation. Accounting for all significant experimental variables, the reaction time and movement time measurements are modelled by regression analysis. Although a lack of a statistical significance was noted, the supine orientation induced higher amounts of workload on the operator than the upright orientation. Temporal demand and frustration were the largest contributors to the subjective workload ratings, while mental demand and frustration contributed the least to workload. The trackball yielded the best performance and induced the least amount of workload. Using the joystick resulted in better performance than using the keyboard arrows, but the keyboard arrows induced less workload than the joystick.

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Preface

In July of 1969 I remember sitting with my family as we watched Apollo 11 touchdown on the moon. I was caught up in the frenzied hyperactive *race to the moon* - I was almost five years old. My generation and those to follow have a birthright to the stars, planets, and solar system. We are the Space Generation; never before in history has a generation grown up with access to outer space. The uniqueness of the *Space Age* carries with it the possibility of a metamorphosis of human philosophy. Rather than "racing for the moon," I dream of all humanity uniting in space and transferring this unity back to our planet Earth.

Humanity is entering a new era - the space generation has been born. In the near future, humans will live and work in outer space not only as temporary travelers, but as permanent inhabitants. The idea that the space environment is something for humans to survive, master, and endure on a time-limited trip from the Earth is being transformed into the notion of humans permanently living in space. I feel that future space generations have an obligation to humanity to create harmonious space habitats rather than creating independent nation-state space dwellings.

I foresee myself working on space education and research for the peaceful uses of outer space throughout my career. After receiving my Bachelor of Science degree in Aerospace Engineering from the University of Notre Dame, I entered graduate school at MIT to study Astronautical Engineering specializing in biomedical applications. I am very interested in studying humans in space and enthusiastic about attaining knowledge in the field of space human factors. I had the opportunity to conduct research on the

Mental Workload and Performance Experiment (MWPE) in the Man Vehicle Laboratory (MVL) at MIT.

My academic interests are not limited to space engineering, but extend into the realm of space politics as well. The omnipresent excitement of politics entices me. I entered graduate school in the wake of the Challenger accident and space policy and the future of the American space program are continually on my mind. In light of this, I entered the Technology and Policy Program hoping to specialize in space policy for a second and complimentary Master's degree to my engineering degree. In this thesis MWPE is explained from an engineering development perspective and from a policy analysis perspective.

As I see it, engineering technology and politics are vital to each other's success. Dr. Forman states, "Politics unsupported by technology produces impotence in the modern world. But technology unsupported by politics becomes irrelevant." My desire is to become educated and proficient in both space technology and policy.

In order to understand MWPE and shape its experimental design I first needed to learn about human factors engineering. For me, MWPE is not just another experiment to be flown on the Space Shuttle, but rather a learning tool which has given me a glimpse into space research, the proceedings surrounding a flight experiment, and the entire policy arena of an experiment. In this thesis I attempt to give insight into MWPE engineering development by reporting the results of ground-based experiments. After the results, I delineate some policy aspects that have shaped MWPE. I hope to integrate my engineering research with the political pathways of MWPE in this thesis.

I maintain that the cosmic religious feeling is the strongest and noblest motive for scientific research.

-Albert Einstein
Ideas & Opinions (1954)

Chapter 1 - Introduction.

Critical issues for space habitation include human requirements for extended spaceflight especially once we live in space on a continual basis. Both physical and social needs of astronauts must be given attention. The gloriousness and awe of space exploration are dimmed by the realities of living in isolation, deprivation, and risk. Space offers a totally alien lifestyle as compared to Earth standards. Space is "inhospitable to life as we know it" (Conners, 1985) and adapting both physically and mentally to this environment is a challenge for human occupants of space. Initial space occupancy has already begun.

Humans currently live in space; as a matter of fact every ninety minutes a human-inhabited space station, the Soviet space station - MIR, orbits the Earth. Yet the "human factor" limits space research and space habitation because of limited understanding about humans living in and adapting to microgravity. Technologies exist for building structures and vehicles for future space bases, while the physical and mental needs of humans in space is more evasive.

In order to facilitate people working in space we need to determine to what extent humans can sustain useful productivity in microgravity. The effects of weightlessness on the body range from muscle atrophy to motion sickness to cardiovascular deconditioning. Human psychological and social adjustment to space includes the topics of human performance capability, mental health, and adaptability. All of these areas need attention in order to prescribe measures for living in space.

The projected operational requirements of a space station and the complexity of its systems necessitate onboard computer automation and crewmember supervisory responsibilities. Many of the daily space station tasks will be facilitated by expert systems in which the crew will spend a considerable amount of time deciphering displays and then recording information into databases. It is projected that the space station will have at least eight computers operating in two hundred different modes with over three thousand control displays. With this level of complexity it becomes critical to understand the demands placed on the astronaut's perceptual and mental capabilities while engaged in computer interaction tasks, including the operation of graphic input devices such as joysticks or trackballs. Therefore, the need exists to design space workstations with efficient computer display formats and input devices. It is yet to be determined if ground-based measures and techniques apply in the weightless environment of space. The interaction of neuromuscular cursor control tasks and mental workload in microgravity is unknown. In order to enhance space station design, system engineers and designers require performance data of graphic input devices in conjunction with workload measurements for the microgravity environment.

Areas for which crew performance is of interest include (Conners, 1985):

- Monitoring & controlling the operations of on-board systems.
- Controlling spacecraft movements in performing various dynamic operations (orientation, stabilization, approach, docking, orbital correction, descent from orbit, and landing).
- Conducting radio communications and television reporting.
- Conducting visual observations, scientific experiments, and investigations.
- Operating special gear.
- Assembling and disassembling individual units of the spacecraft, and performing various operations outside the spacecraft.
- Carrying out onboard documentation.

The first five areas listed above require the human to operate a computer and thus, an experiment which attempts to measure the workload and performance of a human using a computer seems beneficial. The topic of this thesis, the Mental Workload and Performance Experiment (MWPE), is designed to measure the workload and performance of a human executing a cursor control task on a microcomputer using a graphic input device to execute a target identification and a target acquisition task. Microgravity data will be obtained in 1991 when MWPE flies on the International Microgravity Laboratory Space Shuttle mission. Ground-based MWPE results, detailed in this thesis, validate the MWPE experiment and serve as a data base. The controlled laboratory ground-tests provide a means to investigate MWPE experimental variables directly. Important findings will aide future MWPE research and the actual flight experiment on the Space Shuttle.

MWPE attempts to bridge the gap between human and machine tasks in the space environment. Humans reason and exercise judgement very well, whereas, computers surpass humans in performing repetitive routine tasks. Which activities should humans perform and which activities should be computer-automated? Human factors engineering attempts to establish the optimal role of each human-machine component.

The Mental Workload and Performance Experiment addresses four main objectives. The first objective is to investigate the human-machine interface for repetitious tasks on a microcomputer. The second objective is to assess subjects' mental workload and performance associated with computer tasks on Earth in preparation for microgravity studies. Controlled laboratory ground-tests are essential in assessing human behavior variables and serve as precursors for flight experiments. MWPE is executed in two postural orientations, namely, the upright and supine positions in order to achieve the third objective of assessing performance and workload differences between the two positions. Finally, recommendations regarding MWPE and design of an adjustable microgravity workstation to be used in future space experiments and facilities are given. This thesis considers the first three objectives and McDade (Master's Thesis, MIT, 1988) addresses the fourth objective.

Chapters Two through Five explain the theory, give the rationale and methods, report the results, and outline future recommendations, of MWPE. Chapter Two discusses the theory behind performance and workload measurements and reviews the literature on these topics. Performance factors which reveal demands made on an operator in space are measured by reaction time and movement time. Sternberg memory search tasks are reviewed and correlated to reaction time. Fitts' Law of movement time is also reviewed. A combination of the two yields a Fittsberg dual-task paradigm. Workload, a contributing cause of human behavior, is explained in the remaining sections of Chapter Two. Workload, or pressure and amount of work imposed upon a person, is measured by subjective experience. If designers and engineers are aware of the workload imposed on a human's capacity to process information and respond to task demands then they can provide suitable designs and allocate appropriate tasks to be carried out in the space environment.

Does executing the experiment in two different postural orientations have a profound effect on the results? Chapter Three gives the rationale behind MWPE experimental sessions. The human subjects performed MWPE in the upright orientation and the supine orientation to assess the performance and workload differences between the two orientations. In the upright orientation the subjects operate MWPE from a seated position in a chair. In the supine (or recumbent) position the subjects lie horizontally on their backs and operate the computer which is secured to a vertical workstation hanging at arm's length above their chest. Operating a computer from the supine orientation is an unfamiliar or "altered" postural position for a human operator, whereas, operating a computer while seated in a chair is a "familiar" postural position. Also, a brief description of the microgravity environment as it pertains to a human factors experiments is given.

Chapter Three then details the experimental methods and procedures. MWPE nomenclature, experimental variables, and experimental protocol are discussed. Questionnaires and anthropometric (body-type) measurements were recorded in order to categorize the subjects (i.e. gender, size, etc.). Subjects received a briefing on subjective workload measurements and filled out a subjective workload preference sheet. The first MWPE experimental session was a training session in which the subjects became familiar with the GRiD microcomputer and the user-friendly software. Data was collected in the following six MWPE experimental sessions.

Chapter Four reports the results of the ground-based experiments. The results review experimental data taken in the upright and supine postural orientations. These results highlight human behavior characteristics for completing a cursor controlled computer task. Reaction time, movement time, and human subjective opinion are representative measurements that reflect human behavior. The interaction of experimental variables is statistically investigated and comparisons between MWPE data and the theoretical equations are given. Subjects record slower reaction times and movement times in the supine orientation as compared to the upright orientation. A comparison of the graphic input devices (computer keyboard arrows, joystick, and trackball) yields that the trackball produces the best performance and least amount of workload for the computer tasks. The reaction time measurements primarily depend on the size of the memory set and secondarily depend on the direction of target alignment. Movement time measurements depend on both the index of difficulty of the target acquisition and the direction of target alignment.

After the detailed analysis in Chapter Four, Chapter Five outlines future recommendations for the Mental Workload and Performance Experiment. Since MWPE is manifest on the 1991 International Microgravity Laboratory (IML) Space Shuttle mission, experimental improvements can be implemented in the next year before the flight. Recommendations on flight experiment procedures, integration, and manifestation are suggested. In sum, MWPE attempts to provide new insight into human performance and workload which could help eliminate the limiting "human factor" for future space exploration.

Chapters Six and Seven describe space policy formulation and the system in which MWPE operates, respectively. The policy formulation starts with background information on American space policy. Then MWPE policy formulation is introduced which is followed by the details surrounding the genesis of MWPE. Chapter Seven starts off by revealing the participants who have shaped MWPE and their roles in the experimental development. Then the MWPE timeline is given. The thesis concludes with recommendations and a course of action for MWPE. The political pathways of MWPE are traced in Chapters Six and Seven.

Grey are all theories,
And green alone Life's golden tree.
-Goethe: Faust I.iv.

Chapter 2 -Performance and Workload Measurements: Theory.

I attempt here to reveal the three important concepts, reaction time, movement time, and subjective rating measurements of the Mental Workload and Performance Experiment. It was not until I reviewed the literature that I understood the constructs of of human behavior. The origin of these measurements is the essential element needed for an explanation of MWPE protocol. This chapter answers questions like "how many?" "what are they?" "where did they come from?" and "what is their use?" regarding two objective performance measurements, reaction time and movement time, and the measurement of subjective workload for MWPE.

Three quantities are measured for MWPE: reaction time, movement time, and subjective ratings. Reaction time and movement time provide objective performance information by measuring the time it takes the subject to respond to a task and complete the task. Subjects provide their personal experiences of workload through subjective ratings which are discussed in the Workload Section (See Section 2.4).

Where did performance and mental workload tasks originate? *Sternberg* memory search tasks (Sternberg, 1975) explore reaction time and *Fitts'* target acquisition tasks (Fitts and Peterson, 1964) examine movement time. The *Fittsberg* dual-task paradigm (Hartzell, Gopher, Hart, Lee, and Dunbar, 1983) includes both a Sternberg and a Fitts' task and is the basis for MWPE paradigm. Reaction time and movement time are conventional performance measurements and have been detailed in the literature which I will now review.

2.1 Performance

2.1.1 Sternberg Memory Search Task - Reaction Time

Traditionally human memory was studied upon failure, but Sternberg proposed an alternate approach of studying memory. He studied performance when it was almost free of errors; he studied "successful memory." Sternberg hypothesized that human subjects reveal their memory retrieval mechanisms, not by how they fail, but by how much time it takes them to perform a task successfully. Therefore, Sternberg maintained that reaction time studies infer the organization of perceptual and cognitive processes. (Sternberg, 1975). The theory suggests that the processing time, reflected in the reaction time measurement, increases linearly with the amount of information processed.

Sternberg's memory search task involves *item recognition* of a prescribed *memory set* (the memory sets given in MWPE consist of either a single letter of the alphabet or four letters). An example four-letter memory set given to a subject to memorize might contain the letters, Z, C, R, and F. After memorization, a *test stimulus* is presented and the subject recognizes which letter of the stimulus is a memory set letter. If the test stimulus is N, Q, B, and Z, then the subject recognizes Z as being a member of the memory set. The next test stimulus might be S, L, O, and R, and for this case the letter R is recognized as a member of the memory set.

Reaction time is measured from the onset of the test stimulus to the response. For MWPE, reaction time is measured from test stimulus onset to initial cursor (represented by a '+' on the computer screen) movement, the time it takes the subject to recognize the letter from the memory set and initiate cursor movement toward the letters. The manner in which the human brain processes information and provides reactions to stimuli is not fully understood, but theoretical models predict the additive and linear nature of the empirical data.

Zaleski and Moray (1985) notes that quantitative parameters of a memory search resemble the reaction time parameters proposed by Hick (1952) and Hyman (1953). They defined a response entropy, H, which is related to the number of possible members in a memory set. For an equally probable number of stimuli (letters), n, there exists a 1/n probability that each stimulus corresponds to a correct response selection. Response entropy is the information required to raise the probability from 1/n to 1 and is expressed in bits of information as:

$$H = \log_2(n) \qquad (2.1)$$

The Hick-Hyman law relates reaction time, RT, to response entropy and simply states that RT increases as information processing requirements increase:

$$RT = a + b\,H \qquad (2.2)$$

where *'a'* is an inherent reaction time, independent of the memory set size. This nominal reaction time component can be thought of as an information processing *overhead.* This overhead may reflect the time it takes the person to focus on the screen or it may possibly be a neurophysical delay associated with initiating the brain for information processing. The rate of increase for each additional bit of information required for the memory selection corresponds to *'b'*. Combining the first two equations yields the following reaction time equation:

$$RT = a + b\,\log_2(n) \qquad (2.3)$$

This means that RT increases approximately linearly with memory set size, or response entropy. Sternberg's experiments (Sternberg, 1975) yielded a rate of increase of 38 ms for each additional member of the memory set, thus, Equation 2.3 has a slope of 38 ms. Sternberg's memory sets contained between two and seven letters. The overhead, *'a'*, was found to be approximately 400 ms, thus, Equation 2.3 becomes:

$$RT = 400 + 38\log_2(n) \tag{2.4}$$

2.1.2 Fitts' Law - Movement Time

In the early 1960s movement time, or response duration, received experimental emphasis for its connection with the information capacity of the human motor system. After defining a movement as a neuromuscular task, the information content of the task was sought. Similar to the reasoning in the previous section, Fitts tried to break a task down into its components in order to assess the amount of information required for the movement. Fitts (1954) reasoned that the average amplitude, A, of a human movement and the width, W, of the target being acquired defined an index of task difficulty, ID, in bits of information that has the following logarithmic representation:

$$ID = \log_2\left(\frac{2A}{W}\right) \tag{2.5}$$

Fitts and Peterson assumed that "motor processes followed the same type of law as perceptual-motor processes." (Fitts, Peterson, 1964) An increase in index of difficulty would reflect an increase in the amount of information communicated for a motor movement. Fitts' Law became:

$$MT = c + d \text{ ID} \qquad (2.6)$$

where '*c*' and '*d*' are constants. Combining the last two equations yields:

$$MT = c + d \log_2\left(\frac{2A}{W}\right) \qquad (2.7)$$

Fitts' Law defines movement time, the time it takes to enter into a target, as a function of combined effects of distance to the target and target width. Fitts' Law predicts movement time as a linear function of the index of difficulty. It seems logical that MT increases if movement amplitude increases or target width decreases because under these prescribed conditions the target becomes further away and smaller, respectively. The act of actually "capturing the target" on the MWPE computer screen requires movement deceleration because the subject terminates movement velocity in order to stop the cursor within the target boundary rather than entering the target and passing through it.

A person playing "pin the tail on the donkey" may not hit the donkey because he is blindfolded and disoriented from being spun. If allowed to open his eyes, the person could "pin the tail on the donkey." More information was communicated to the man and he was able to use visual and acute motor skills to pin on the donkey's tail. If the man moves further away from the donkey, his movement time will increase and if he is instructed to pin it in a precise location his movement time may increase further.

An analogy between Fitts' subjects making hand movements with a stylus to acquire a target (making contact between stylus and target plates) and MWPE subjects moving a cursor into a target block was made by MWPE designers (Fordyce, 1986). Therefore, the results in Chapter Four will be compared to classical Fitts' data to test whether the empirical formulas describe motor control of cursors as well as hand movements. Figures 2.1 through 2.4 illustrate Fitts' tasks:

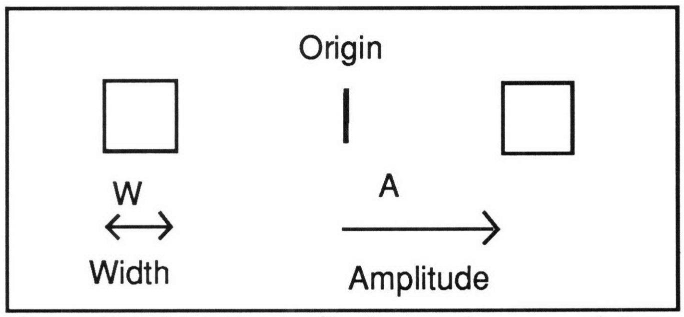


Figure 2.1 Fitts' task display and nomenclature.

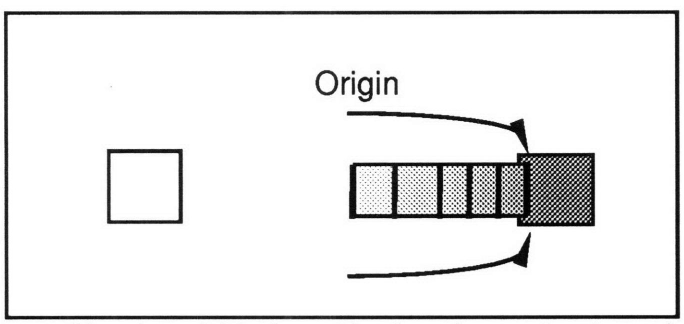


Figure 2.2 Simulated Motion: Moving the stylus into the target (target acquisition).

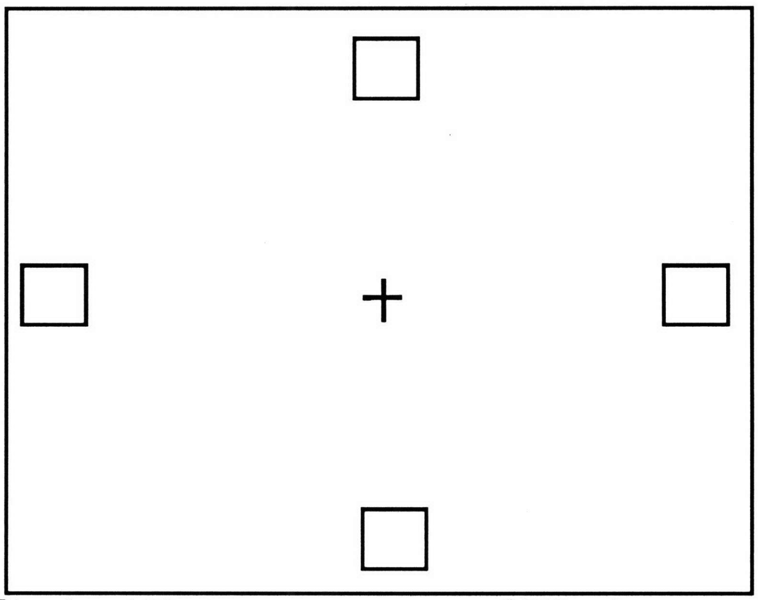


Figure 2.3 Simulated Fitts' targets as seen on GRiD microcomputer screen.

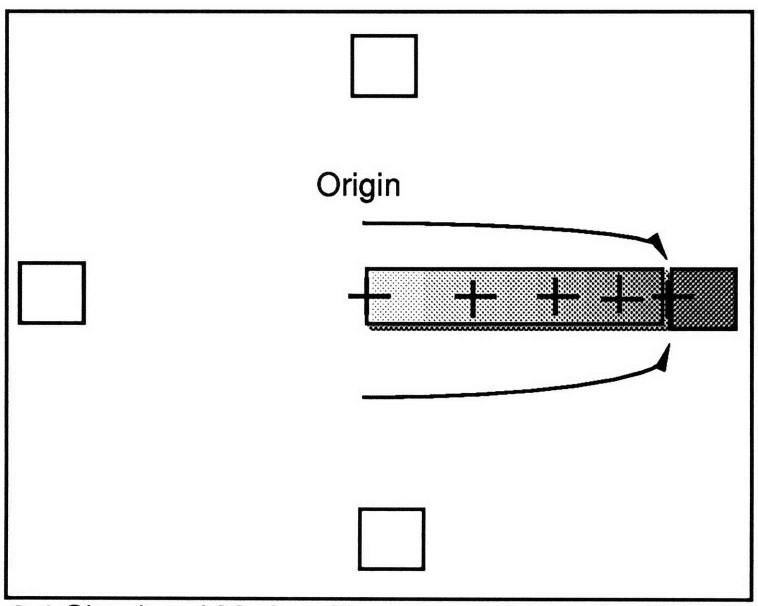


Figure 2.4 Simulated Motion: Target acquisition for MWPE.

Fitts' Law is a generally accepted motor control model for predicting movement time, but additional motor control theories should be mentioned. More recently, modifications for Fitts' Law have been suggested by Welford (1968) to incorporate the discrepancies he found in Fitts' Law for small and large movement time tasks. Welford suggests the following relationship:

$$MT = K \log_2\left(A/W + 1/2\right) \qquad (2.8)$$

Kvålseth (1981) proposes a power law to describe motor control which is non-analogous to Fitts' Law of MT.

MacKenzie's experiments (1987) claim that precision movements are solely a function of target width. MWPE target acquisition tasks could be categorized as precise movements because the change in movement amplitude is small. The simulated Fitts' task of MWPE includes precisely moving a cursor into the target block. Chapter Four reports detailed results of the effects that target width and movement amplitude have on performance.

2.1.3 *Fittsberg* Dual-Task Paradigm

The *Fittsberg* dual-task paradigm combines a *Sternberg* memory search task with a representative *Fitts'* target acquisition task (Hartzell et. al., 1983). The output of the memory search task serves as an information input to the target acquisition task. Are the two tasks independent or dependent on one another? Are they executed serially or in parallel? Consensus favors the serial execution theory while dissenting opinions support the theory of the two processes being executed in parallel (Zaleski and Moray, 1985).

The literature makes no definitive statements on the independence of memory response selection and response duration. Assuming the tasks can be viewed independently, the Fittsberg paradigm is very powerful because the difficulty of response selection and response duration can be varied independently. This produces reaction times which primarily depend on response entropy and movement times which depend on movement amplitude and target width. The noticeable experimental trends from Hart's experiments are: RT, not MT increases as mental difficulty of response selection increases and

MT, not RT, as index of difficulty increases. (Hart and Staveland, in press) MacKenzie argues that for precise motor control tasks movement time depends solely on target width regardless of movement amplitude.

The Fittsberg paradigm allows many experimental variables to be tested in MWPE. MWPE memory sets consist of either one or four letters. The movement amplitude and target width are also varied. Experimental conditions and variables for MWPE are further discussed in Chapter Three and independence of variables is analyzed in Chapter Four using statistical methods.

The objective measures of performance, reaction time and movement time, are coupled with the subject's personal rating of the task (subjective rating) to give understanding to human performance and workload within the context of MWPE. Do subjective workload ratings given by subjects tend to follow objective performance measures? Chapter Four provides the answer to this question. The remainder of this chapter discusses the concept and importance of workload as it relates to human behavior.

2.2 Workload

2.2.1 Subjective Workload

The recent explosion of computer automation has caused the human operator's role to change from that of a manual controller to that of a planner, coordinator, and supervisor. Increasing demands are being placed on the operator's perceptual and mental capabilities. With each successive spacecraft design has come an overwhelming increase in the number of panels and control displays that the human operator must decipher.

The Mercury spacecraft had 3 panels, 143 control displays, and no computers. Apollo had 40 panels, 1374 control displays, and 4 computers operating in 50 different modes. It is projected that the space station will have 200 panels, 3000 control displays, and at least 8 computers operating in 200 different modes (Loftus, 1986). When does the human operator's data processing system become saturated? Workload measurements provide insight into the changing role of humans and machines for spacecraft design.

The notion of "mental workload" seems to be intuitive; it may be analogous to the construct of intelligence, which requires an operational definition (Liu and Wickens, 1987). After writing a proposal for fifteen straight hours I know I have put in an intense amount of mental workload. I may not be able to quantify my efforts, but I can rate my workload in comparison to other tasks. Writing the proposal took twice as much effort as preparing my last book review. Workload is evasive and a concrete definition does not exist. However, workload assessment techniques are continually improving.

The human operator's cost in achieving a specific level of performance is a widely accepted operational definition of workload. Also, it is commonly agreed that mental workload is multidimensional. Workload is human-centered and contributes to human behavior, rather than being task-centered or a by-product of task demands (Hart and Staveland, in press; Sheridan and Stassen, 1979). Subjective experience accounts for many factors which influence the subject's objective tasks (memory recognition and target acquisition for MWPE). The effects of altering the variables of memory response selection and motor response execution on workload are recorded in MWPE by subjective ratings.

The three most common workload assessment techniques are categorized as: performance, physiological, and subjective assessment. Subjective assessment is used for MWPE; it is the most commonly used method. The reasons for it popularity are: its high face validity and the fact that it is quick, cheap, somewhat nonintrusive, and easy to implement (Liu and Wickens, 1987). Subjects are expected to be able to report their experiences of workload. As Sheridan states, "subjective perceptions of cognitive effort may constitute the essence of workload and provide the most generally valid and sensitive indicator" (Sheridan, 1979, 1980).

There are ongoing disputes about the validity of verbal reports. Mandler and Miller proposed that humans have no direct access to the higher order mental processes required for evaluation, judgement, problem solving, and initiation of behavior (Mandler, 1975; Miller, 1962). However, the majority opinion states that subjective ratings provide the most applicable and sensitive workload measurements. As Liu and Wickens point out, "the construction of a workload scale is determined by the researcher's understanding and definition of the concept of workload, and psychometric considerations (Liu and Wickens, 1987).

Many workload scales have been developed in the past twenty years, but the Cooper-Harper scale (Cooper and Harper, 1969) is the oldest and most recognized. The Cooper-Harper scale accounts for two main effects, tracking and manual control but does not provide insight into the correlation of these two effects. The NASA bi-polar rating scale is widely used because it accounts for the multidimensional nature of mental workload. The NASA bi-polar subjective rating scale was developed at NASA-Ames Research Center (Hart and Staveland, in press).

MWPE incorporates the NASA bi-polar rating scale into its experimental paradigm. The bi-polar rating consists of six subscales that are relevant to the subject's experience, namely, mental demand, physical demand, temporal demand, frustration, performance, and effort. Table 2.1 gives rating scale descriptions. The Human Performance Group at NASA-Ames found these six categories to have independent contributions on workload. A seventh workload rating, nausea, is used in MWPE spaceflight software, but not for ground-based experiments. Nausea was added to assess the effect of Space Adaptation Syndrome on workload associated with the experimental tasks.

Table 2.1 Workload Rating Scales used in MWPE.

TITLE	ENDPOINTS	DESCRIPTIONS
MENTAL DEMAND	Very Low / Very High	How mentally demanding was the task?
PHYSICAL DEMAND	Very Low / Very High	How physically demanding was the task?
TEMPORAL DEMAND	Very Low / Very High	How hurried or rushed was the pace of the ask?
PERFORMANCE	Perfect / Failure	How successful were you in accomplishing the task?
EFFORT	Very Low / Very High	How hard did you have to work to accomplish your level of performance?
FRUSTRATION	Very Low / Very High	How insecure, discouraged, irritated, and annoyed were you?
* NAUSEA	None / Vomiting	How much stomach awareness or nausea did you feel?

* The seventh rating scale is only applicable for the Space Shuttle flight version of MWPE.

Collecting subjective workload ratings has two components: first, the six bi-polar rating scales are used to evaluate the most important contributing factors to workload and secondly, a weighting factor is determined for each of the six elements to account for personal biases and to find the most influential contributor to workload for the human subject operating the experiment. Subjects assign a relative importance to each rating category through an initial questionnaire. Then the ratings are combined to find an overall workload rating (Vidulich and Tsang, 1985). The method of subjective workload ratings is further detailed in Chapter Three.

Subjects execute a specific number of trials and then asses the "magnitude" of the six subjective workload ratings for each block of experimental trials. The "magnitude" lies between two adjective end points, "very low" and "very high", which serve as anchors. The name "bi-polar" comes from the two end point rating scale axis. Figure 2.5 illustrates a rating scale with the cursor first in the initial position and then displaced to give an assessment of the magnitude of mental workload in the second picture.

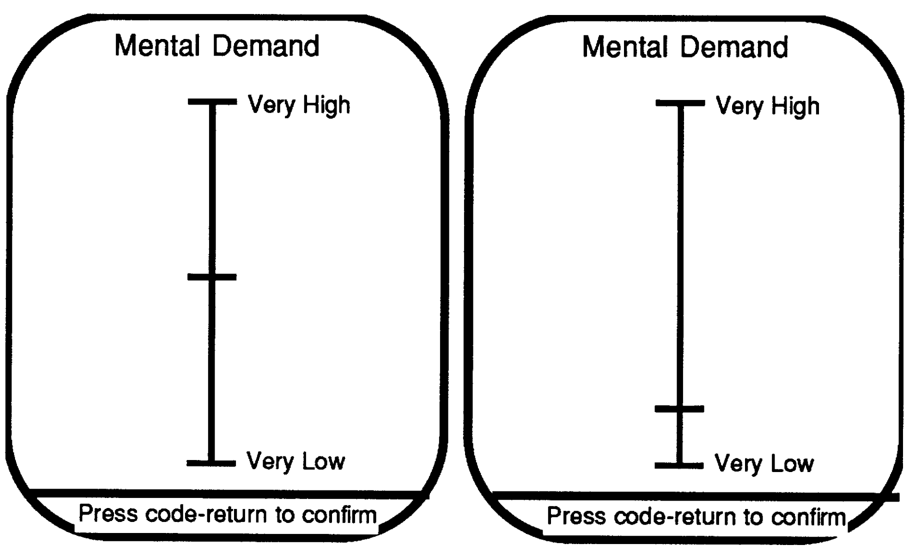


Figure 2.5 Mental workload rating scale with end points.

The anchors provide a frame of reference for the subject. Subject's ratings reflect comparative judgements against the extreme values. Anderson (1982) suggests that displaying the ratings in this graphical format is preferable to a discrete numeric format. The magnitudes are converted to numeric values from 0 to 100 in the data analysis to obtain empirical workload ratings.

The interest in subjective ratings stems from an attempt to attain a human subject's perceived workload for a task. The Fittsberg dual-task paradigm combines memory response selection and response execution. Reaction time, movement time, and subjective ratings measure the performance and workload of the human operator while executing the Mental Workload and Performance Experiment. Keeping the theory of performance and workload measurements in mind, the rationale and protocol for the experimental sessions is outlined in Chapter Three.

Ah, but a person's reach should exceed her reach,
Or what's a heaven for?
- adapted from Robert Browning:
Andrea del Sarta

God has no intention of setting a limit to the efforts of man to conquer space.
- Pius XII

Chapter 3 - Experimental Rationale and Procedure.

3.1 The Upright and Supine Postural Orientations

Human subjects executed the Mental Workload and Performance Experiment in two postural orientations: upright and supine. These two positions were used to identify any differences that may occur in performance or workload while a subject uses a graphic input device. The angular position of a human's body can influence her performance and workload because behavioral responses may be altered for different orientations. Neuromuscular control and coordination vary when people are subjected to altered positions. For instance, writing on a horizontal surface is easy, whereas, writing on a vertical surface is often much more time consuming and difficult.

Howard (1966) defines postural orientation by the angular position of the body (or head) in relation to a stable external reference system. Two lines in a plane, the *variable line* and the *fixed line*, help define the geometry for orientation. The angular rotation of the variable line moving about the fixed line also contributes to the definition of orientation. Angular rotation is labeled either clockwise, CW, or counterclockwise, CCW. The fixed line for MWPE is gravity and movements along this line are up and down; positive polarity is defined by movements in the up direction (or the direction opposite to the force of gravity). The variable line coincides with the body axis of the person and positive polarity point out of the head, whereas, negative polarity is toward the feet.

The upright orientation for MWPE experimental sessions is defined as a person seated in a chair with the gravity line and the body axis line in the same direction and having a zero angle of rotation (See Figure 3.1). The supine orientation for MWPE is defined by specifying the person's waist as the point of intersection of the fixed gravity line and the variable body axis line, an angular rotation of 90^{o} CCW results in the variable body axis line pointing horizontally (See Figure 3.2).

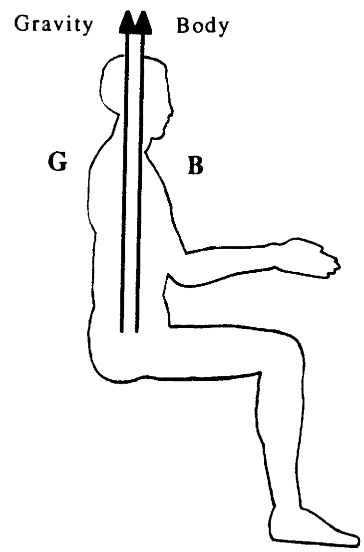


Figure 3.1 A characteristic male in the seated *upright postural orientation* with the fixed gravity line and variable body-axis line denoted.

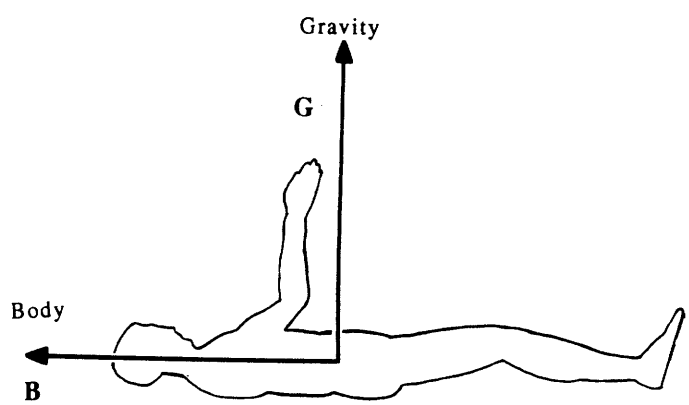


Figure 3.2 A characteristic female in the *supine postural orientation* with the fixed gravity line and variable body-axis line denoted.

Humans are familiar with operating computers in the upright position; I consider the upright orientation to be a normal equilibrium position between the body axis and an external reference system for operating computers (See Figure 3.3). Disturbing this equilibrium position may affect operators' performance and judgements. When operators execute MWPE in the supine orientation they lie on their backs with the GRiD computer and input devices secured on a vertical workstation (See Figure 3.4). Operating a computer while lying on your back is not a familiar position, so we might expect noticeable differences in performance between the upright position and the supine position.

Performance differences are possibly attributed to the change in tonic stimulus of the otolith organs. There is evidence that suggests fundamental reflexes (i.e. ocular counter-rolling) are influenced by a change in postural orientation (Arrott, 1985), so one might hypothesize that altered orientations also affect motor control . Nicogossian states that, "altered static loads of the limbs and neutral body posture lead to changes in performance and manual tasks in space." (Nicogossian, 1982) The altered neuromuscular loading in the supine position may cause degraded performance of MWPE manual target acquisition tasks. Comparing the results from experiments run in these two positions provides insight into executing MWPE in different orientations.

Figure 3.3 A subject executing MWPE in the *upright postural position.*

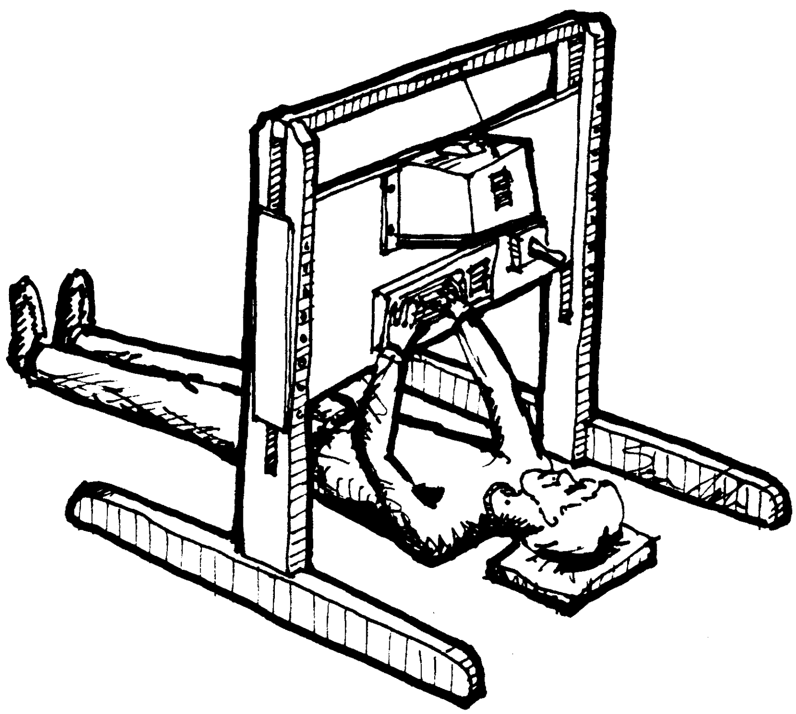


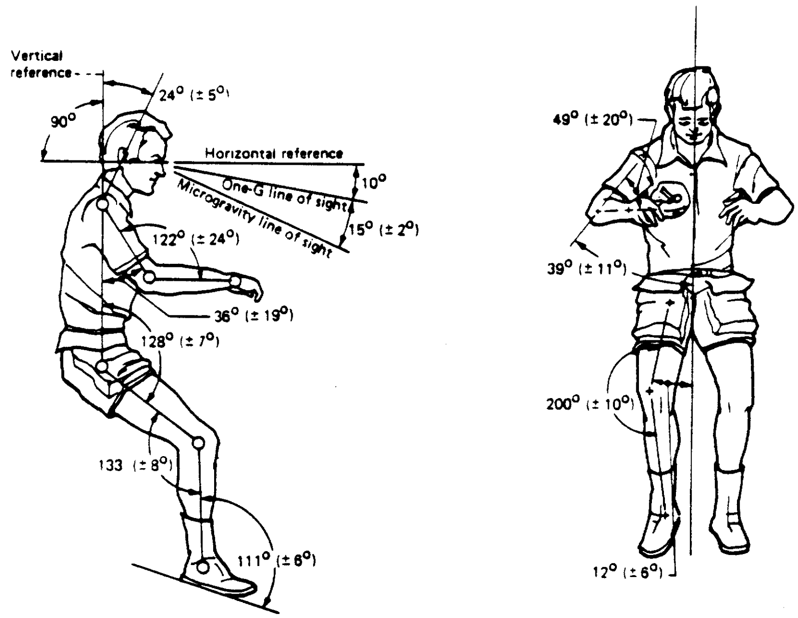
Figure 3.4 A subject executing MWPE in the *supine postural position.*

The upright and supine orientation experiments were performed on the Earth, whereas, MWPE will also be performed in microgravity on the Space Shuttle IML-1 Mission. Microgravity is an altered environment often described as zero-gravity (0-g) or weightlessness. MWPE supine experiments are executed in an unfamiliar orientation, but they do not simulate microgravity experiments because there exists an omnipresent gravitational force on Earth. Even though experiments up to date have not been performed in microgravity it is worth discussing the weightless environment for which MWPE is designed. Ground results and microgravity results will ultimately be compared to arrive at conclusions about performance and workload measurements for future spacecraft experiments and workstation design.

3.2 The Microgravity Environment

Workspace layout and body position in the workspace are important design parameters for the microgravity environment. In space, or microgravity, relaxed body posture differs from that of 1-g. The equilibrium limb position for muscles changes in microgravity due to the altered static loads of limb weight. The decrease in intervertebral spinal pressure causes an increase in seated and erect body heights. The difference in heights coupled with body fluid redistribution tends to shift the center of mass of the whole body headward. "Since the pull of gravity on the arms will be eliminated, the shoulders will tend to move upward, and the elbows upward and akimbo (NASA Ref., 1978).

The working position in microgravity differs substantially from the 1-g position. The seated position is more or less eliminated because it is not natural in 0-g and restraints have to be used to keep crewmembers seated. The "standing" position in microgravity is called the neutral body position of weightlessness and is characterized by a forwardly bent, straightened spine, semi-erect position. The body assumes this relaxed position in the absence of external forces. Also, the line of sight is depressed by an additional 15° due to the tendency of both the head and neck to drop in microgravity. (In a 1-g environment the line of sight is 10° below the horizontal.) Figure 3.5 depicts a crewmember in the neutral body position.



Note:
The segment angles shown are means. Values in parentheses are standard deviations about the mean.
The data was developed in Skylab studies and is based on the measurement of 12 subjects.

Figure 3.5 A crewmember in the neutral body position of microgravity.

Presumably, performance is initially degraded and spacecraft crewmembers learn to compensate for limb movement errors in microgravity, but this could be at the expense of additional mental processing and workload. Crewmembers perform MWPE on Earth and in microgravity so measurements of performance and mental workload can be assessed and compared. Ultimately, the information gained from MWPE will be used to allocate appropriate functional tasks to crewmembers operating computers and to design an adjustable workstation which is best suited to a person's needs in the microgravity environment.

3.3 Nomenclature & Explanation of Experimental Variables

The Mental Workload and Performance Experiment is an integrated human factors experiment on the GRiD microcomputer. Software development was targeted for the GRiD because it is the only spaceflight qualified microcomputer. Performance and workload measurements are recorded for a subject operating MWPE. The experiment nomenclature, experimental variables, and the experimental protocol are described in the following sections. Eight graduate students from the Massachusetts Institute of Technology (MIT), four female and four male, served as the human subjects for the experiment. They each performed seven experimental sessions, the first was a training session and the remaining six sessions were used for baseline data collection.

The experimental design of the Mental Workload and Performance Experiment incorporates variables to measure the performance and workload of a human subject operating a GRiD microcomputer to complete a target identification task and a target acquisition task. There are four categories of experimental variables: the computer device, the direction of cursor movement, the index of difficulty for target acquisition, and the size of the memory set. The experimental task is to select a target on a computer screen display by moving a cursor from the center of the screen to inside the target boundary.

The comparison of three different computer devices identifies the fastest device and the device that induces the least amount of workload for repetitious computer tasks. The three MWPE computer devices are the GRiD computer keyboard arrows, a joystick, and a trackball. There are four arrows on the GRiD's keyboard for up, down, left, and right cursor movements. The joystick is a velocity control device. The cursor velocity is dependent on how far the joystick is deflected from its resting position; cursor velocity increases with joystick deflection. The cursor quickly halts as the spring-loaded joystick is released and returns to its neutral position. The trackball is a positioning device which the subject operates by rolling the ball with her palm or fingers which in turn moves the cursor. When the trackball is rolled "left", the cursor scrolls "left" across the screen. Photographs of the devices and the workstation mock-up are seen in Figures 3.6 and 3.7.

Figure 3.6 The GRiD microcomputer and graphic input devices for MWPE.

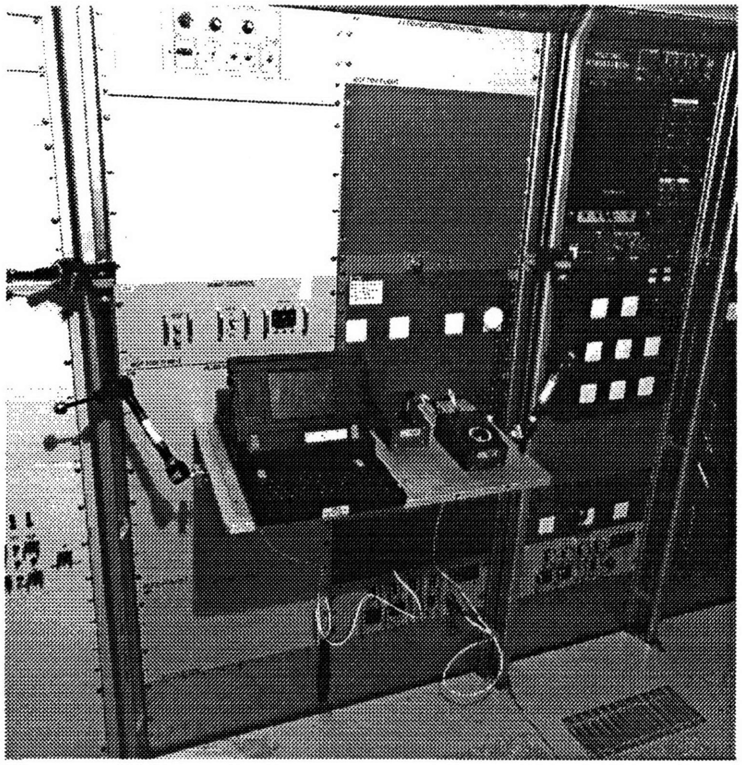


Figure 3.7 MWPE in a mock-up of the Spacelab module.

The next category of experimental variables account for the arrangement of target layout. MWPE has two patterns for the target layout direction, either a diagonal or a cardinal arrangement. Four targets are displayed on the computer screen diagonally or cardinally from the center cursor. In the diagonal arrangement the targets are oriented at a 30^{o} angle from the horizontal axis of the cursor's origin. For the cardinal pattern, the targets are oriented in a North, South, East, West alignment. The four targets are separated by 90^{o}. Figures 3.8-3.9 illustrate the two directional patterns.

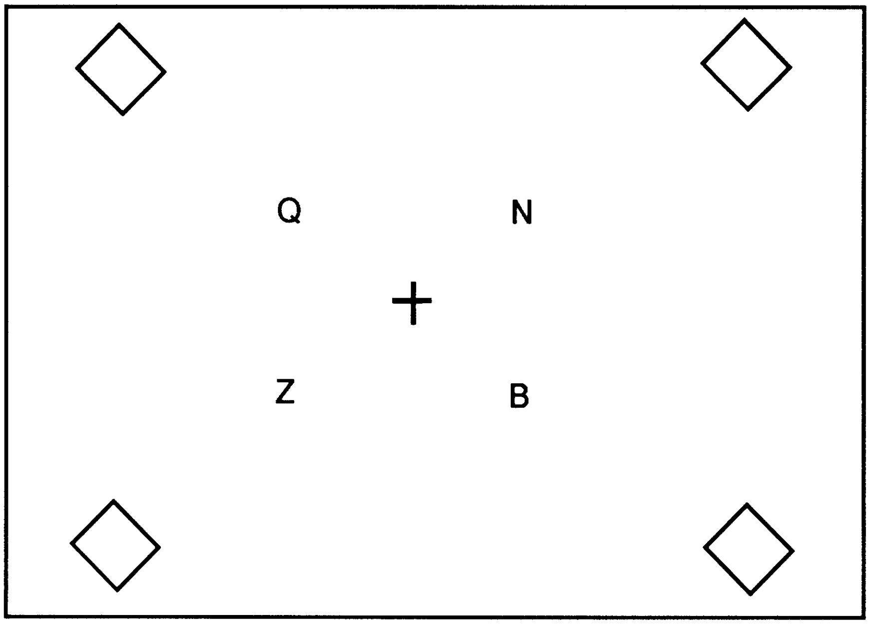


Figure 3.8 *Diagonal* target arrangement for MWPE on the GRiD microcomputer.

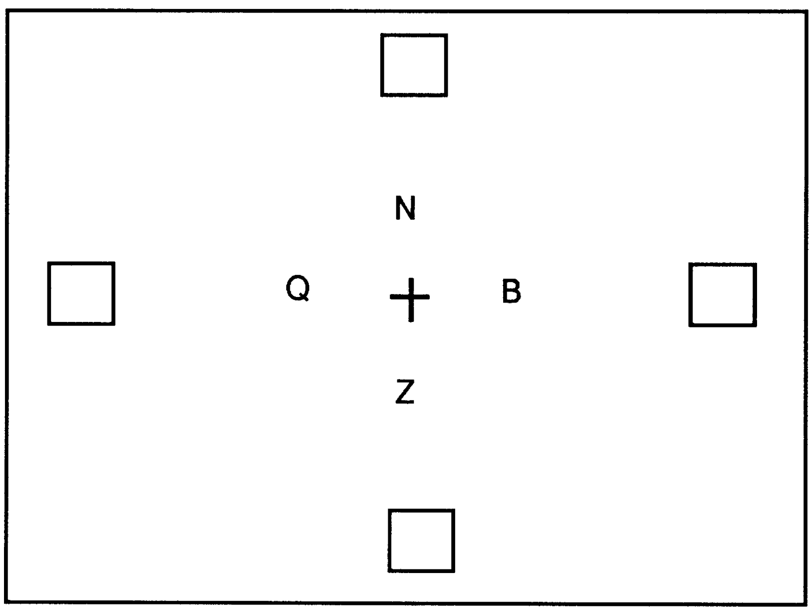


Figure 3.9 *Cardinal* target arrangement for MWPE on the GRiD microcomputer.

Does the direction of cursor movement impact reaction time or movement time measurements? From the discussion in section 2.1, we recall that reaction time is dependent upon the response entropy which is determined by the memory set size. Thus, cursor movement direction should not affect the reaction time. The possibility of cursor movement direction affecting reaction time is statistically analyzed in the results section. According to theory, movement times are dependent upon movement amplitude and target width. The direction of movements does not receive detailed mention in the literature. To this end, assessing the influence of cursor movement direction on movement time seems to be novel. I do not make a strong hypothesis for the direction of a movement to statistically affect movement time, but direction is a worthwhile test variable that may provide some insight into the effect spatial orientation has on the human operators' performance during a target acquisition task. Finally, is subjective workload is affected by the two directional alignments is considered in the results section?

The index of difficulty contains the third category of variables for MWPE which rely on movement amplitude and target width. Target acquisitions are characterized as 'easy' or 'hard'. A target which is easy to capture has an amplitude of 60 pixels from the origin and a width of 20 pixels while a target which is hard to capture has a 100 pixel amplitude and measures 10 pixels across. The operator has increased difficulty positioning the cursor to stop inside a target which is further away and has a decreased width. Figure 3.10 and 3.11 illustrate the easy and hard index of difficulty displays.

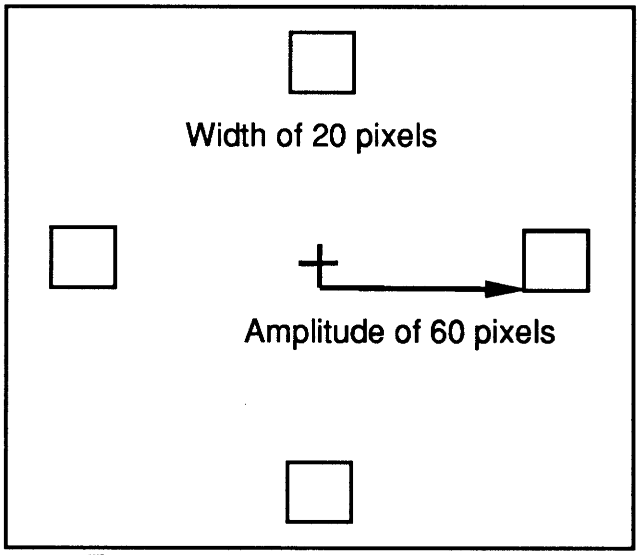


Figure 3.10 *Easy index of difficulty* with a 60 pixel amplitude and a 20 pixel target width for MWPE on the GRiD microcomputer.

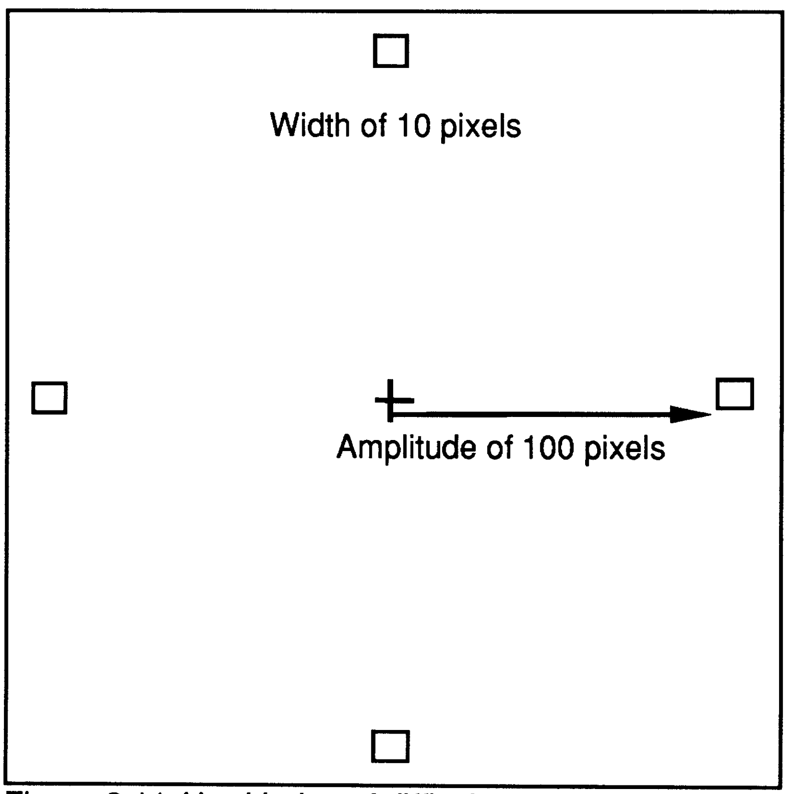


Figure 3.11 *Hard index of difficulty* with a 100 pixel amplitude and a 10 pixel target width for MWPE on the GRiD microcomputer.

Movement time is expected to increase as the index of difficulty, ID, increases. Recall equations 2.5 and 2.7 in which MT and ID are defined in terms of movement amplitude, A, and target width, W.

$$ID = \log_2\left(2A/W\right) \tag{2.5}$$

$$MT = c + d\log_2\left(2A/W\right) \tag{2.7}$$

The results of varying the index of difficulty for MWPE are detailed and graphically represented in Chapter Four.

The final category of variables encompasses the memory set size, or response entropy. As mentioned in Chapter Two, the human subject is presented with a memory set containing one letter of the alphabet or four alphabet letters. From the discussion of Sternberg memory search tasks we expect memory set size to have a direct impact on reaction time. It was stated that an overhead of 400 ms was nominal, and reaction time increases at a rate of 38 ms for each additional bit of information processed. Does the data from MWPE subjects agree with Sternberg's reaction time equation? The results are shown in the next chapter.

The four categories of experimental variables in MWPE have been previewed. Figure 3.12 displays all the categories and variables.

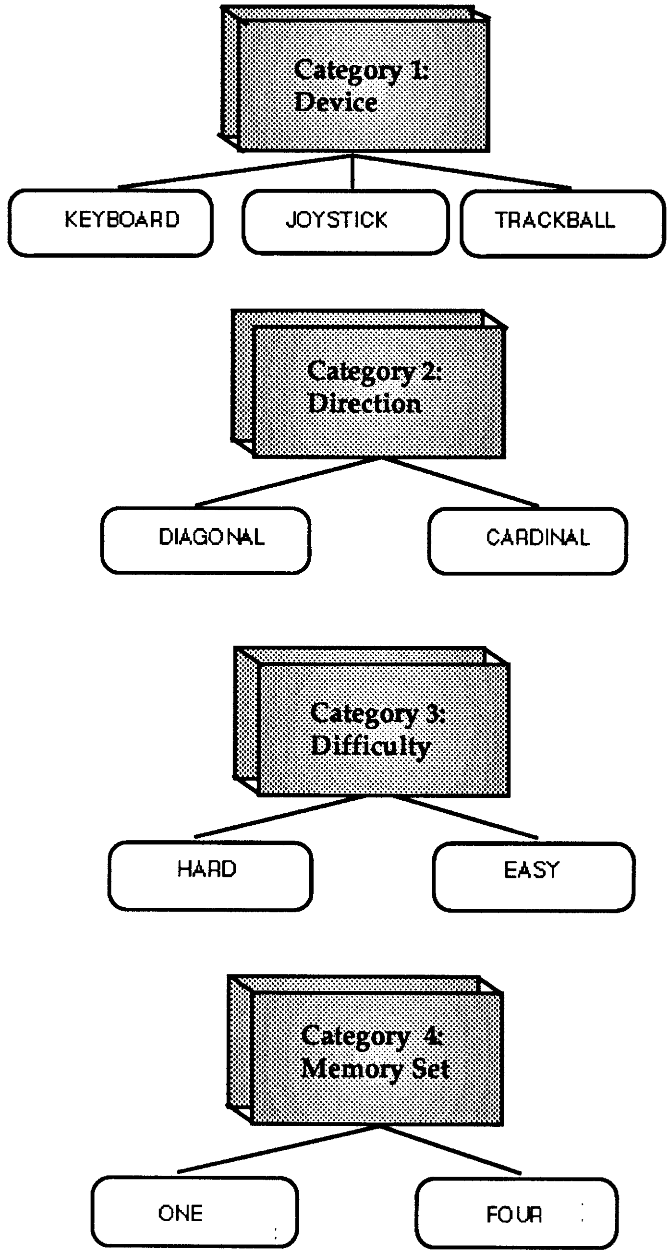


Figure 3.12 The four categories of MWPE experimental variables.

3.4 Experimental Protocol

The timed portion of the experiment starts with the subject having a hand on the device that is to be used in the first series of data runs; the subject receives a prompt from the computer telling her which device to use. she memorizes the memory set letter(s) and then proceeds with the subsequent target identification and acquisition trials. After five seconds the memory set disappears and four targets appear on the computer screen. One of the four targets corresponds to a letter from the memory set and using the device the subject moves the cursor into the target which is next to the corresponding letter (See Figures 3.13 and 3.14). The target becomes highlighted during this process which is referred to as a trial. The subject is given instructions to perform the target identification and acquisition task as quickly as possible.

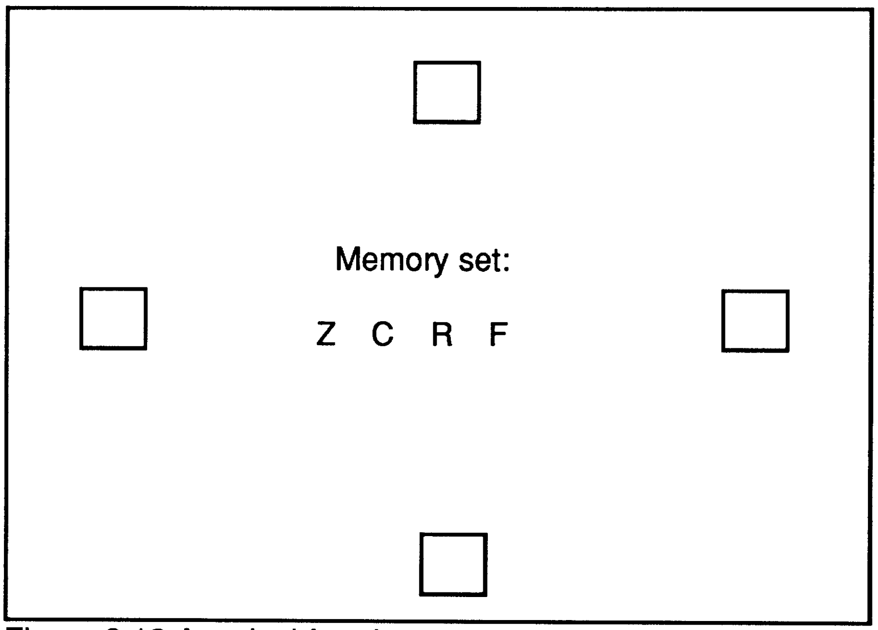


Figure 3.13 A typical four-letter *memory set* for a trial block.

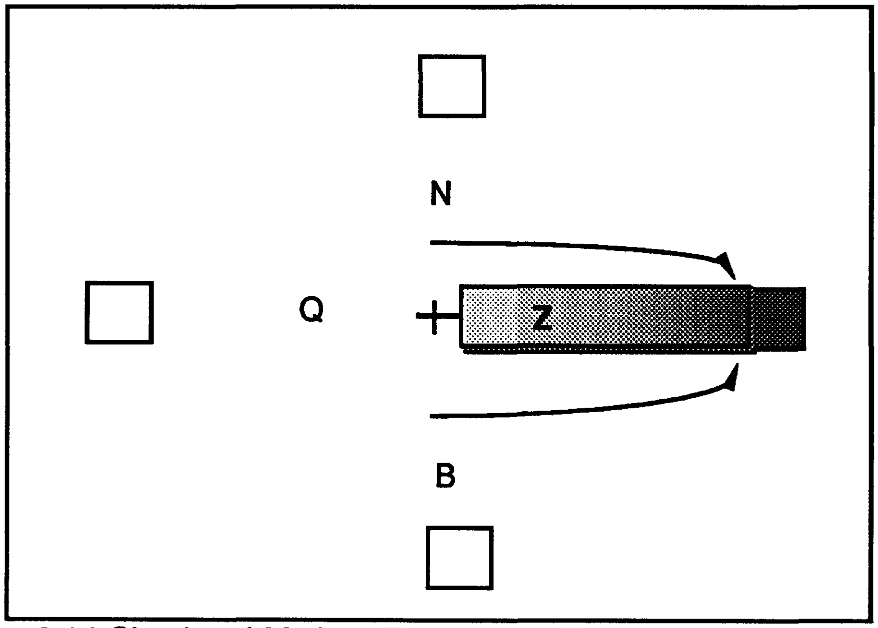


Figure 3.14 Simulated Motion: *Target identification and acquisition for a typical trial block memory task.*

A sequence of eight trials is used for each memory set. If the memory set contains one letter then it will be used in all eight trials, whereas, if the memory set contains four letters then each letter is used twice. Eight trials are used to allow for repeated measurements of the same task. In addition to the memory set, the trials are coded by device, direction, and index of difficulty information. For example, the first eight trials may be denoted by TDH4 which contains the following information: the trackball was the device used, the targets were arranged in a diagonal pattern, the index of difficulty was hard, therefore, large movement amplitude and small target width was used, and the memory set contained four letters.

Subjects evaluate the workload imposed on them for each specific block. The subject is presented with the six NASA bi-polar rating scales immediately following the eight trials (See Figures 3.15 through 3.20). The subject records her assessment of workload by moving the horizontal tick mark (–), initially positioned in the middle of the scale, to a point between the end points that best reflects her experience of workload. The tick mark is moved by whatever computer device is in use for the trials. Once the six workload components have been recorded a single "block" of trials has been completed.

The next block of eight target identifications and acquisitions begins with the presentation of a new memory set on the computer screen. The block of trials is again completed by rating the workload components. Eight different block conditions exist for each device. After completing the eight blocks, the subject is prompted to switch to the next computer device. This assures that all combinations of variables appear for all three devices. There are two variables in each category which results in eight block conditions per device: 2 directions * 2 difficulties * 2 memory sets. The eight block conditions are repeated for all three devices resulting in a total of 24 blocks which contain 192 trials: (3 devices * 2 directions * 2 difficulties * 2 memory sets) * 8 trials/block. The measurements from the 192 trials constitute one MWPE experimental session. Table 3.1 lists all the possible combinations of variables that are presented to the subject for MWPE. The software was written to counterbalance the presentation of variables to the subject (See Fordyce, 1986 and Appendix A for experiment instructions).

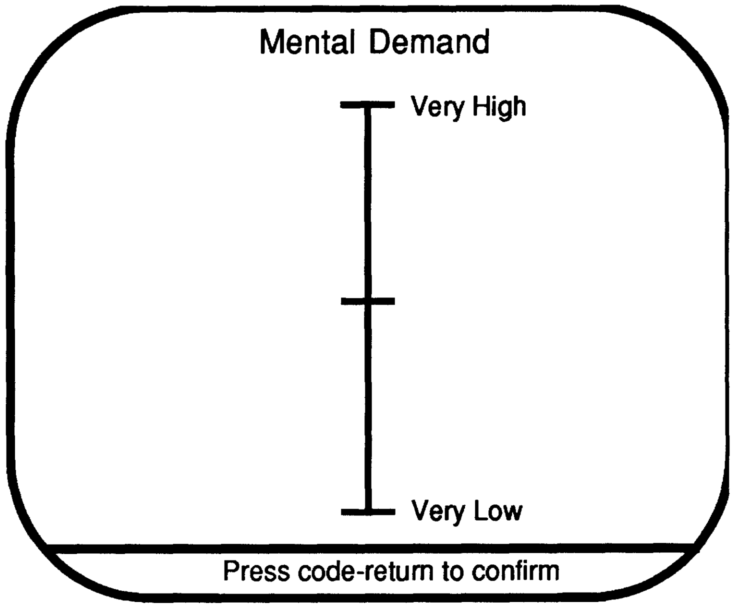


Figure 3.15 Mental workload rating scale.

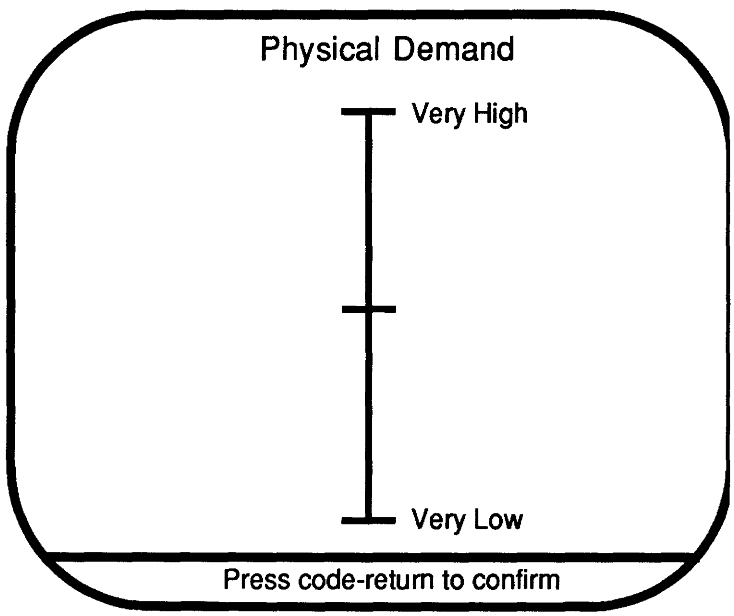


Figure 3.16 Physical workload rating scale.

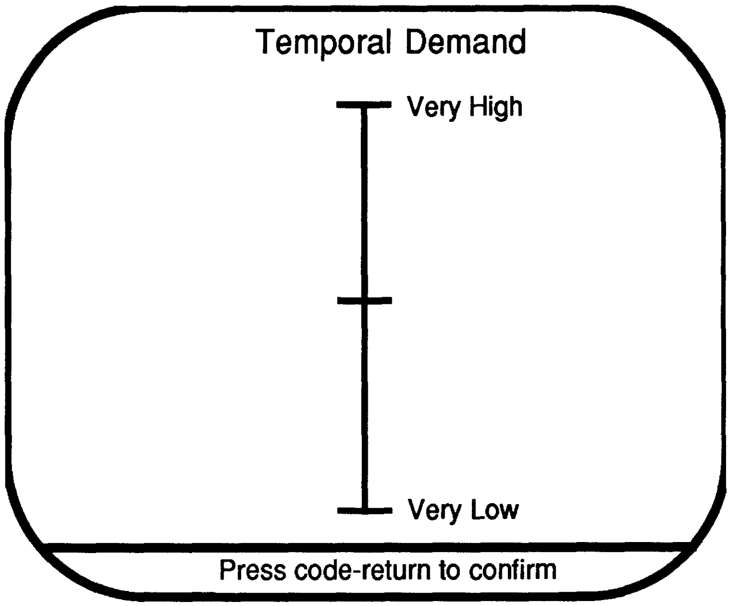


Figure 3.17 Temporal workload rating scale.

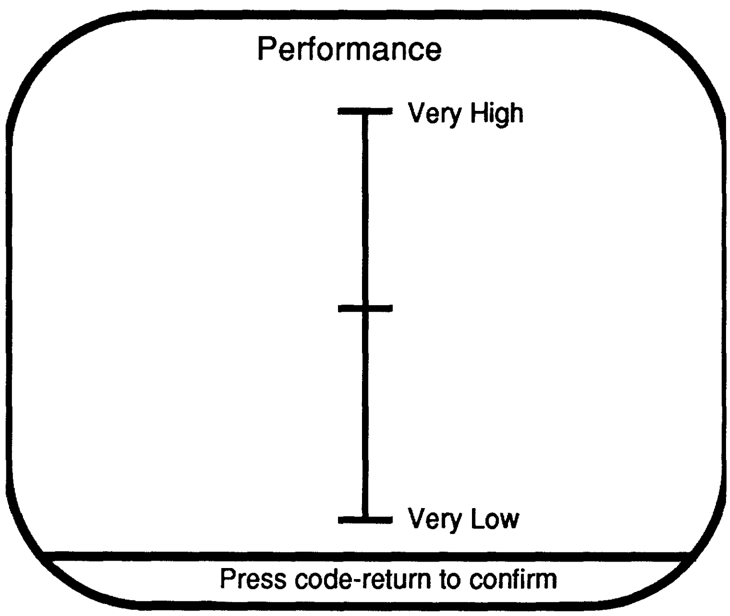


Figure 3.18 Performance rating scale.

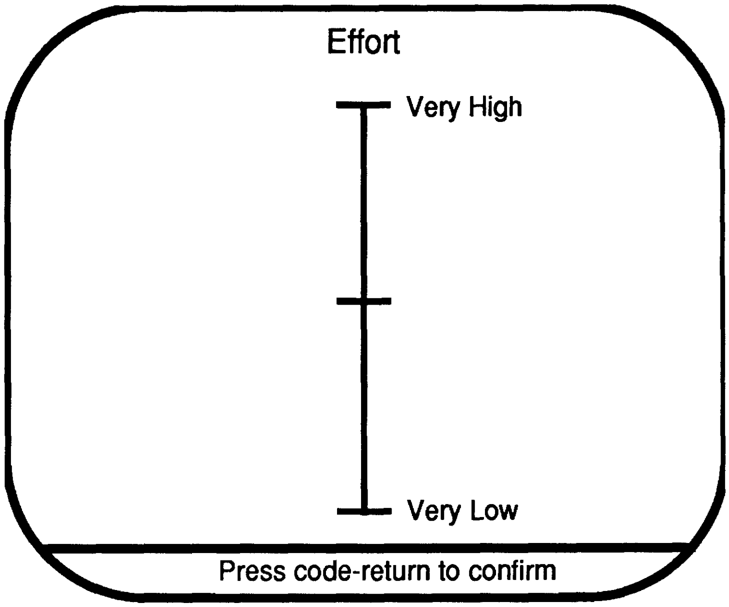


Figure 3.19 Effort rating scale.

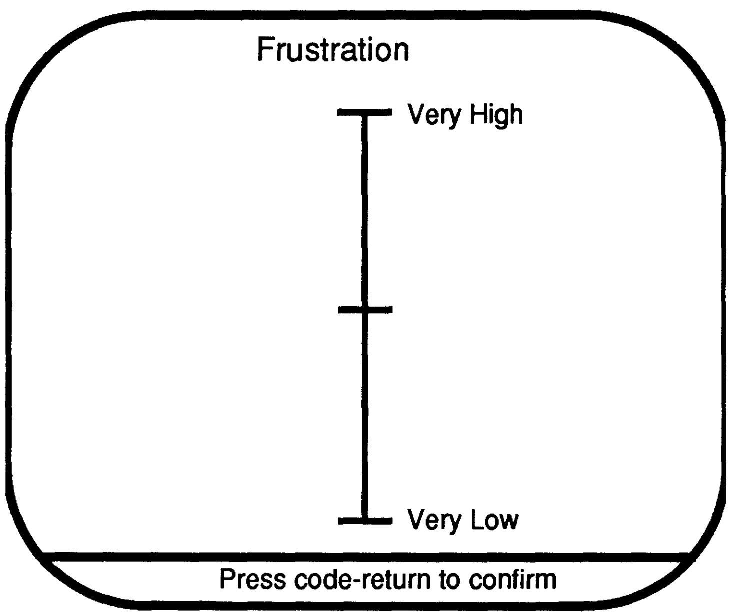


Figure 3.20 Frustration rating scale.

Table 3.1 Combination of Variables for MWPE.

JCE1	KDE4	TCE4
JDH4	KCE1	TDH1
JCH1	KDH4	TCH4
JDE4	KCH1	TDE1
JDE1	KCE4	TDE4
JCH4	KDE1	TCH1
JDH1	KCH4	TDH4
JCE4	KDH1	TCE1
KDH1	TCH4	JDH1
KCE4	TDH1	JCH4
KDE1	TCE4	JDE1
KCH4	TDE1	JCE4
KCH1	TDH4	JCH1
KDE4	TCH1	JDH4
KCE1	TDE4	JCE1
KDH4	TCE1	JDE4
TCE1	JDH4	KDH1
TDE4	JCE1	KCE4
TCH1	JDE4	KDE1
TDH4	JCH1	KCH4
TDE1	JCH4	KCH1
TCE4	JDE1	KDE4
TDH1	JCE4	KCE1
TCH4	JDH1	KDH4

Four female and four male graduate students from the Massachusetts Institute of Technology (MIT) served as the subject population. Each subject performed seven MWPE sessions. The initial session familiarizes the subject with subjective ratings and introduced her to MWPE. The final six sessions provide the baseline data for experimental results. Subjects performed three of these six sessions in the upright position and the other three in the supine position. Upright and supine sessions were presented in a counterbalanced fashion to the subjects to account for learning effects.

3.5 Subjects' Initial Session on MWPE

The initial session started with subjects reading a three page explanation of the subjective rating scales (See Appendix B). Then the subjects performed 15 paired comparisons between the six subjective ratings. (Recall the six subjective ratings: mental demand, physical demand, temporal demand, performance, effort, and frustration.) The subject indicates which member of the pair she feels contributes more significantly to perception of workload. These paired comparisons are used to define a personal weighting factor for each rating. The weighting factor reflects the importance the subject assigns to the workload components and has a value from zero to five. This means that the rating that is chosen the most times in the paired comparisons receives a weighting factor of five and the rating that is chosen the least receives a weighting factor of zero. A normalized workload value is determined by multiplying each rating by its weighting factor; in this manner subjective ratings can be compared across experimental conditions and subjects. An overall workload rating is attained by averaging the six normalized workload ratings.

Next, seven anthropometric measurements, gender, and age were recorded for each subject. Anthropometric measurements were recorded to investigate my hypothesis that body-type may contribute to the performance of a person operating MWPE. People with different body-types, specifically hand measurements, may be adept to using one device versus another device for cursor control tasks. Gender is an important consideration also. Do females or males generally perform repetitious computer tasks quicker, and which sex reported less workload? Women's average arm length tend to be three inches shorter than men's arm length. Will this affect performance on the computer? Age was recorded because differences in body size are marked by age as well as gender. However, I used a homogeneous group of subjects to try and alleviate unaccountable variabilities amongst subjects. All of my subjects were between 22 and 29 years of age. (See Appendix C for measurements).

The seven anthropometric measurements were: thumb-tip reach, forearm-hand length, forearm circumference (flexed), wrist circumference, hand circumference, hand breadth, and hand length. Thumb-tip reach is the horizontal distance from the wall to the tip of the thumb, measured with subject's back against the wall and arm extended forward. The forearm-hand length is the distance from the elbow to the tip of the longest finger. Forearm circumference, wrist circumference and hand circumference measure the distance around the respective members. Hand breadth is the distance between metacarpal-phalangeal joints II and V. Hand length is the distance from the wrist to dactylion. The definitions were adapted from the Anthropometric Source Book (NASA Ref., 1978).

All of these measurements were taken because they may directly affect subject performance, they serve as general body descriptions, and they guide workspace design and layout. No statistical analysis was performed on subjects' anthropometric measurements, but rather they are used for categorizing subjects. Trends may be noticed between subjects with similar body-types or members of the same sex.

The final hour of the initial session was spent teaching the subjects about MWPE and letting them familiarize themselves with the computer and protocol. Subjects practiced in both the upright and supine positions with all three devices. Each device was used until subjects reported that they were completely comfortable operating it. I was present during this orientation session to explain and answer questions, but in the following MWPE sessions the subject is isolated in order to minimize external distractions. MWPE is user friendly and subjects require no assistance to run the experiment.

3.6 MWPE Database Collection

The baseline data is comprised of six MWPE sessions for each subject for a total of forty-eight sessions. At the beginning of each session the amount of sleep the subject got the previous night was recorded. I felt this information might be pertinent to the subjects performance and assessment of workload. The subject was positioned in the proper postural orientation at the onset of each MWPE session and then the experiment began. After verifying MWPE was working properly I left the room and the subject completed the experimental session by herself.

The six sessions were performed within a ten day period. An upright session and a supine session were performed on the same day to expedite the process. Subjects were given a minimum of a half hour break between the sessions in order for them to recuperate from any fatigue experienced in the first session of the day. The subjects break usually consisted of playing Aerobie or walking along the river. Subjects were forbidden to look at a computer screen in the interim between sessions. After the six sessions were completed subjects were asked for their overall rankings of each of the three computer devices and the manner in which they operated each device. Since I was not in the room during the actual experimental sessions, I was curious to find out the actual method subjects used while operating the devices. For example, some people use the "one finger approach" and others use two fingers simultaneously to depress two arrows on the computer keyboard to move the cursor into a target.

Chapter Four presents the results from the statistical analysis of the baseline data. The difference between measurements taken in the upright and supine orientations is discussed. The variables that contribute to reaction time and movement time are revealed and the findings are compared to the theoretical models.

Results! Why, man, I have gotten a lot of results. I know several thousand things that won't work.

- Thomas A. Edison

Everything should be made as simple as possible, but not simpler.

- Albert Einstein

Chapter 4 - Results of the Ground-based Experiments.

MWPE ground tests insure the robustness of the experimental protocol in preparation for future microgravity experiments. The ground-based experiments provide baseline data for MWPE executed in two orientations, upright and supine. The four categories of experimental variables were analyzed for their contributions to reaction time, movement time, and subjective ratings. Recall the experimental variables displayed in Figure 3.12:

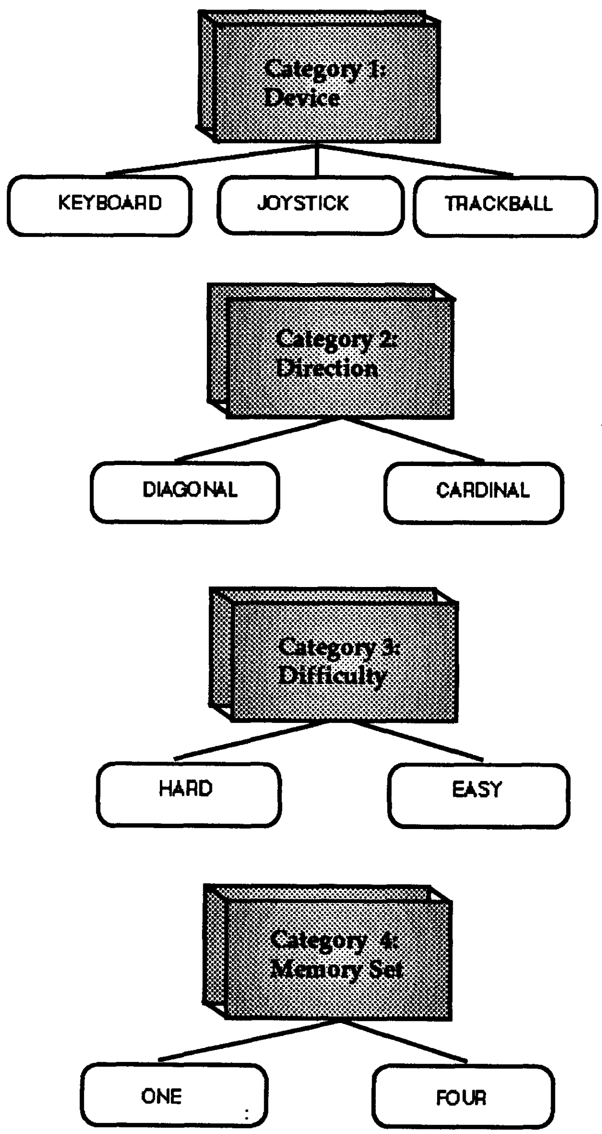


Figure 3.12 The four categories of MWPE experimental variables.

4.1 Statistical Analysis Preview

The two objective MWPE time measurements, reaction time and movement time, were analyzed as well as subjective ratings for workload. MWPE database containing these performance and workload measurements is comprised of data from eight subjects; four male (Subjects 1-4) and four female (Subjects 5-8) all of whom are graduate students at MIT. The entire database and individual subjects data is reviewed in this chapter. (See Reference 1, Appendices A, B, & C for the detailed statistical analysis.)

The SAS software system for data analysis was used for the statistics and data reduction performed on the database. Analysis of variance (ANOVA) calculations were the first statistics performed on the experimental parameters. The statistical significance of interaction and independence of variables was sought. Throughout this chapter, results which are stated as having 'statistical significance' or 'significance' correspond to data with F ratios of $p<0.05$ and often exhibit $p<0.001$. (See Reference 1, Appendices A-D for detailed statistical parameters.) Student-Newman-Keuls (SNK) tests were performed on the data to delineate the statistical parameters within the four categories of MWPE variables. After the ANOVA, regression analysis was performed and regression coefficients were analyzed for the data. Finally, the data was compared to theoretical values.

4.2 The Effect of Upright vs. Supine

The effects of the two experimental postural positions, upright orientation and supine orientation, are statistically significant when the entire database is averaged over all other conditions analyzed. (See Reference 1, Appendix A.) The average reaction times, RT, in the upright and supine orientations are 643 milliseconds (ms) and 663 ms, respectively. Average movement times, MT, of 1106 ms in the upright position and 1154 ms in the supine position were recorded. The subjects reported a slight increase in workload for the supine orientation as compared to the upright orientation, but the difference between the subjective ratings for the two postural orientations lacks significance. Figure 4.1 displays the database reaction time and movement time measurements for the two postural orientations.

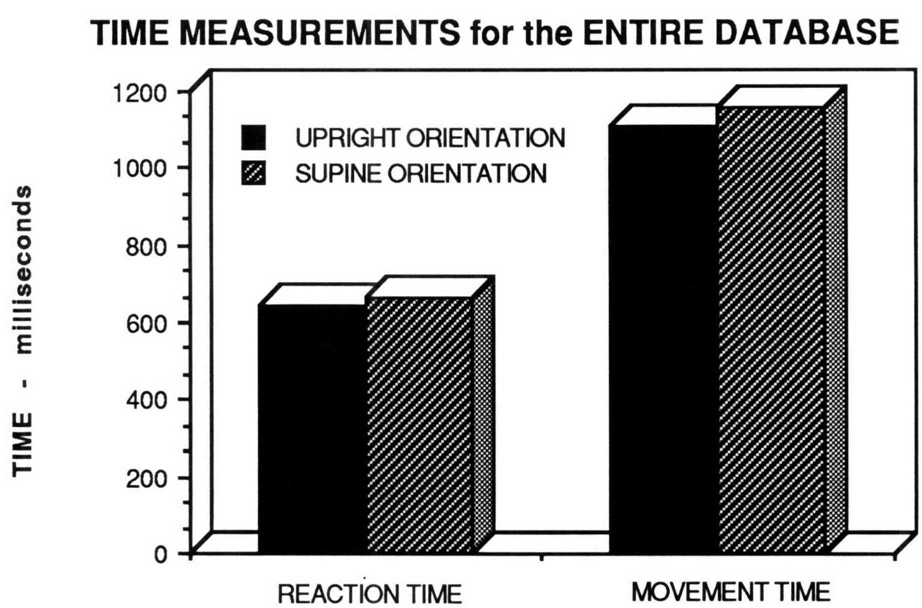


Figure 4.1 Reaction time and movement time for the upright and supine orientations.

A closer investigation of the data reveals a lack of statistical significance between postural orientations for roughly half of the subjects. For reaction time and movement time measurements, the data from three out of eight subjects yields a statistical significance between the upright and supine conditions. During the reaction time phase, the difference between the upright and supine orientations is significant for Subjects 3, 5, and 6. Subjects 3, 4, and 8 have statistically significant movement times when the two postural orientations are compared. (See Table 4.1)

Even though the upright and supine results lack unanimous statistical significance, the trends exhibited in the data are revealing. As expected, better performance (faster times) was measured in the upright position than the supine position. Figures 4.2 through 4.9 illustrate individual subject's upright and supine data in terms of reaction time and movement time for the three computer devices. The first three experimental sessions represent the upright orientation and sessions four through six account for the supine sessions.

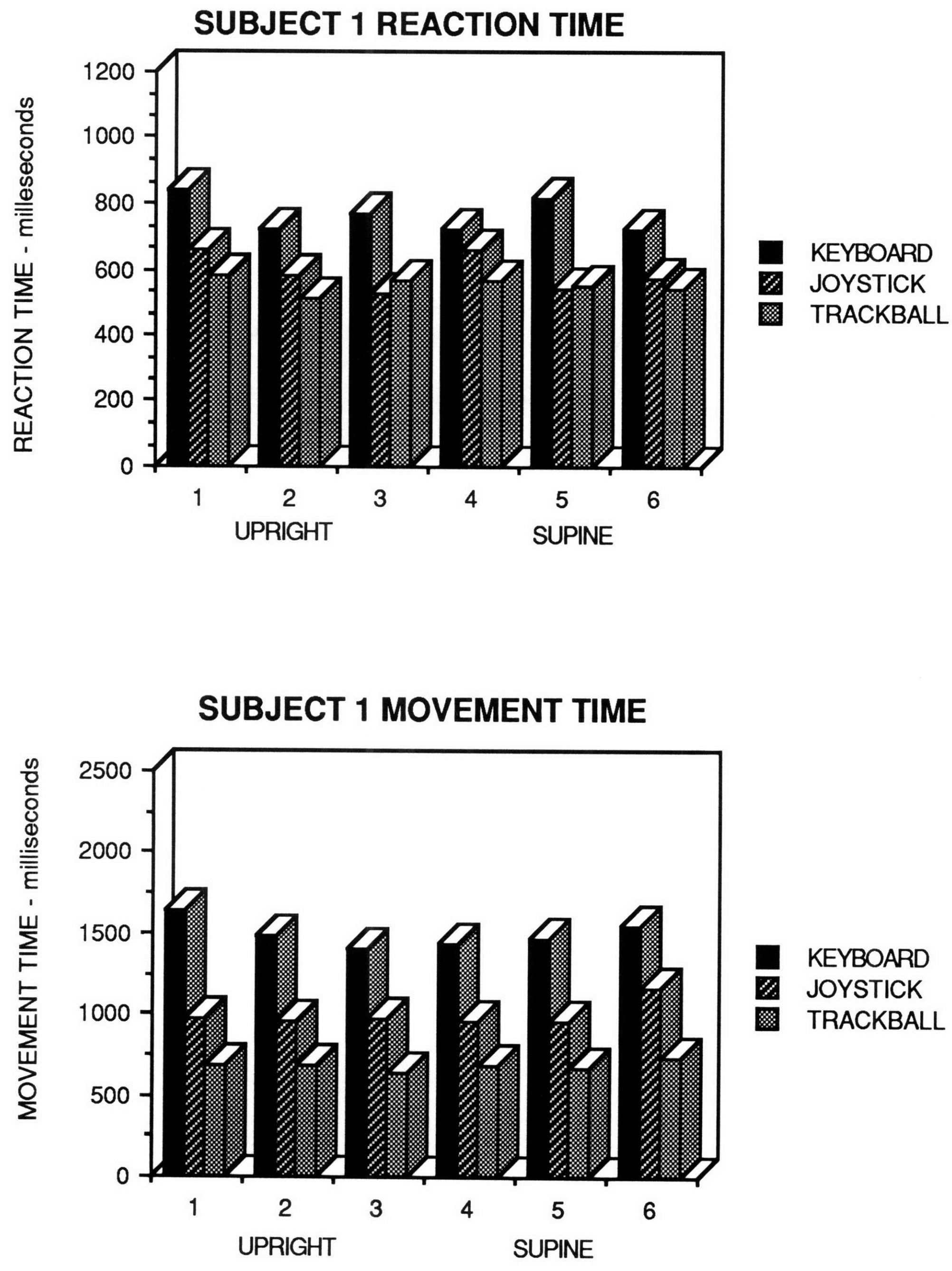
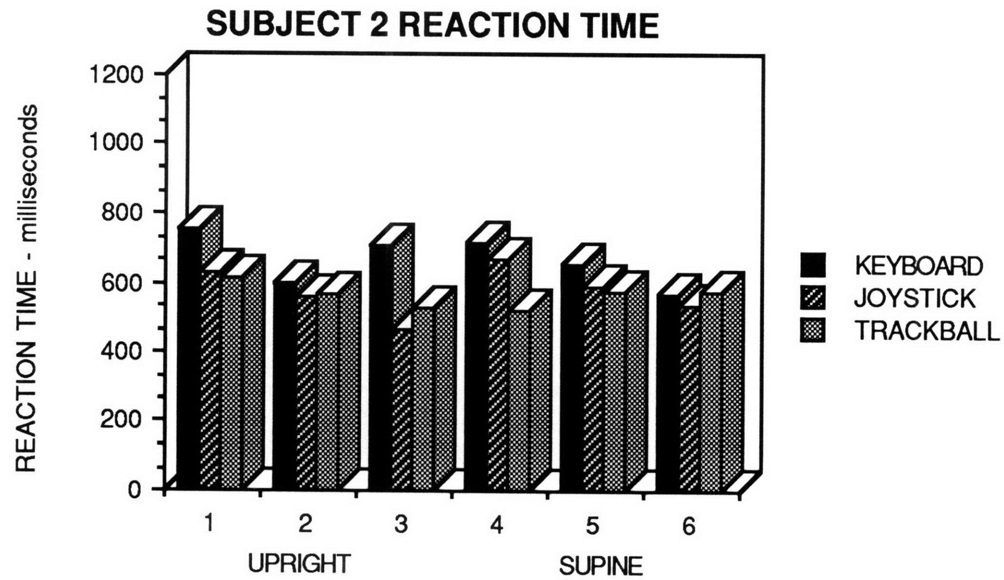


Figure 4.2 Subject 1 - Time measurements according to postural orientation.



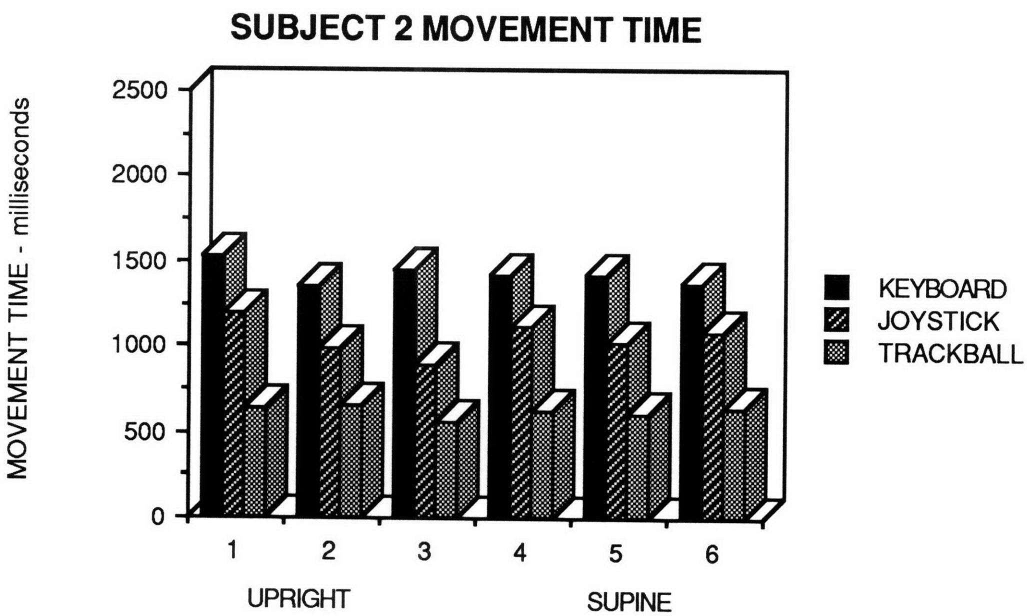
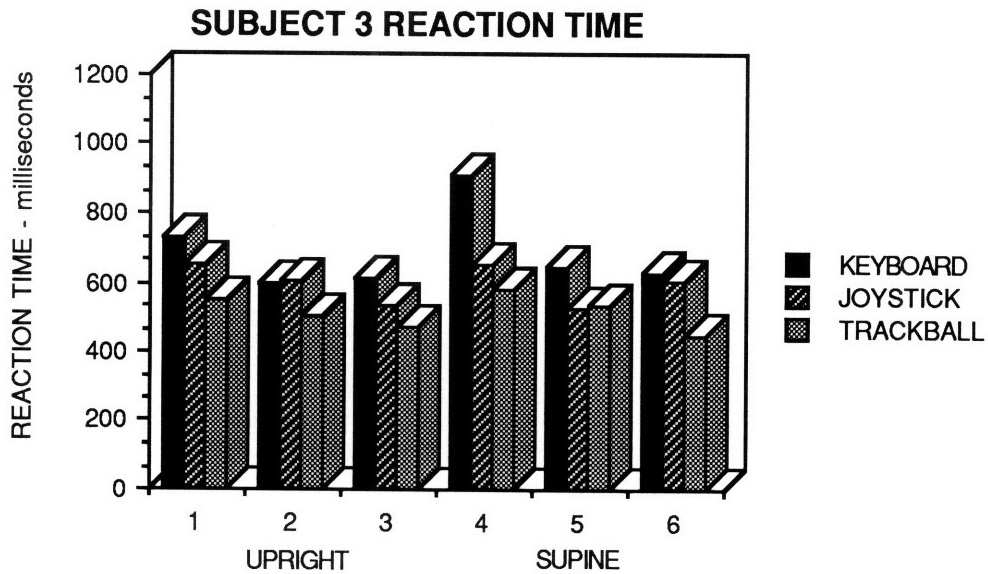


Figure 4.3 Subject 2 - Time measurements according to postural orientation.



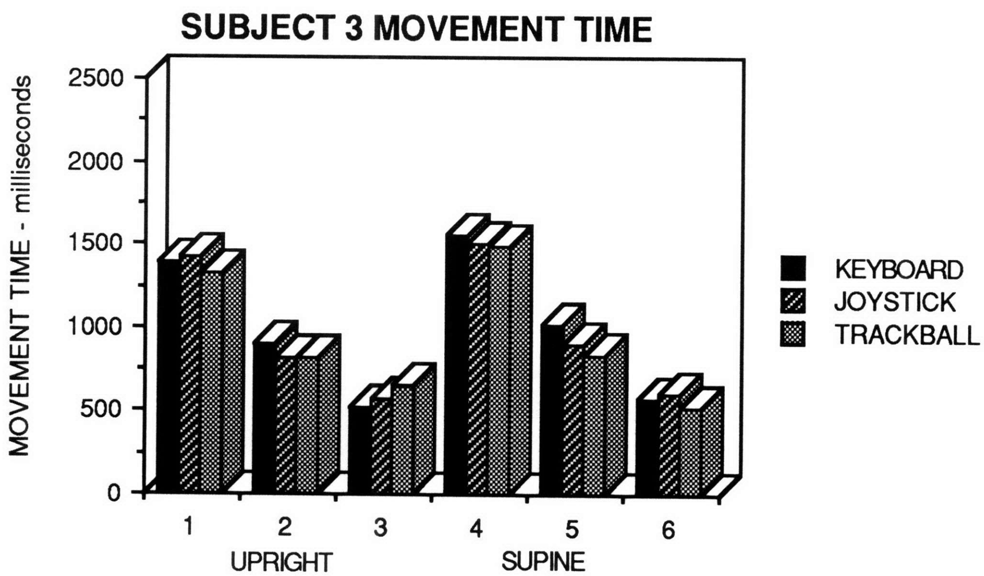
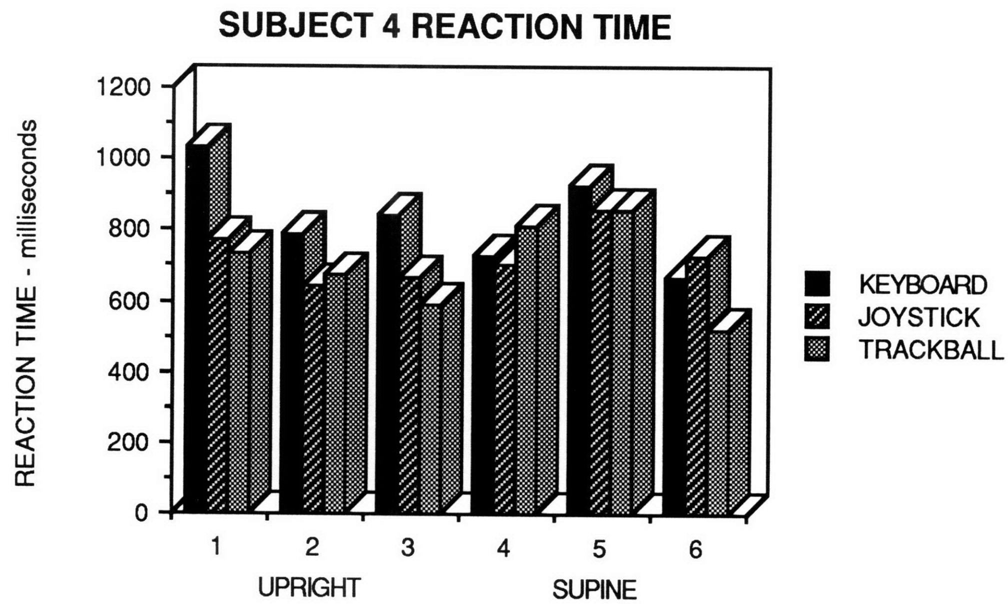


Figure 4.4 Subject 3 - Time measurements according to postural orientation.



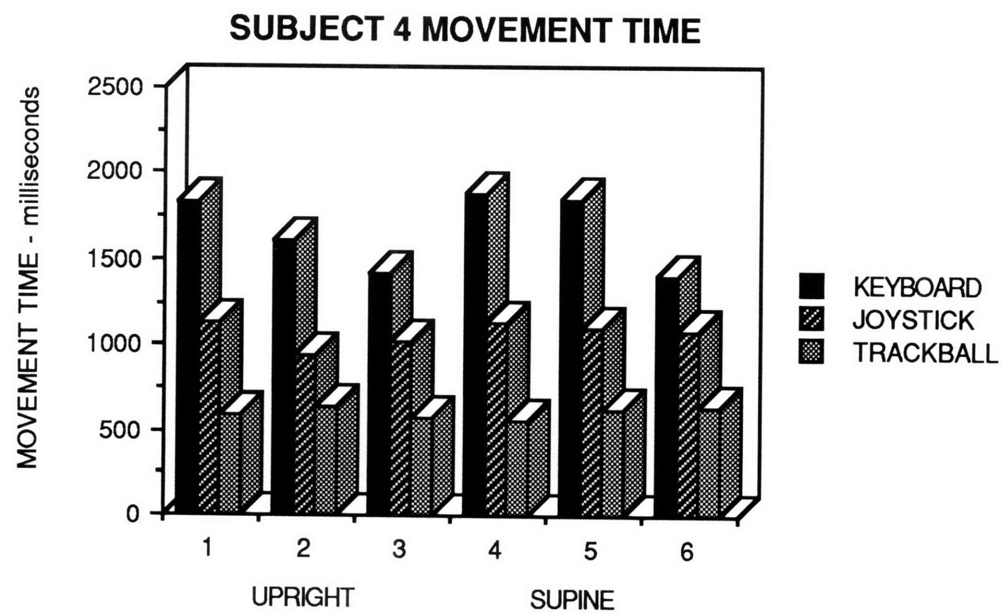
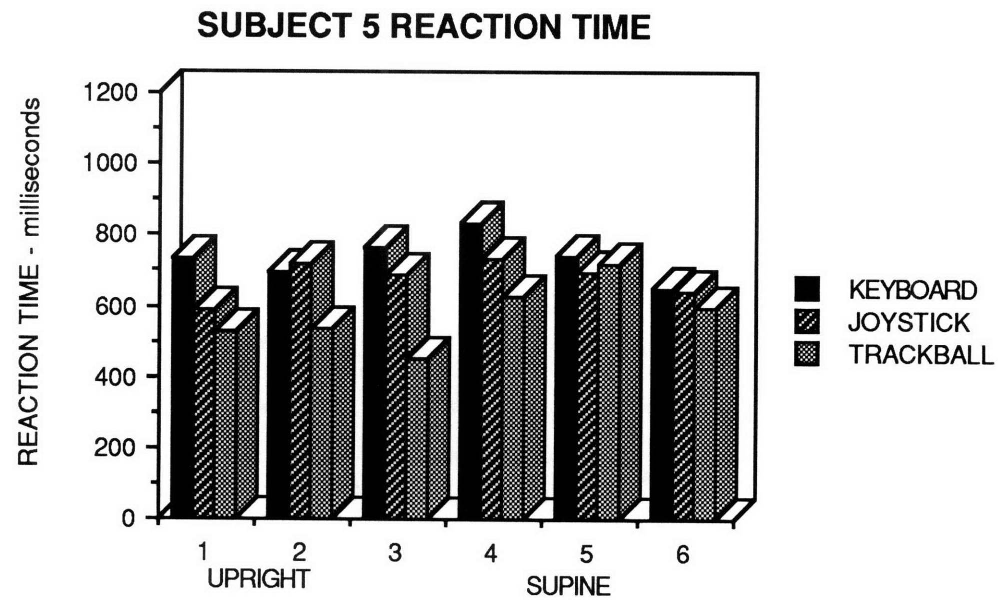


Figure 4.5 Subject 4 - Time measurements according to postural orientation.



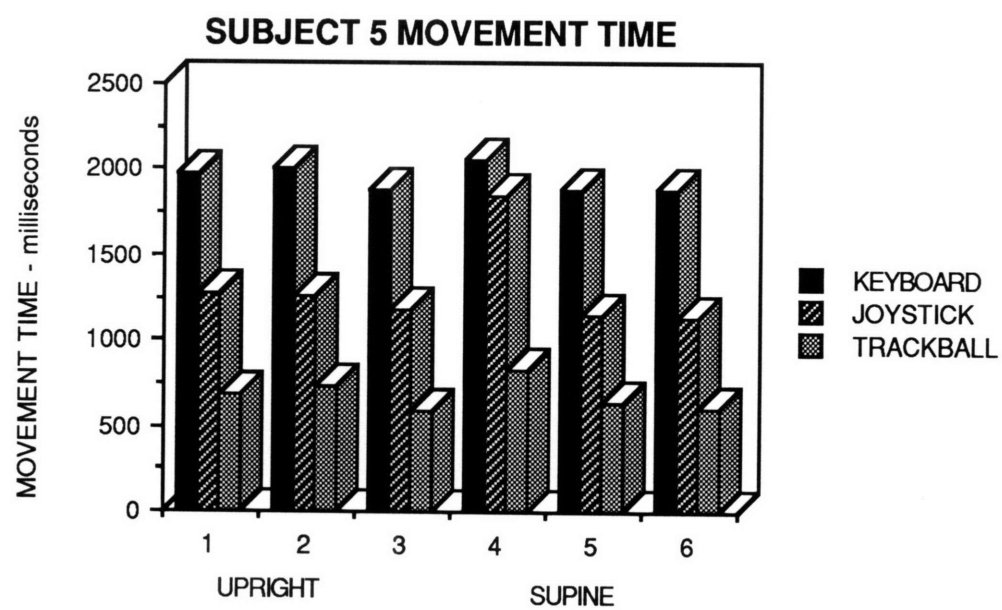
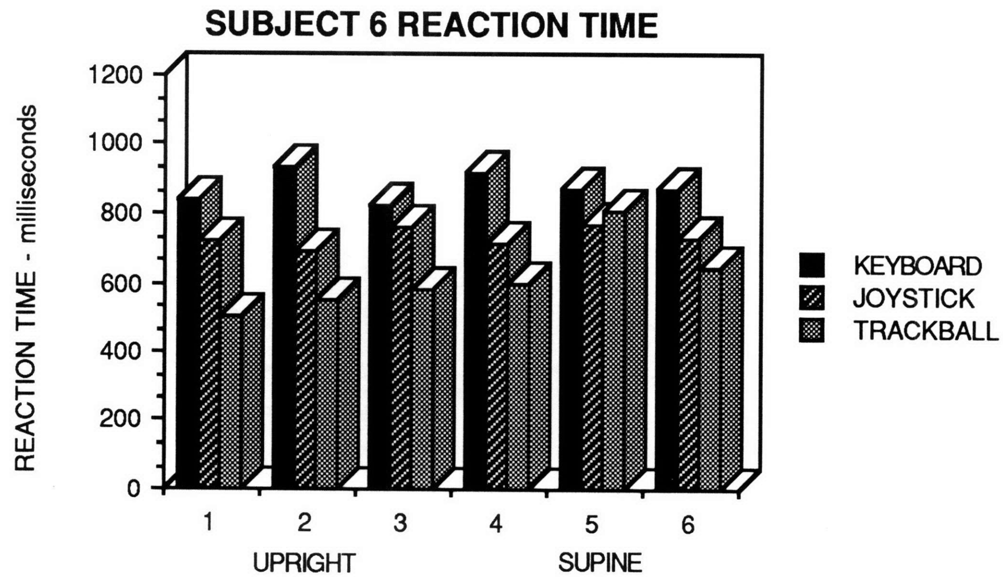


Figure 4.6 Subject 5 - Time measurements according to postural orientation.



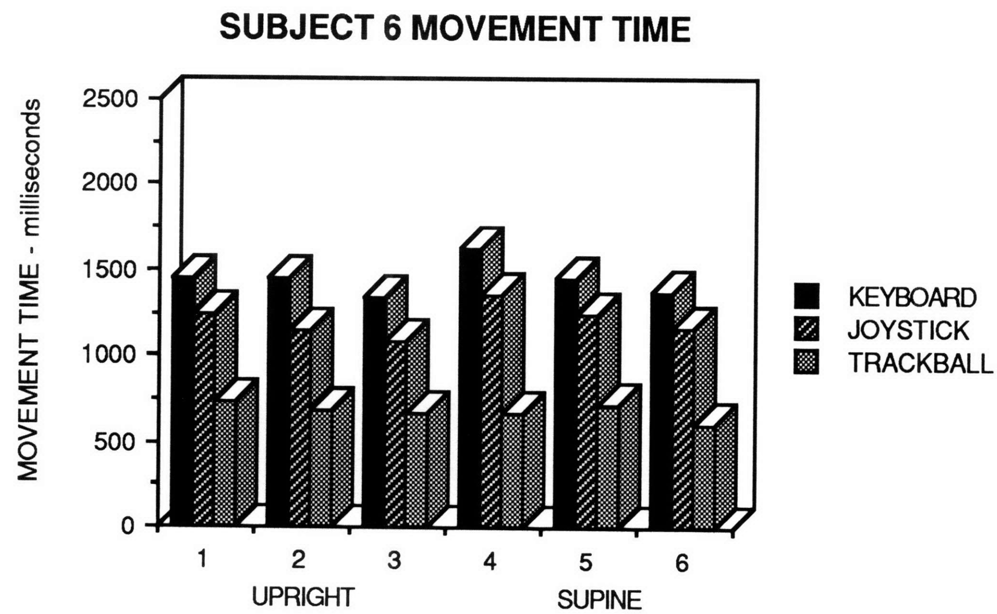
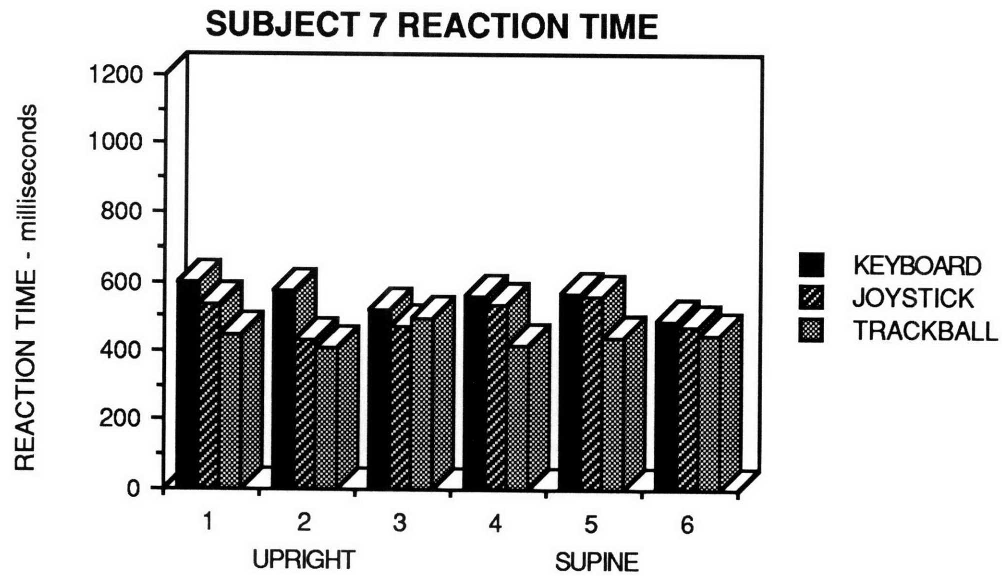


Figure 4.7 Subject 6 - Time measurements according to postural orientation.



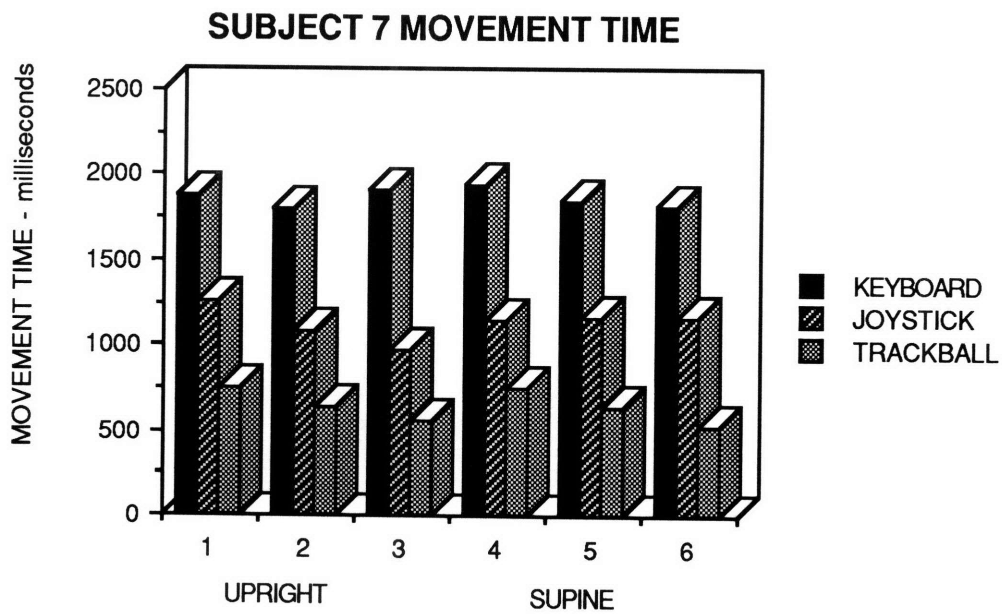
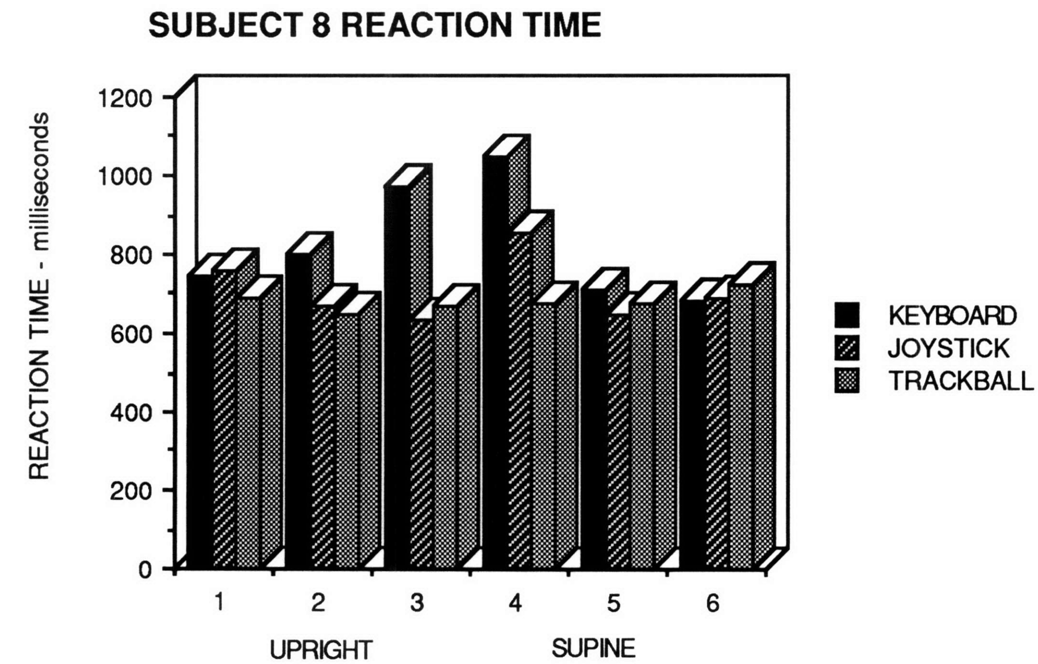


Figure 4.8 Subject 7 - Time measurements according to postural orientation.



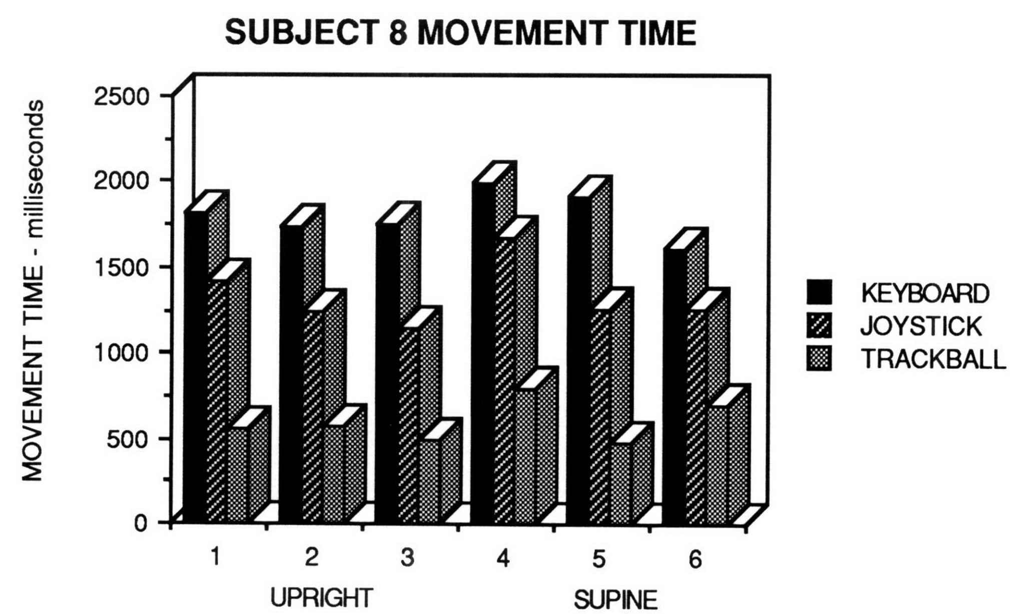


Figure 4.9 Subject 8 - Time measurements according to postural orientation.

4.3 Investigation of MWPE Variables

The four categories of experimental variables:

1. Computer input device.
2. Direction of target alignment and cursor movement.
3. Index of difficulty of target acquisition.
4. Size of the memory set.

govern MWPE *Fittsberg* target identification and acquisition tasks. These variables will be analyzed in terms of their effects on reaction time, movement time, and subjective workload. For convenience an explanation of the nomenclature used for the variables in the Appendices of Reference 1 is given below:

UPSUP: The parameter used to signify the postural orientation.
Upright -0 (i.e. The Upright Orientation is coded with a 0.)
Supine -1 (i.e. The Supine Orientation is coded with a 1.)

DEVICE: The computer input device; the first level of variables.
Keyboard Arrows -0
Joystick -1
Trackball -2

DIR: The direction of target alignment and movement.
Diagonal -0
Cardinal -1

DIF: The index of difficulty of the target acquisition.
Easy -0
Hard -1

MEM: The size of the memory set.
One Letter -0
Four Letters -1

A comparison of the devices yields that the trackball produced the best performance and least amount of workload for MWPE experimental trials. The hypothesis of reaction time depending predominantly on the size of the memory set was substantiated. As expected, movement time was dependent on the index of difficulty (including both movement amplitude and target width). However, the direction of cursor movement had a surprisingly significant effect on reaction time and movement time.

4.4 Reaction Time Results and Discussion Analysis of Variance (ANOVA)

According to Sternberg's hypothesis, the entropy of the memory set influences reaction time. In accordance with this hypothesis, the reaction times for MWPE experiments were seen to be heavily dependent on the size of the memory set in both the upright and supine orientations. The computer input device and direction of target alignment also have significant effects during the reaction time phase of MWPE. For the overall database (all subjects), index of difficulty term has no significance on reaction time. Although, data from two of the eight individual subjects yield significance for index of difficulty. Table 4.1 qualitatively represents the Student-Newman-Keuls t-test results of individual subjects for reaction time and movement time and will be referred to throughout this chapter. The Xs signify statistical significance between two parameters.

Table 4.1 SNK T-TEST RESULTS

		REACTION TIME								MOVEMENT TIME							
		SUBJECT								SUBJECT							
		1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
EXPERIMENTAL CONDITION: POSTURAL ORIENTATION	NOMENCLATURE: UPSUP																
	Upright -0			X		X	X					X	X				X
	Supine -1																
EXPERIMENTAL VARIABLES:	DEVICE																
	Keyboard -0	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	Joystick -1	X				X	X	X		X	X	X	X	X	X	X	X
	Trackball -2	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	DIRECTION																
	Diagonal -0	X	X	X	X		X		X	X	X	X	X	X	X	X	X
	Cardinal -1																
	DIFFICULTY																
	Easy -0					X			X	X	X	X	X	X	X	X	X
	Hard -1																
	MEMORY SET																
	One Letter -0	X	X	X	X	X	X	X	X	X	X		X				
	Four Letters -1																

'The Xs signify statistical significance between two parameters.
A comparison is made between two variables.
For example, the X in the Upright row and Subject 5 column signifies a statistical significance between the Upright and Supine conditions for Subject 5 during Reaction Time.
The three Xs for all of the devices under Subject 7 shows statistical significance between all three devices for Reaction Time, whereas, the two Xs for Keyboard and Trackball under Subject 2 show statistical significance between the Keyboard and Joystick (the X appears in the row of the variable that appears first) and the Trackball and Keyboard, but there is no statistical significance between the Joystick and Trackball for Subject 2 during Reaction Time.

4.4.1 Device Effects on Reaction Time

Initially the entire database was analyzed and data was categorized by the two postural orientations (See Reference 1 Appendices B for ANOVA statistics). The difference between all three devices was statistically significant for the upright and supine data. The trackball produced the fastest reaction times, followed by the joystick, and finally the keyboard as seen in Figure 4.10.

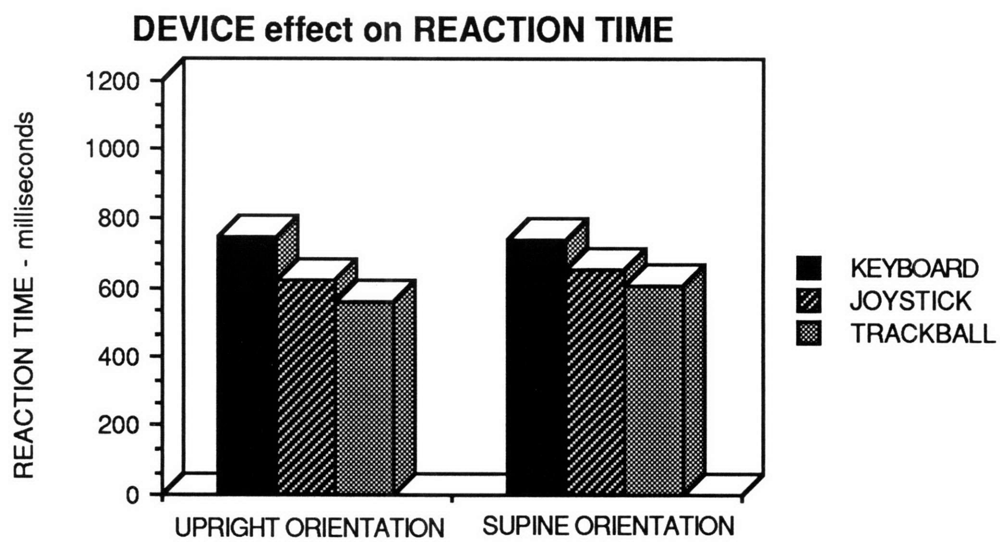


Figure 4.10 Reaction time as affected by the keyboard, joystick, and trackball.

The slowest reaction times are recorded when the keyboard is the input device. This is because the operator has to make a decision as to which letter is in the memory set and then choose the proper keyboard arrow(s) to initiate the correct cursor movement. There exists a short lag time during keyboard response since the arrow must be fully depressed to initiate cursor movement. For the joystick and trackball the subjects have their hand on the device from the onset of the memory search and can readily activate the device. Reaction time is primarily attributed to neural procession and the effect of the devices is probably due to the mechanical properties of the devices.

Results for the individual subjects offers additional information. It is interesting to note from Table 4.1 that only one of the four male subjects has statistically significant data between the joystick and the trackball, but significance occurred for three of the four female subjects between these two devices. I suggest that there exists a gender difference in operating the joystick and trackball during the reaction time phase of MWPE. The difference is probably linked to the physical size of the subjects, particularly, the subjects' hand size. A male with larger hands probably finds the trackball to fit comfortably in his palm, but the operator's large hands may make grasping the skinny joystick harder. A smaller boned female may have the advantage of operating either device equally well.

4.4.2 Direction of Target Alignment Effect on Reaction Time

The direction variables, diagonal and cardinal, exhibit significance for the database taken as a whole and for six of the eight subjects during reaction time. (See Table 4.1) The fastest reaction times were recorded when subjects were upright and the trials consisted of cardinally aligned targets. The slowest reaction times were recorded in the supine position when the targets were in a diagonal arrangement. The average reaction times associated with the cardinally aligned targets are 607 ms and 626 ms for the upright and supine positions, respectively. The reaction times for the trials consisting of diagonally aligned targets are 678 ms and 700 ms in the upright and supine orientations, respectively (See Figure 4.11).

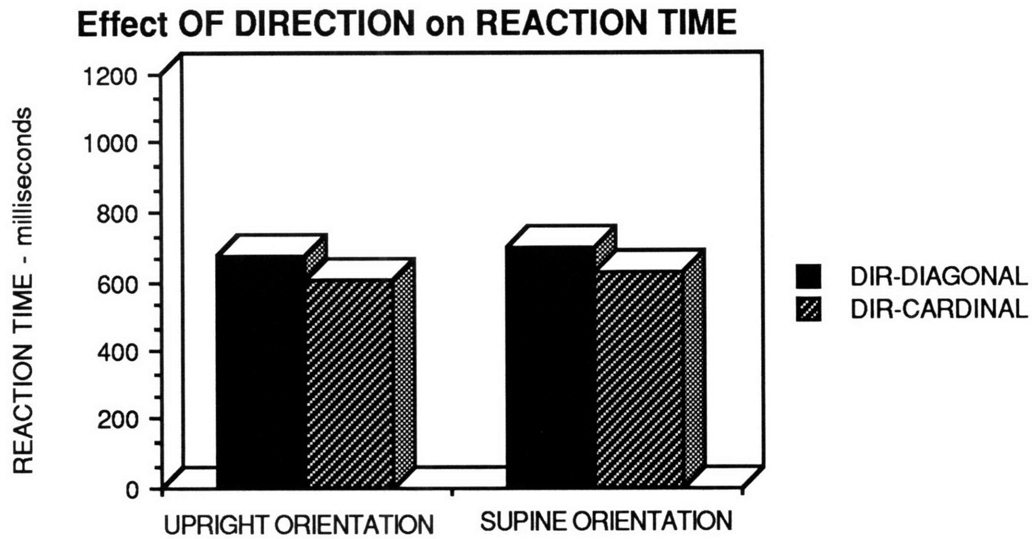


Figure 4.11 Reaction time as affected by diagonal and cardinal target alignments.

In Table 4.1 all of the data from male subjects displays significance between diagonally and cardinally aligned targets. Half (2/4) of the data from female subjects shows significance between the directions. Once again, an explanation for results differing by gender may stem from anthropometric characteristics of the subjects and mechanical properties of the devices. Females typically have more ambidextrous fingers and smaller hands than their male counterparts. Assuming the subjects use their fingers and hands to operate the devices, the lack of statistical significance between operating the devices in either the diagonal or cardinal direction for female subjects could be from this dexterity. I suggest that the significance between the direction of target alignment can be attributed to physical and mechanical phenomena rather than a phenomenon of subjects' mental processing.

4.4.3 Index of Difficulty Does Not Affect Reaction Time

Overall, the index of difficulty does not significantly effect reaction time measurements. (See Reference 1, Appendix B for detailed statistics.) In addition, the ANOVA reveals a lack of significance for the cross terms of subjects and difficulty (SUB*DIF). This means that there are no significant preferences of subject for level of difficulty; or the concept of difficulty is uniform over the subjects. The data from Subjects 5 and 8 were the only subjects to show significance between 'easy' and 'hard' target acquisitions in Table 4.1.

The index of difficulty variables for target acquisition were denoted as 'easy' or 'hard'. Easy target acquisitions coincided with a 20 pixel target width, W, and a 60 pixel movement amplitude, A. Hard target acquisitions are defined by a width of 10 pixels and an amplitude of 100 pixels.

4.4.4 Memory Set Size Governs Reaction Time

Memory set size is the largest and most significant contributor to reaction time. The two MWPE memory sets, one letter and four letters, dramatically effect the memory search task which is measured by reaction time. Average reaction times in the upright position of 505 ms and 780 ms were recorded for a one-letter memory set and a four-letter memory set, respectively. For the same memory set conditions, the reaction times in the supine orientation were 527 ms and 798 ms. Both orientations yield statistical significance for size of the memory set (response entropy). Figure 4.12 graphically depicts these results. Data for individual subjects parallel the overall database results. The difference between a one-letter memory set and a four-letter memory set is statistically significant in all eight subjects.

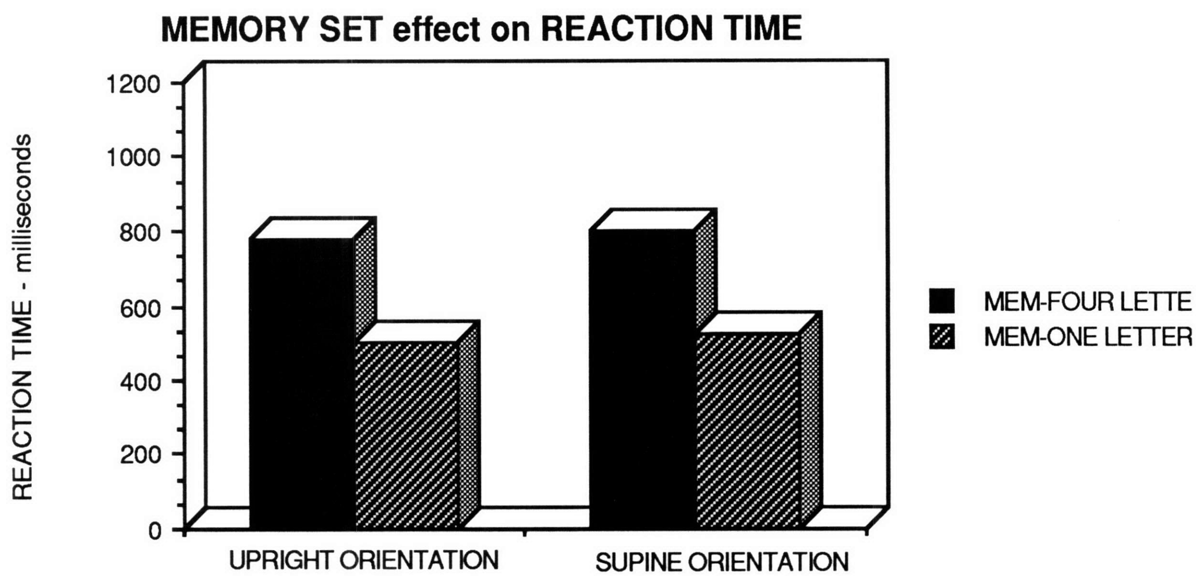


Figure 4.12 Reaction time is governed by the memory set variable.

4.5 Movement Time Results and Discussion Analysis of Variance (ANOVA)

Movement time, MT, for MWPE is the time it takes to acquire a target. Fitts' Law correlates the index of task difficulty, ID, with movement time. The amplitude of movement and the width of the target define the difficulty of the task. The index of difficulty is the largest contributing variable to MT for MWPE experiments. The movement time is also significantly dependent upon input device, direction of target alignment, and memory set.

4.5.1 Device Effects on Movement Time

All three devices, the keyboard, the joystick, and the trackball have independently significant effects on movement time. As seen in Figure 4.13 the trackball yields the fastest movement times, followed by the joystick, and then the keyboard. Results for individual subjects are similar. All three devices are statistically significant for all eight subjects.

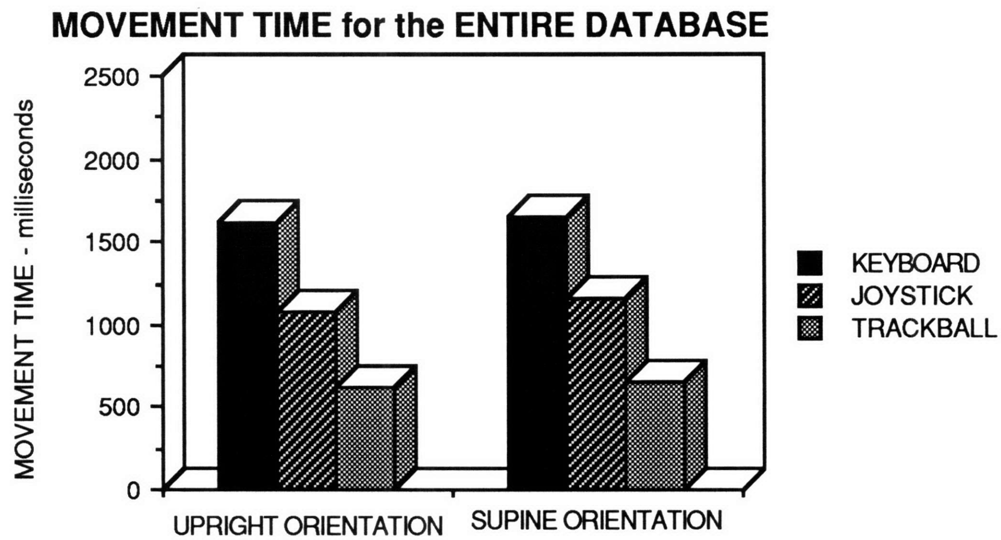


Figure 4.13 Movement time as affected by the keyboard, joystick, and trackball.

The fastest device is the trackball and hence would be endorsed for computer target acquisition tasks. The rolling ball arrangement of the trackball is easy to operate. The joystick is a velocity sensitive device in that the amount of 'stick' movement causes the cursor to move at a proportional speed to stick deflection. Very high velocities can be reached with the joystick, but extreme velocity is not required for MWPE target acquisitions since the movement amplitudes are relatively small. When using the joystick, the speeding cursor is hard to control and often overshoots the target. The keyboard arrows move at a constant velocity which is relatively slow compared to the other devices, thus, an inherent disadvantage exists for the keyboard.

4.5.2 The Effect of Direction on Movement Time

The difference between the diagonal and cardinal target patterns during the movement time phase of MWPE is statistically significant for all subjects. The MTs for cardinal targets are faster than for diagonal targets. Movement times of 1291 ms and 920 ms were recorded for diagonal and cardinal target patterns in the upright position, respectively. Increased MTs were recorded for the supine position, namely, 1360 ms and 949 ms. See Figure 4.14 for a graphic display of the results and Reference 1, Appendix B for the ANOVA statistics.

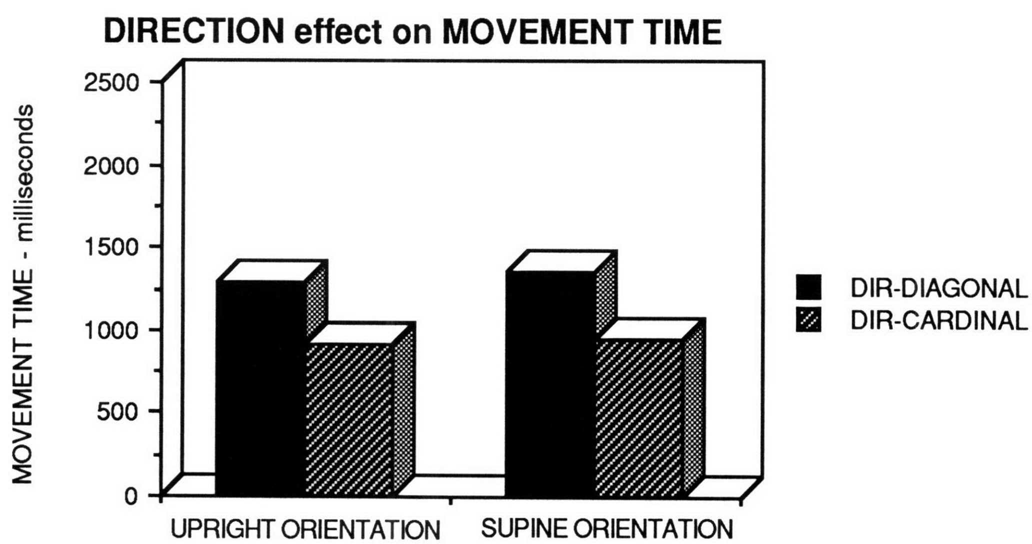


Figure 4.14 Movement time as affected by diagonal and cardinal target alignments.

Both diagonal and cardinal cursor movements are exemplary of computer tasks. Cardinal tasks (up, down, left, and right) use to be the primary movements, but with the advent and increasing popularity of mouse-type and trackball devices, movements in all 360 degrees are becoming more common.

The direction of target alignment has a great effect on MT and must be accounted for in the models of MT. Hence, target width and movement amplitude are not the only contributors to movement time. The magnitudes and percent contribution of all experimental variables are further detailed in the regression analysis section.

4.5.3 Effect of Index of Difficulty on Movement Time

The index of difficulty is the largest and most significant contributor to MT. This is in accordance with Fitts' Law and follows from the hypothesis in Chapter Two. Average movement times for easy and hard indices of difficulty are seen in Figure 4.15. There is almost a 600 ms difference between easy and hard target acquisitions. Hard target acquisitions are on the order of 1400 ms while it takes an average of 820 ms to acquire an easy target. (See Reference 1, Appendix B for ANOVA statistics on index of difficulty variables.)

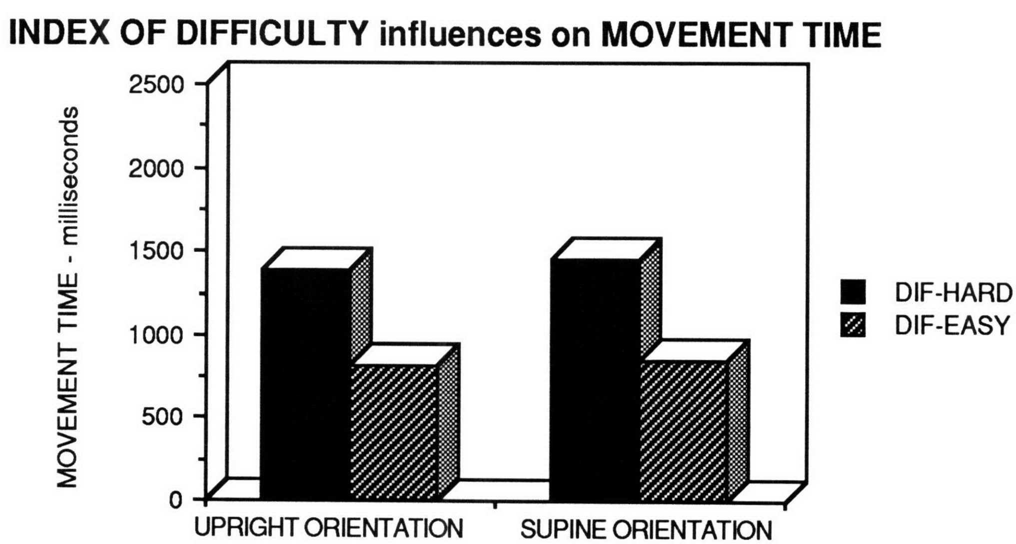


Figure 4.15 Index of difficulty influences MT measurements.

4.5.4 Memory Set Influence on Movement Time

The size of the memory set has a slight effect on MT. For the upright orientation the memory variables are statistically significant. The size of the memory set is not statistically significant for the supine orientation. Table 4.1 shows significance in three of the eight individual subjects' data for the memory set variable. All three subjects are males which alludes to the possibility that there may exist a correlation with gender; but this is speculation. MTs are clearly a function of the device mechanics and parameters of motor control during movement. The neural processing associated with the memorization of letters does not intuitively tie in with the construct of movement time, thus, a lack of significance is expected.

Do the Sternberg and Fitts models predict the RT and MT of MWPE? The next section compares MWPE data to the theoretical models and then regression analysis is investigated. The regression analysis reveals the interaction and magnitude of experimental variables.

4.6 Comparison of MWPE data with Classical Models

4.6.1 Reaction Time Implications

The Hick-Hyman Law relates RT to the size of the memory set, response entropy. Recall Equation 2.3:

$$RT = a + b \log_2(n) \qquad (2.3)$$

where 'n' is the number of letters in the memory set. Sternberg's experiments yielded a rate of increase of 38 ms for each additional bit of information to be processed and an overhead of 400 ms. Recall Sternberg's Equation :

$$RT = 400 + 38\log_2(n) \qquad (2.4)$$

The response entropy, H (or $\log_2(n)$), defines the information processing requirements for a memory search and is measured in bits. A memory set of one letter requires less than 1 bit and a four-letter memory set requires 2 bits of information. Figure 4.16 was obtained by varying only the size of the memory set, and keeping the other variables constant which is the method proposed by the Hick-Hyman and Sternberg Equations. Linearity is assumed because there are two points which define the lines. Variance in MWPE results and Sternberg's classical model exists.

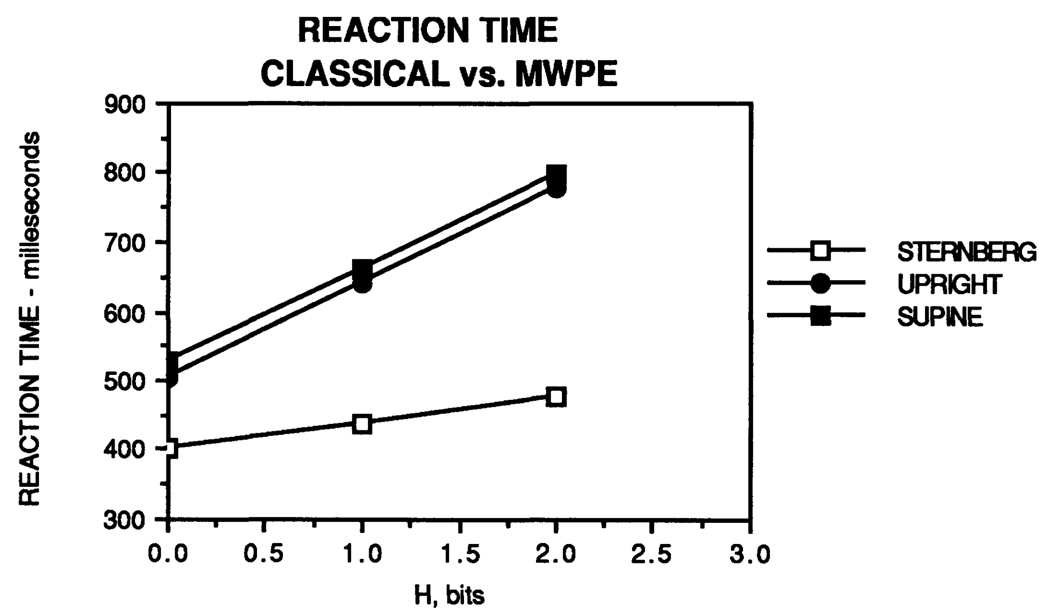


Figure 4.16 Reaction time comparisons - Sternberg vs. MWPE.

4.6.2 Movement Time Implications

An attempt to fit MWPE movement time data to Fitts' model is displayed in Figure 4.17. Recall Fitts' Law:

$$MT = c + d\ ID \qquad (2.6)$$

where Index of Difficulty, ID, is defined by Equation 2.5:

$$ID = \log_2\left(\frac{2A}{W}\right) \qquad (2.5)$$

The amplitude, A, and width, W, for easy targets are 60 pixels and 20 pixels, respectively. The amplitude and width for hard targets are 100 pixels and 10 pixels, respectively. The IDs for MWPE are 2.6 bits for 'easy' targets and 4.3 bits for 'hard' targets. MWPE data is fit to a linear line in Figure 4.17. From the analysis of variance it is known that ID is not the only contributor to movement time and, thus, this figure should be looked at skeptically.

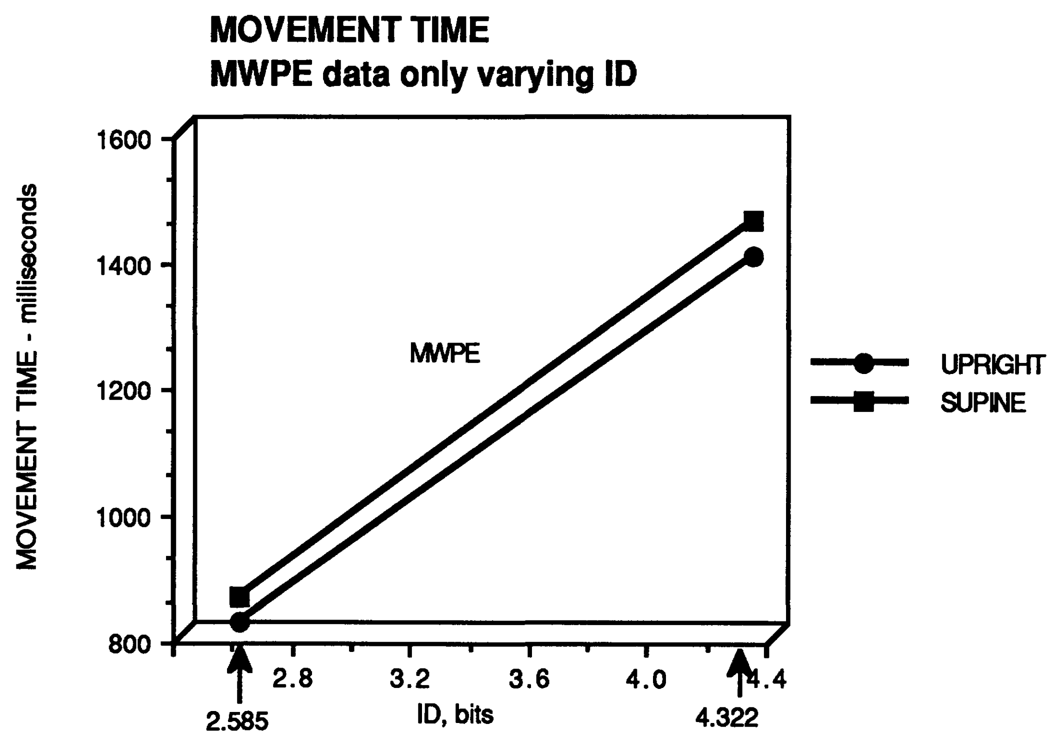


Figure 4.17 Movement time model for MWPE data varying only difficulty variable.

4.7 Regression Analysis - Interaction between Reaction Time and Movement Time

Regression analysis helps to clarify and substantiate claims made for MWPE database. The purpose of regression analysis is to identify the intercept and regression coefficients for a particular dependent variable. The data was fit with a linear multiple regression line model of the following form:

$$y = \alpha + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k + e \qquad (4.1)$$

The dependent variables of reaction time, RT, and movement time, MT, coincide with the 'y' term in Equation 4.1. An intercept (INTERCEPT)* term is represented by alpha, a. The beta terms (b_1, b_2, ... b_k) are the regression coefficients. The independent variables of postural orientation (UPSUP-upright/supine orientation)*, direction of target alignment (DIR)*, index of difficulty (DIF)*, and memory set (MEM)* coincide with the x_1, x_2, x_3, and x_4 terms. There is an additional error term, e.

* - Signifies the nomenclature used in the Appendices to define the experimental variables.
** - Regression coefficients that appear as negative numbers in Equations and in Appendices are a result of one binary variable having a greater effect than the other binary variable for the same parameter. For example, the *-73 DIR* in Equation 4.2 indicates that cardinal target arrangements produce faster reaction times than diagonal target arrangements because the binary coding for direction of target alignments is 0-for diagonal and 1-for cardinal.

The regression analysis for the baseline data (8 subjects) yields the contributions of each MWPE variable to RT and MT:

$$RT = \{532 + 20UPSUP - 73DIR + 21DIF\} + 136 \log_2(n) \qquad (4.2)^{**}$$

{ coincides with *'a'* }

$$MT = \{983 + 48UPSUP - 391DIR + 49MEM\} + 350 \log_2(2A/W) \qquad (4.3)^{**}$$

The error term for the RT regression analysis is ±7 ms and ±14 ms for the MT equation. The numeric regression analysis is detailed in Reference 1, Appendix D. All of the variables in Equation 4.2 are statistically significant, therefore, it appears that reaction time is affected by postural orientation, direction of target movement, index of difficulty for target acquisition, and the memory set size. There are two essential questions to ask about the data.

1. What do the results for independent subjects look like?

2. What is the magnitude of the effects of each coefficient?

Averaging over the entire database tends to mask the data. after a detailed regression analysis for each individual subject the results seem to be more concise. The postural orientation variable, UPSUP, was a statistically significant contributor to the regression line model in three of the eight subjects for reaction time and movement time. This was previously mentioned in the ANOVA discussion.

A closer look at the direction variable, DIR, shows that for six of the eight subjects significance is substantiated for reaction time, and the direction variable shows significance in all eight subjects for movement time measurements.

The difficulty variable, DIF, is a significant parameter in only two of the eight subjects during reaction time measurements. In the movement time measurements, all subjects reveal a significant difficulty regression coefficient.

The memory variable, MEM, is always significant for reaction times, but significant in only three of the eight subjects during movement time measurements. The magnitude of the coefficients of the individual subjects' regression model follow:

$$RT = 489.8 - \mathit{1.0}\ \mathbf{UPSUP} - 61.4\ DIR + \mathit{20.0}\ \mathbf{DIF} + 331.7\ MEM \qquad \text{Subject 1} \tag{4.4}$$

$$RT = 497.2 - \mathit{3.5}\ \mathbf{UPSUP} - 72.9\ DIR + \mathit{7.5}\ \mathbf{DIF} + 272.2\ MEM \qquad \text{Subject 2} \tag{4.5}$$

$$RT = 497.2 - 30.67\ UPSUP - 54.0\ DIR + \mathit{2.3}\ \mathbf{DIF} + 222.9\ MEM \qquad \text{Subject 3} \tag{4.6}$$

$$RT = 674.8 + \mathit{6.0}\ \mathbf{UPSUP} - 117.3\ DIR - \mathit{12.4}\ \mathbf{DIF} + 277.9\ MEM \qquad \text{Subject 4} \tag{4.7}$$

$$RT = 467.6 + 59.4\ UPSUP - \mathit{3.7}\ \mathbf{DIR} + 52.5\ DIF + 281.6\ MEM \qquad \text{Subject 5} \tag{4.8}$$

$$RT = 621.6 + 60.0\ UPSUP - 134.0\ DIR + \mathit{18.7}\ \mathbf{DIF} + 293.0\ MEM \qquad \text{Subject 6} \tag{4.9}$$

$$RT = 414.0 - \mathit{2.1}\ \mathbf{UPSUP} - \mathit{14.5}\ \mathbf{DIR} + \mathit{17.2}\ \mathbf{DIF} + 164.6\ MEM \qquad \text{Subject 7} \tag{4.10}$$

$$RT = 590.6 + \mathit{11.9}\ \mathbf{UPSUP} - 123.8\ DIR + \mathit{63.7}\ DIF + 343.9\ MEM \qquad \text{Subject 8} \tag{4.11}$$

$$MT = 843.4 + \mathit{22.6}\ \mathbf{UPSUP} - 218.2\ DIR + 475.8\ DIF + 145.7\ MEM \qquad \text{Subject 1} \tag{4.12}$$

$$MT = 828.2 + \mathit{2.6}\ \mathbf{UPSUP} - 247.1\ DIR + 553.3\ DIF + 95.6\ MEM \qquad \text{Subject 2} \tag{4.13}$$

$$MT = 782.6 + 65.5\ UPSUP - 206.1\ DIR + 479.7\ DIF + \mathit{30.4}\ \mathbf{MEM} \qquad \text{Subject 3} \tag{4.14}$$

$$MT = 976.1 + 56.7\ UPSUP - 421.3\ DIR + 570.4\ DIF + 63.4\ MEM \qquad \text{Subject 4} \tag{4.15}$$

$$MT = 1225.6 + \mathit{53.1}\ \mathbf{UPSUP} - 622.5\ DIR + 679.0\ DIF + \mathit{56.7}\ \mathbf{MEM} \qquad \text{Subject 5} \tag{4.16}$$

$$MT = 911.8 + \mathit{47.3}\ \mathbf{UPSUP} - 327.8\ DIR + 619.2\ DIF + \mathit{57.0}\ \mathbf{MEM} \qquad \text{Subject 6} \tag{4.17}$$

$$MT = 1177.1 + \mathit{17.6}\ \mathbf{UPSUP} - 539.3\ DIR + 594.9\ DIF - \mathit{0.01}\ \mathbf{MEM} \qquad \text{Subject 7} \tag{4.18}$$

$$MT = 1117.0 + 124.4\ UPSUP - 542.5\ DIR + 724.1\ DIF - \mathit{51.9}\ \mathbf{MEM} \qquad \text{Subject 8} \tag{4.19}$$

Key: Variables which are in bold and italics are **not** statistically significant.

We see from Figure 4.16 that both the overhead and slope of MWPE results differ from the Sternberg model of Equation 2.4. The overhead component of the RT Equation 4.2 is a function of all significant experimental variables rather than a constant and the rate of increase of response entropy is larger then Sternberg's slope of 38 ms. Likewise for MT, all significant experimental parameters contribute to the intercept term. These discrepancies might suggest that the Sternberg and Fitts tasks of the "Fittsberg" dual-task paradigm should not be analyzed as two independent tasks because operators may start preparing for the target acquisition task while they are finishing their target identification task. Further experimentation is required to substantiate this claim.

4.8 Subjective Ratings of Workload

MWPE incorporates subjective rating scales for two main reasons. The first reason is to compare and contrast the subjective ratings with the objective measurements. The second reason is to account for the multidimensional mature of a person's feelings of workload while executing the specific target identification and acquisition tasks of MWPE. Subjective ratings often lack statistical significance and assigning discrete numbers to personal feeling leaves margin for error. The trends of the subjective ratings obtained from MWPE will be discussed rather than the statistical relevance of the parameters.

The supine postural orientation tends to induce slightly higher workload than the upright orientation, but significance is lacking from the data. Overall, the subjective ratings tend to agree with the objective performance measurements with the exception of two devices, namely, the keyboard and the joystick. The trackball elicited the lowest workload ratings overall. For every subject a memory set of one letter produced lower workload than a memory search with four letters. It was unanimous among the subjects that the cardinal direction of target alignment elicited lower workload ratings than the diagonal direction. Easy target acquisitions caused the subjects to feel less workload than the hard target acquisitions.

Temporal demand and effort are the two subjective rating subscales which receive the highest workload ratings. Mental demand and frustration subscales are reported to induce the least amount of workload. Physical demand and performance contribute an average amount to workload.

4.8.1 Device Effects on Subjective Workload

In the order of lowest to highest workload the computer input devices are ranked trackball, keyboard, and joystick. This trend is substantiated by averaging across all subjects regardless of orientation. However, the results differ if subjective ratings are looked at in relation the the postural orientations in which the subjects performed MWPE. The trackball induces the least workload in the upright position, but in the supine orientation, the keyboard induced the least amount of workload, followed by the trackball, and finally the joystick.

Another interesting point is that two individual subjects ranked the trackball as having the highest workload content. It may be coincidence, but the two subjects that ranked the trackball as inducing the largest amount of workload were the only two foreign students in the subject pool. My hypothesis was that these two subjects were not familiar with the trackball. After conferring with the subjects I found this hypothesis to be true and one of the subjects remarked,

"*Le trackball demande plus de concentration parce - qu'on a tendance a faire des grands mouvements et a depasser la cible . Aussi, il s'agit d'un outil qui m'est peu familier*" which means, The trackball demands greater concentration because you make a big sweeping motion and tend to overshoot the target. Also, it is an unfamiliar tool to me.

The six American subjects ranked the trackball as inducing very little workload.

Overall, the keyboard induces less workload than the joystick. Objective measures of joystick performance rank it ahead of the keyboard because faster times are attained with the joystick, but the subjective ratings suggest that this better performance is at the cost of increased workload. Figures 4.18 Figure 4.19 illustrate subjective ratings as a function of input device.

Reference 1, Appendix E contains the tables of overall subjective ratings and the individual subjects' subjective ratings.

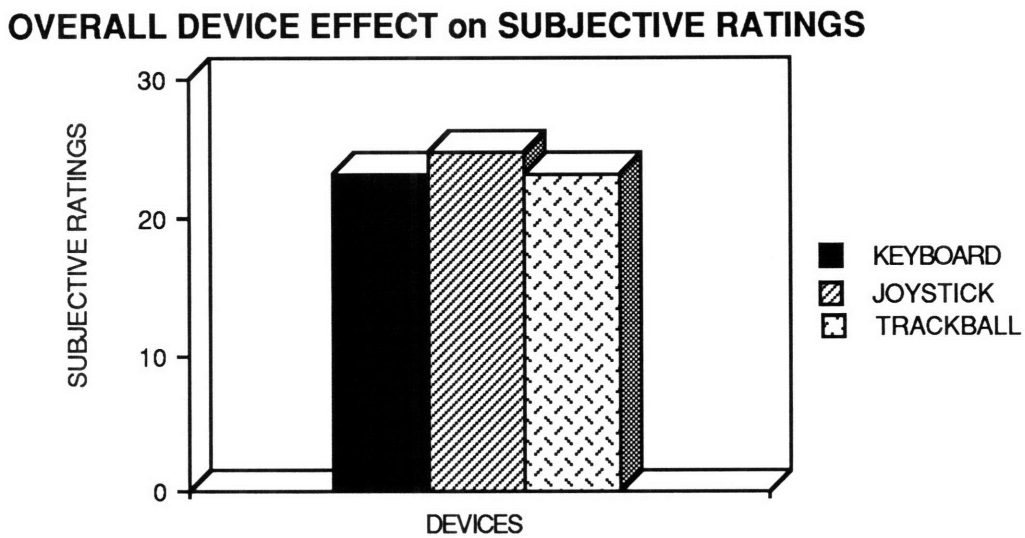


Figure 4.18 Device effect on subjective ratings.

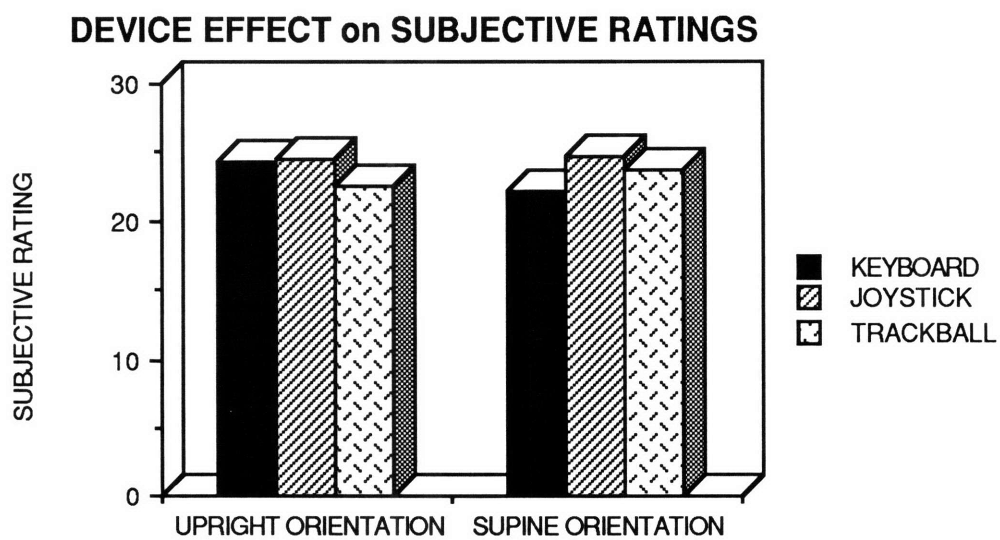


Figure 4.19 Device effects on subjective ratings according to device.

4.8.2 Direction of Target Alignment Influences Subjective Ratings

Cardinally aligned targets induce less workload than diagonally aligned targets. There is an average of a 18.5% increase seen in the subjective ratings between the two directions. Figure 4.20 illustrates this trend.

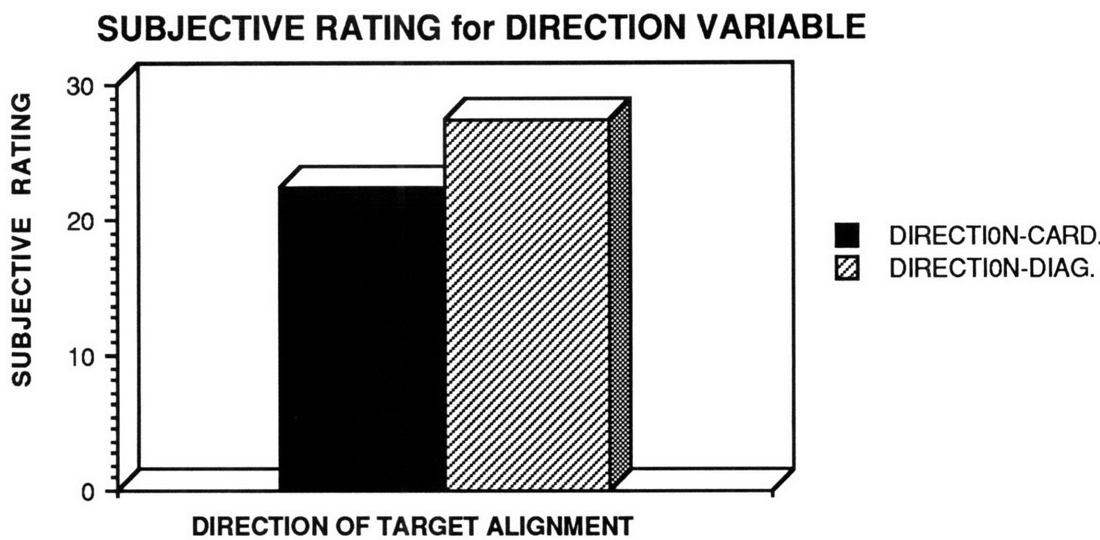


Figure 4.20 How diagonal and cardinal directions affect subjective workload ratings.

4.8.3 The Effect of Index of Difficulty on Subjective Ratings

The index of difficulty variables effect the subjective ratings to a lesser degree than the previous MWPE variables. There is an average of a 14% increase in subjective ratings of hard target acquisitions than easy target acquisitions. Figure 4.21 shows the results.

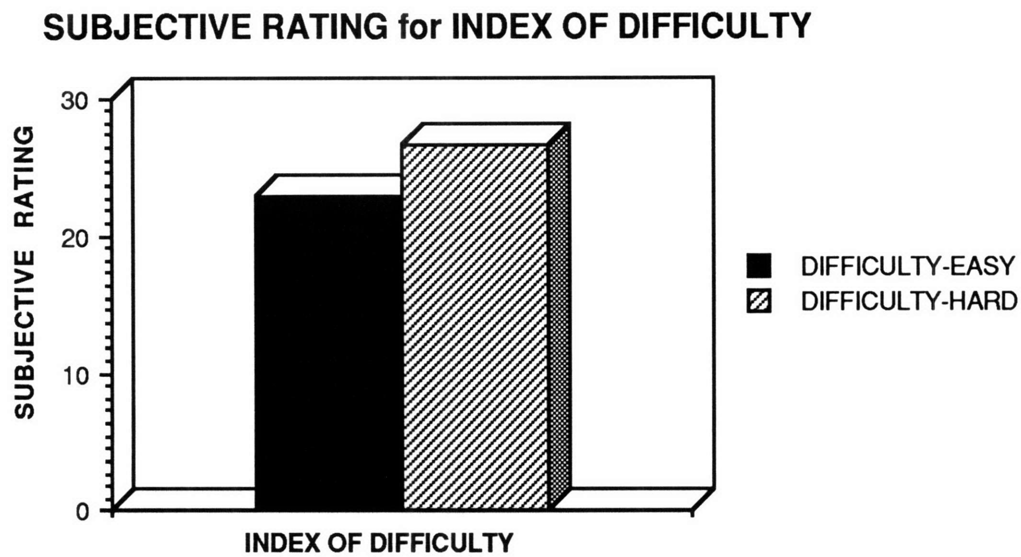


Figure 4.21 Index of difficulty influences on subjective workload.

4.8.4 The Effect of Memory Set Size on Subjective Ratings

Subjects reveal that they encounter the greatest workload for memory set with four letters rather than memory set with one letter. This makes intuitive sense and there is an average increase in workload of 27% associated with a memory set of four letters as compared with a memory set containing one letter. Figure 4.22 displays the effect of memory set on subjective ratings.

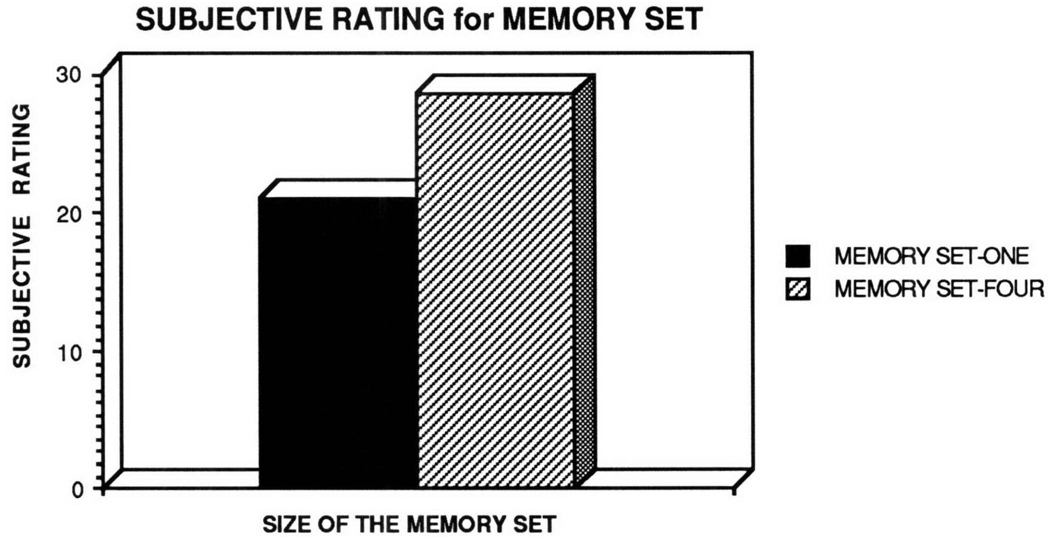


Figure 4.22 The effect of memory set size on subjective ratings.

4.9 Conclusion

The simplistic models displayed in the previous figures do not fully explain MWPE reaction time and movement time measurements. RT for MWPE is not solely dependent on the size of the memory set. The MT data for MWPE depends on index of difficulty, as well as, direction of target alignment, and to a lesser degree postural orientation, and size of the memory set.

The regression analysis models in Equations 4.2 and 4.3 show the complex interactions between variables for RT and MT for MWPE protocol. The RT equation suggests a nominal neural processing time of 532 ms for the memory search task. The experimental variables contribute varying magnitudes to the RT model. The size of the memory set contributes 71%, direction of target alignment contributes 19%, and postural orientation and index of difficulty each contribute 5% to the RT model. MT has a 988 ms intercept. Index of difficulty contributes 54% to the MT model and is closely followed by a 36%

contribution from the direction variable. Postural orientation and size of the memory set each contribute 5% to the MT model. Figure 4.23 illustrates the composition of RT and MT for MWPE data:

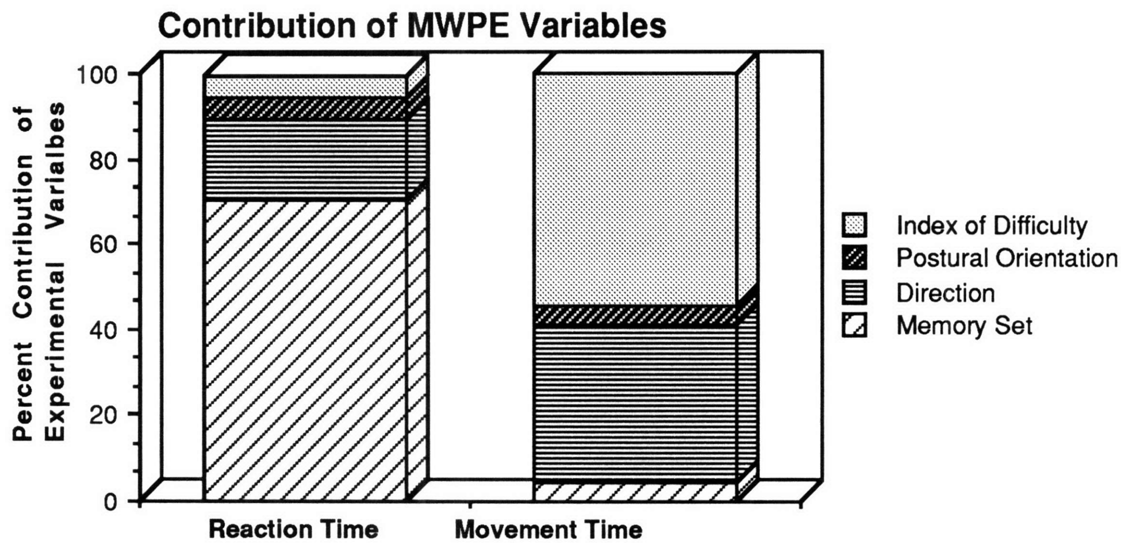


Figure 4.23 Contribution of MWPE experimental variables on performance time measurements.

Subjects report that the trackball and keyboard require similar amounts of workload and they report that the joystick induces the greatest amount of workload. Cardinally aligned targets induce less workload than diagonally aligned targets. There is an average of a 19% increase seen in the subjective ratings between the two directions. The index of difficulty variables effect the subjective ratings to a lesser degree than the previous MWPE variables. There is an average of a 14% increase in subjective ratings of hard target acquisitions than easy target acquisitions. Subjects reveal that they encounter the greatest workload for memory set with four letters rather than memory set with one letter. This makes intuitive sense and there is an average increase in workload of 27% associated with a four-letter memory set as compared with a one-letter memory set.

In conclusion, MWPE results show similar trends to the classical models for RT and MT. Yet MWPE results show interaction among many experimental variables which are not accounted for in the classical models of reaction time and movement time. RT is not solely dependent on size of the memory set; the direction of target alignment was also a substantial contributor to RT. MT is not solely a function of ID, but was also a function of the direction of target alignment. Subjective mental workload ratings tend to agree with the objective measures of RT and MT for MWPE. The only noticeable difference being the increased amount of workload for the joystick as compared to the keyboard. Although a lack of a statistical significance was noted, the supine orientation induced higher amounts of workload on the operator than the upright orientation. Temporal demand and frustration were the largest contributors to the subjective workload ratings, while mental demand and frustration contributed the least to workload. The trackball was the 'best' device for MWPE because subjects obtained the fastest target identifications and acquisitions and least amount of subjective workload with the trackball.

The important thing is not to stop questioning. Curiosity has its own reason for existing. One cannot help but be in awe when he contemplates the mysteries of eternity, of life, of the marvelous structure of reality. It is enough if one tries merely to comprehend a little of this mystery every day. Never lose a holy curiosity.

- Albert Einstein

We shall not cease from exploration
And the end of all our exploring
Will be to arrive where we started
And know the place for the first time.

- T.S. Eliot

Chapter 5 - Recommendations for MWPE Engineering Development.

It is now necessary to perform MWPE in the microgravity environment of space. In order to assess space human factors this experiment and many others must fly on the Space Shuttle and be implemented on the space station laboratory facilities in the future. What do we expect to find from MWPE microgravity experiments? Are the results going to duplicate the ground-based studies?

As suggested in Chapter Three, altered static loads of the limbs and neutral body posture of weightlessness lead to changes in performance of manual tasks in space. It is plausible that the three computer devices may operated differently in microgravity. For example, the lack of gravity on the trackball may have the effect of increasing target acquisition time or inducing additional operator workload. In the case that microgravity results are similar to ground-based tests we will have attained verification of a space experiment from the ground-based experiments, and future space experiments for human-computer interactions can use this experimental protocol information.

The ultimate goal of MWPE is to improve orbital workstation interfaces and design in order to enhance the performance and ease the workload of astronauts. The performance measurements obtained in weightlessness will provide baseline data for fine motor control tasks in space. MWPE will be executed toward the beginning and the end of the mission, thus, any improvement in performance throughout the flight may reveal adaptation effects. A careful look at microgravity workload measurements may provide insight into the operator's mental processing abilities. Also, the multidimensional aspects of workload will reveal the main contributors to workload in weightlessness. The current suggestions for MWPE could bring about improvements in experimental protocol for the Space Shuttle version of the experiment. Future recommendations could shape workstation design for the space station and possibly space bases.

The first MWPE enhancements should incorporate additional memory sets and target amplitudes and widths. Then the comparisons between the classical Sternberg and Fitts models and the multiparameter MWPE models in Equations 4.2 and 4.3 can be further substantiated. We should not expect equations to exactly model human responses and motor control, but models which yield reasonable estimates of performance are sought. My results suggest that there may be more going on then the Sternberg and Fitts' models take into account. This claim will be resolved by running additional MWPE sessions with more experimental conditions.

Further understanding of human motor control during manual tasks would be gained by recording the initial trajectories of cursor movements. Comparing the direction of the target to be acquired and the initial direction of cursor movement results in a tracking error. This error measurement could be very useful in providing investigators with movement control and data, especially for the weightless environment. Movement data for ground-based experiments abounds, but our knowledge of arm, wrist, and hand movements and adaptation in microgravity is limited. This MWPE software enhancement would lead to increased understanding of human performance and muscular control for arm movements while executing manual tasks in space.

Before the recommendations regarding graphic input devices are implemented into space workstation design, further experiments should be run in which the input devices are mechanically equivalent. Currently, there is an inherent disadvantage for the keyboard because the cursor moves at a slower rate than for the other devices. Also, additional input devices should be tested. Given the explosive popularity of mouse-type input devices, future ground-based experiments should include the use of a mouse and development of a microgravity mouse should be investigated. It may be possible to have a mouse device work in microgravity by means of a vacuum or suction mouse pad to keep the mouse attached to the working surface rather than floating away.

The final recommendation relates to the subjective ratings. Further research should be done on the applicability of subjective ratings to computer target identification and acquisition tasks. A precise measurement yielding statistical significance is sought for MWPE subjective rating system. It is important to keep in mind the laborious time constraints of flight qualifying experiment enhancements which make changing flight experiments very unlikely.

The limiting 'human factor' forces space human factors research to the forefront of the agenda. Among the goals of space human factors research are improving astronaut performance, reducing workload, increasing safety, improving efficiency, and increasing comfort. Hopefully MWPE can provide helpful information that will touch on at least one of these areas. The space station will offer investigators a unique opportunity to conduct space laboratory research. Establishing a human presence in space assumes the knowledge of human performance and workload in the microgravity environment.

The exploration of space will go ahead whether we join in it or not. We choose to go to the Moon in this decade, and do all other things, not because they are easy, but because they are hard.

- John F. Kennedy

The moon cannot be stolen.

- Paul Reps, Zen Flesh, Zen Bones

Chapter 6 - MWPE Policy Formulation.

6.1 Background on American Space Policy

Sputnik I, the world's first artificial satellite, circled the Earth in 1957 and the Space Age began. The Soviet Union shocked the world with this unsurpassed technological feat, but the technological achievement was to take second seat to the political importance of initiating the Space Age. The political and social effects of the Space Age could possibly shape humankind as never before in history. The *opening up of space* has allowed us to view our beautiful planet from the outside, rather than having an internal view. An appropriate question to ask thirty years into the Space Age might be "are there only two ends to space exploitation? Harmony or destruction? McDougall whispers warnings for future space endeavors, "for reason cannot predict whether our tools and dreams, which together permit us to *invent the future,* will lead us to perfection or annihilation or unending struggle against Nature and ourselves."

I suggest that technology serves politics in this day and age of technocracies. Research and development (R & D) were of the utmost importance during WWI and WWII. Intense R & D efforts produced the British development of radar, the American atomic bomb, the German ballistic missile, and the American electronic computer. The distrust and competition among nations of after WWII gave the Soviet Union incentive to launch a maximum effort in science and R & D. Sputnik was a technological feat, but more importantly it was a political feat in which the Soviet technocracy wished to surpass the achievements of the capitalistic states.

'WHO ELSE CAN GIVE YOU A MOON?'

October 13, 1957. Courtesy of the *Sacramento Bee.*

American space policy was first shaped under President Dwight Eisenhower and had its initial base in the missile and space program of the Department of Defense (DoD). Spy satellites and space systems were justified for reasons of national defense such as providing accurate intelligence and monitoring arms control. The second face of American space policy was open and cooperative. America portrayed an open and cooperative space program which contrasted to the closed and secretive Soviet space program. The National Aeronautics and Space Administration (NASA) was established to guide the American civilian space program, thus, dividing the space program in two. Military space and civilian space activities were envisioned as separate entities, but overlap exists in the space research and funding of military and civilian interests.

President John F. Kennedy is given credit for sending men to the moon and establishing America as the world's leading space nation. Kennedy was not always a space enthusiast, after the Sputnik launch the Senator "could not be convinced that all rockets were not a waste of money, and space navigation even worse." (McDougall, 1985) When the political climate was right, JFK committed America to putting a man on the moon. He noted that the United States

> "should commit itself to achieving the goal, before this decade is out, of landing a man on the moon and returning him safely to earth. No single space project in this period will be more impressive to mankind, or more important for the long-range exploration of space; and none will be so difficult or expensive to accomplish."

President Kennedy delegated responsibility for the space program to Vice President Lyndon B. Johnson .

"Fill 'Er Up—I'm in a Race"

Herblock, May 24, 1961. Copyright 1961 by Herblock in the *Washington Post.*

The 1960s saw a sixfold increase in federal space R & D and the *Space Age* and the *Race for the Moon* were on. Fueled by competition among nation states, rather than global cooperation, the technically proficient nations were gearing up to send humans to the moon. In America, technology was still ruled by politicians. The technological advancement of science and engineering was largely dependent upon and managed by the politicians running the federal government.

I found a remarkable summary statement about the impact of the Space Age on America in McDougall's ...the Heavens and the Earth. It is a revealing statement about American space policy and the effect that the space program has had on our nation. Defending space development after being asked the question, "Well if we can go to the moon, why don't we take that money and do some of the things that need to be done here?" President Johnson replied,

> "Until Sputnik, the Federal Government hadn't passed any education bills. We didn't have any Federal aid for education...So we started passing education bills, we made a national effort in elementary education, a national effort in higher education, where two million students were brought into our colleges. And they said, "Well, if you do that for space and send a man to the moon, why can't we do something for grandma with medicare?" And so we passed the Medicare Act, and we passed forty other measures...
>
> And I think that's the great significance the space program has had. I think it was the beginning of the revolution of the '60s."

The bleak year that hosted the Tet Offensive and the assassinations of Robert Kennedy and Martin Luther King, Jr. ended in a bright spot, Apollo 8 was in lunar orbit on Christmas Eve 1968. Neil Armstrong and Buzz Aldrin became the first men to step on another body in the solar system when Apollo 11 landed on the moon in July of 1969. The world responded by proclaiming America as the leading space faring nation.

Times were changing though, and the 1970s saw a declining American space program. Funding for the space program had been steadily reduced since the mid 1960s. The pertinent, terrestrial Vietnam War drew attention away from the Space Age and there was a relaxation of Cold War tension. In retrospect, the *panic and react* American space policy after Sputnik and during the Apollo era did grave damage to the space program. McDougall states, "It encouraged Congress and the nation to believe that the Apollo project *was* the space program." Long-term space policy has never been established in America

Three possible scenarios arose out of President Nixon's Space Task Group, 1) a manned mission to Mars by the mid-1980s, an orbiting lunar station and a fifty-man earth-orbiting station served by a reusable shuttle ($8-$10 billion per year), 2) the same scenario as the first except postponing Mars until 1986 (<$8 billion per year), and 3) developing only the space station and shuttle ($4-$5.7 billion per year) (McDougall, 1985). President Nixon chose the third scenario and postponed space station development pending shuttle development. NASA pushed hard for the Space Transportation System (STS, commonly referred to as the Space Shuttle) and got approval in 1972 after cutting the original Space Shuttle cost estimates in half.

The Space Shuttle was emerging, but no long-term goals had been set for the American space program. By the 70s, NASA spending fell to thirty-six percent of its Apollo peak in constant dollars. Europe, lead by France and Germany, was developing a strong cooperative space program. In 1972 the European Space Agency (ESA) was created. Japan, China, and India also forged full speed ahead into establishing national space programs. Under the Reagan administration the civilian minded American space policy of the

Apollo era gave way in 1981 when the DoD space budget surpassed that of NASA.

Token as it may have been, an exchange of "handshakes in space" during the Apollo-Soyuz Test Project in July of 1975 signified cooperation in space between the U.S. and the U.S.S.R. A major cooperative U.S. and European program was the building of the Spacelab by ESA for the Space Shuttle. Largely due to financial considerations, international cooperation in space seems inevitable for the future. However, I hope economic motivation is complemented by future international space cooperation which stems from moral imperatives and the desire for global unity in space as well as on Earth.

The Space Shuttle made its inaugural flight in 1981. Meanwhile, the Soviets' space station, MIR (peace), was built and is presently in orbit. That brings us to the 1980s and I have one last comment on American space policy before detailing the genesis and political pathways encountered by the Mental Workload and Performance Experiment.

In 1984, President Reagan verbalized a national commitment to an international space station proposed by NASA, but it is now 1988 and the space station's existence and future are questionable. How does this reflect American space policy and the future of our civilian space program? On Capitol Hill the Senate Appropriations Committee passed a defense bill June 24, 1988 that includes transfer of $600 million in unobligated R & D money from the DoD to NASA for *national security-related space activities.* Regarding the transfer, Space Station News reported,

> The nebulous phrase likely targets the funds for the Space Shuttle program, freeing up a like amount for the Space Station. The transfer could be critical for the Space Station's survival. The Space Station program took a whopping $767 million cut from the requested $967 million in the Senate HUD and independent agencies subcommittee - - a

> move approved June 22 by the full committee. "The huge reduction is totally unacceptable", Reagan said, but the White House reacted angrily to the move to pull money out of the DoD bill to save the station. In promising to veto the bill Reagan stated, "funding the Space Station at the expense of national security (SDI) violates the budget agreement."

Twenty years of U.S. adherence to doctrine that space is for all of humankind and for passive military weapons and off limits to active weaponry were overturned by Reagan's Strategic Defense Initiative dubbed "Star Wars." This thesis is not about Star Wars, but I felt obligated to report the shift in American space policy from a strong civilian program to a strong military program.

Given this brief background on the American space program, I will now detail the processes which shape a space experiment. I feel a case study of an experiment is an appropriate method for giving the reader a bird's eye view of the complex system which allows us to fly scientific experiments in space. MWPE will be used as a case study.

6.2 Introduction to MWPE Policy Analysis

As an engineering thesis, theories and the experimental protocol for MWPE were explained in Chapters One through Five. Beyond the engineering aspects of MWPE lie some intriguing and unreported questions and processes. Both technical and political choices shape space experiments and it would be naive to leave out either factor in this thesis presentation. Few people actually have the opportunity to work on an actual experiment that will be flown in space. I have been the primary graduate research assistant on MWPE for the past two years and I will capitalize on my fortunate opportunity and use MWPE as an example that illustrates present space policy for space experiments.

It is necessary to integrate the engineering and policy frameworks of MWPE to have a complete understanding of the environment of a space experiment. Space experiments are subject to a system which relies on both technical and political inputs. The background of the American space program was outlined in the previous section. This section introduces MWPE as an example for delineating the lifeline of a space experiment. The following section reports the details surrounding the genesis of MWPE. Chapter Seven begins with a description of the participants involved with MWPE. The next section depicts the flight schedule chronology. The numerous meetings of the investigator working groups, mock-up reviews, critical design reviews, and scientific overviews are outlined and discussed as they play a crucial role in the shaping of an experiment. Finally, recommendations for dealing with the political and technical realms of space flight experiments and specific suggestions regarding the future of MWPE are outlined in Chapter Seven.

MWPE has gone from being a conceptual design at the proposal stage to becoming a manifest hardware experiment on the International Microgravity Laboratory (IML-1) Space Shuttle mission in 1991. The experiment has already been scheduled on four Space Shuttle missions and has been delayed five years. MWPE serves as a good case study for experiment selection, manifestation, and integration. The bureaucracy and political channels MWPE has encountered provide insight into current procedures for space experiments. These procedures are important to outline in order to understand the entire process by which an experiment becomes manifest on a flight and is integrated among the other experiments.

Since policy is a plan or path to get from a current state to an improved state, the recommendations for MWPE have significance. Enhancement of the experiment and political processes can be accomplished before the IML-1 flight. Recognizing the obstacles and special pathways that policy must traverse is the first step of analysis. Coupling this analysis with a course of action to implement recommendations on flight experiment procedures, integration, and manifestation results in an improved plan.

6.3 Genesis of MWPE

The conception of MWPE can be attributed to two men, Dr. Byron Lichtenberg and Dr. Steve Bussolari. From their recollections I was able to report the genesis of MWPE. In August of 1984 Dr. Lichtenberg, an astronaut and MIT alumnus of the Man Vehicle Laboratory (MVL), called Professor Bussolari, an MVL professor who specializes in human factors work. The call was regarding some open crew time on the upcoming Space Shuttle Earth Observation Mission (EOM-1). Originally EOM-1 was scheduled to fly in April of 1985, but it had been postponed to August of 1986.

Dr. Lichtenberg was concerned with workstation design, especially since he had just flown on the Spacelab 1 mission (the ninth flight of the Space Shuttle) and reported fatiguing in his muscles while performing experiments at the multipurpose workstation in the Spacelab module*. He envisioned a new design for an adjustable workstation which would be designed for the

* Spacelab is a modular, reusable scientific research facility. Spacelab fits into the cargo bay of the Space Shuttle and provides an orbiting research center. The laboratory was developed and built by the European Space Agency (ESA) in cooperation with NASA. MSFC is responsible for NASA's Spacelab efforts. (Taken from MSFC 84-4 poster.)

weightless environment accounting for the neutral body position in microgravity. Professor Bussolari was in contact with Ms. Sandra Hart from NASA-Ames Research Center who was conducting experiments using the Fittsberg dual-task paradigm and other human factors experiments. In addition, Mr. Mark Cohen of NASA-Ames was working with Professor Bussolari and was also interested in studying anthropometrics for microgravity.

Within two weeks Dr. Lichtenberg and Professor Bussolari came up with the concept for a quick scientific experiment to be implemented on EOM-1. The Mental Workload and Performance Experiment was envisioned to be a computer experiment in which performance and workload would be assessed for Fittsberg tasks. The computer and input devices would be supported by an adjustable workstation which the astronauts would position to their height and size, therefore, workstation design and anthropometrics would also be incorporated into MWPE. Figure 6.3 shows Spacelab in the Orbiter and Figure 6.4 shows the external design features of Spacelab.

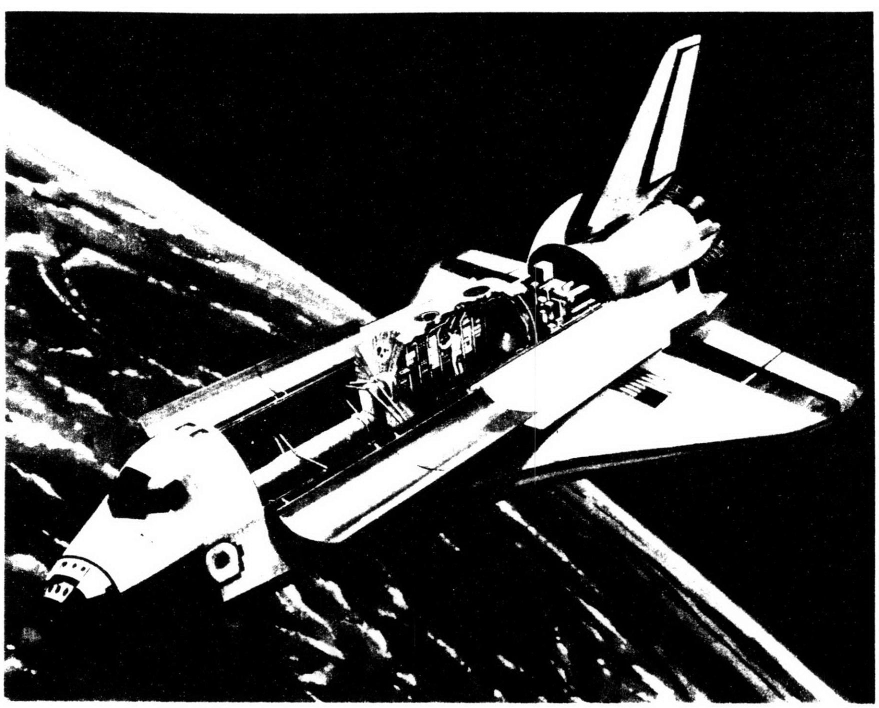


Figure 6.3 *Spacelab and other payload carriers convert the Orbiter into a research facility that can benefit a broad range of science and technology disciplines.*

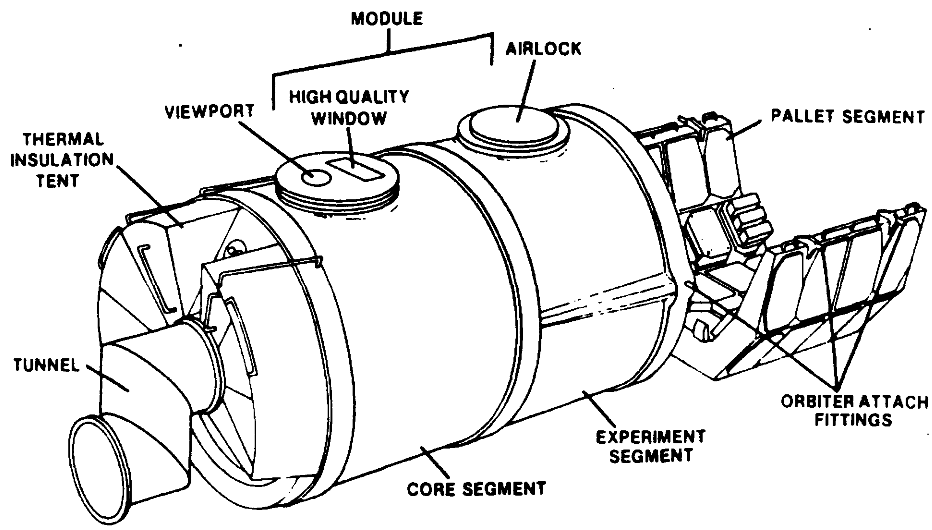


Figure 6.4 *Spacelab External Design Features*

It is important to note a few special circumstances surrounding the Mental Workload and Performance Experiment. First, MWPE had an incredibly short timeline for a flight experiment. The open crew time for EOM-1 that Dr. Lichtenberg mentioned was only 24 months away. Typically the time from a space experiment announcement of request for proposals (RFP) to space flight is ten years (See Figure 6.5). The "NASA folks were skeptical of the short timeline" (Bussolari). However, Dr. Arnold Nicogosian, the director of Life Sciences at NASA Headquarters (NASA HQ) saw the merit of MWPE, especially its application to future space station workstation design and assessment of performance and workload. NASA Headquarters was willing to allocate money to the Johnson Space Center (JSC) for MWPE.

An unsolicited proposal was drawn up by Professor Bussolari and Dr. Lichtenberg and sent to JSC. Typically there is a formal RFP sent out by a NASA Center and then principal investigators (PIs) respond by writing proposals (a solicited proposal). The process of going from RFP notices to proposal responses to the announcement of awards for space experiments usually takes two years. MWPE was slated to fly on the EOM-1 in less than two years. Obviously, standard bureaucratic procedures were going to be hurried along or bypassed if MWPE was to become a manifest experiment on EOM-1 and the scientific development of the experiment would have to be efficiently accomplished in order to meet the short timeline.

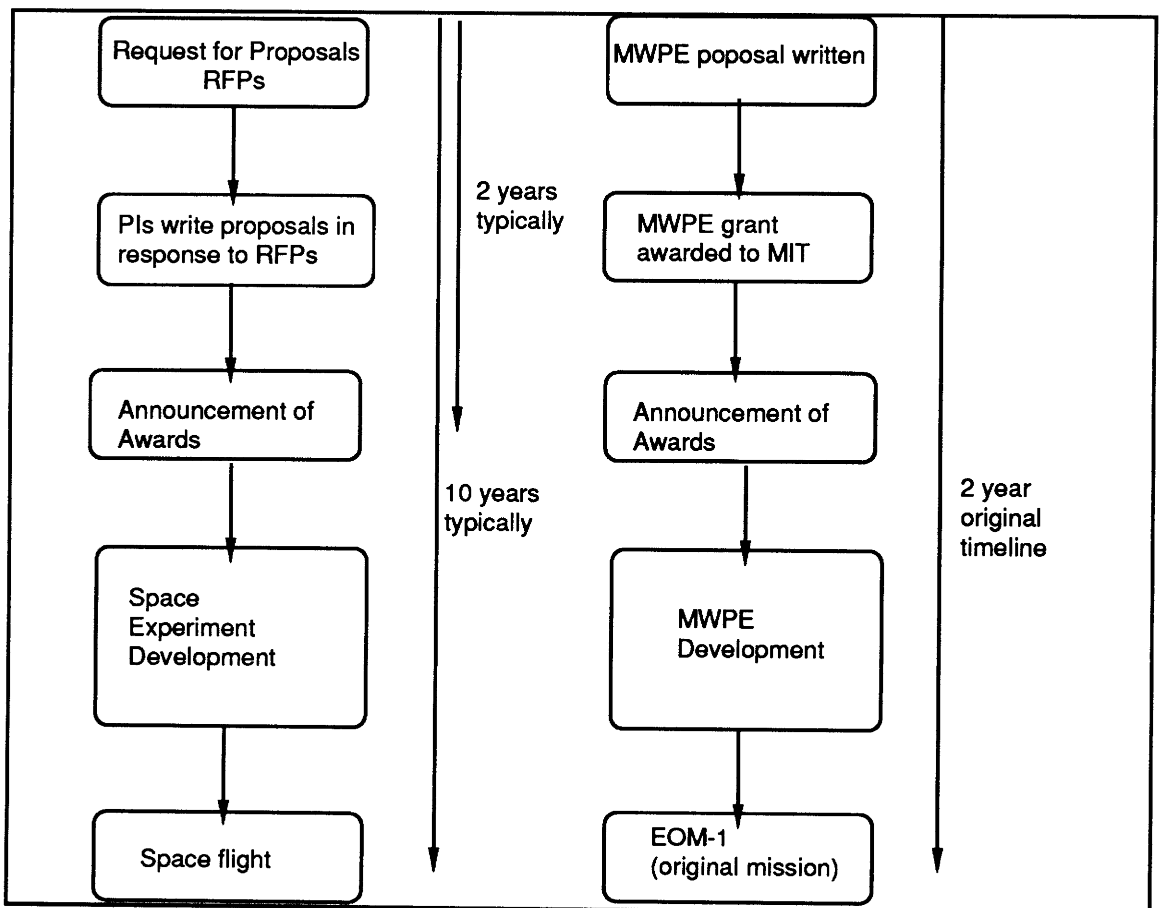


Figure 6.5 The life of a space experiment vs. MWPE's planned life.

The second special circumstance surrounding MWPE was that the MPWE proposal did not follow the standard regiment of going through an open competition for responses to RFPs. Even with support and verbal commitment from NASA HQ, the MWPE proposal was to encounter resistance from the procurement office at JSC. The procurement office objected to awarding a contract to a proposal that was unsolicited. At the the same time the MWPE proposal was held up at procurement, the Space Biomedical Research Institute (SRBI) of JSC conducted a peer review of the proposal and approved MWPE for development. This approval would translate into direct monetary support once the obstacles at procurement were resolved. The resistance of procurement was overcome by not awarding a *contract* for MWPE development, but rather labeling the award a *grant*. Grants are not scrutinized to RFPs and open competition for approval.

In February of 1985 the Life Sciences Project Development (LSPD) directorate of JSC was charged with overseeing MWPE project and a grant was awarded to MIT for the development of MWPE. Dr. Bussolari was the PI and Dr. Lichtenberg would serve as a co-investigator on the grant. MIT sub-contracted to Payload Systems, Inc. (PSI) for MWPE support. MWPE had become a monetary reality and a conceptual experiment in March of 1985, just 17 months before the scheduled flight. The political environment of a space experiment is quite different than the technical environment which encompasses development and experimentation in a remote, tucked away laboratory. A bit of American space policy history oriented us to the *Space Age* and *Race to the Moon*. Then MWPE political case study was initiated by revealing the specific pathways for the genesis of MWPE. I think it is fair to claim that MWPE is in existence today due to "politicking." Being an astronaut, Dr. Lichtenberg was in a great position to recommend a valid science experiment which would fly on his next scheduled mission. Being from MIT, Professor Bussolari and Dr. Lichtenberg have political clout (academically speaking) and credibility. In order to better understand the people and roles they have played in MWPE development I have detailed the participants in Chapter Seven. Also, the ever-changing MWPE flight schedule is discussed. MWPE scheduling and timeline from genesis to flight has been reconfigured countless times and the master schedule illustrates the busy and chaotic MWPE schedule. The ideas, participants, and bureaucracy that have shaped MWPE create the arena for the policy analysis. Finally, Chapter Seven concludes with recommendations for MWPE.

Rise up,
like fishes peering out of the sea, descry the things there, and, if our strength can endure the light,
know that there is "the true heaven, the true light, and the true Earth."
- Plato, Pheado, trans. by W.H.D. Rouse

The fault, dear Brutus, is not in our stars,
But in ourselves, that we are underlings.
- Shakespeare, Julius Caesar I.ii.

Chapter 7 - An Effective System?

7.1 The Participants and Their Responsibilities

Outlining the roles of all the different people and groups responsible for flight experiments gives insight into the intermingled bureaucracy that surrounds a flight experiment. Personal interviews were conducted with the private investigators, the consultants, and the NASA program scientists and engineers who have helped shape MWPE. Their experiences and their roles in this experimental saga are revealed. MIT, PSI, NASA HQ, and JSC have been mentioned in the previous chapter. Their roles will be further delineated along with two additional groups, namely, the Marshall Space Flight Center (MSFC) and the Kennedy Space Center (KSC). These six groups have the closest contact with MWPE (See Figure 7.1). Additionally, numerous subcontractors have helped shape experimental design and development. This list may seem a bit exhaustive; and to think - MWPE is but one small, quick, streamlined experiment that originated due to some open crew time in a Space Shuttle mission.

The grant for the Mental Workload and Performance Experiment was awarded to MIT and the experiment was developed in the Man Vehicle Laboratory under the supervision of Professor Bussolari, the principal investigator. Professor Bussolari and his graduate research assistants formulate and implement the scientific and intellectual objectives of MWPE.

Three graduate research assistants have worked on MWPE. Jess Fordyce developed the MWPE software code for the GRiD microcomputer. He ran the first MWPE experimental sessions and accumulated and analyzed data from over fifteen subjects. Ted McDade was the second graduate student to carry out research under the MWPE grant. Ted is researching the ergonomics and anthropometrics for the adjustable microgravity workstation design. Ted also assisted Jess in the graphic input devices configuration and in the test flights on the KC-135. I am the third graduate research assistant to work on MWPE. Initially I became familiar with MWPE software and hardware. The goals of my research include enhancing MWPE experimental design, making the experiment more robust by establishing the data flow procedures, and furthering the science objectives by establishing baseline data for additional MWPE configurations.

Payload Systems, Inc. is headed by Dr. Lichtenberg. PSI's main role is to supply MWPE support. Specifically, Dr. Lichtenberg gives input and guidance into MWPE design and regularly attends IWG meetings and meetings at MIT with Steve and I. Mr. Bob Grimes of PSI has been in charge of converting MWPE computer code from GRiD-OS to MS-DOS for the ground-based enhancement of MWPE.

The Life Sciences Project Development (LSPD) directorate at the Johnson Space Center oversees the MWPE grant. Mr. Angel Plaza is currently MWPE project engineer and technical monitor. He is the first level interface between MIT and JSC. His responsibilities include monitoring the grant expenditures, overseeing hardware development of the graphic input devices, flight certification of the hardware, and verification and integration of the entire MWPE system. The next paragraph further details the certification, verification, and integration processes.

Temperature, vibration, electromagnetic illumination (EMI), acoustic, and off-gassing tests are conducted during the hardware certification. MWPE hardware (GRiD microcomputer, input devices, cables, and adjustable workstation) is subjected to a temperature profile of 0^{o} F to 100^{o} F. Vibration tests are conducted with the hardware set-up as it would be in the Spacelab module. EMI emissions are measured for numerous ranges and frequencies. The acoustic and off-gassing tests subject MWPE apparatus to standard noise, pressure, and emissions measurements. The verification and integration processes of a flight experiment are performed in order to assure that the entire system works properly. During this phase MWPE is subjected to rigorous operational tests on the power, batteries, cable, leads, and mechanical latches. Then the weight and center of gravity of MWPE are checked. Finally, the experiment undergoes stress and electrical shock tests to make sure the specifications are acceptable for space fight.

There is also an IML -1 project manager from JSC, who is presently Ms. Liz Calla. Her responsibilities entail coordinating all of the JSC sponsored experiments that will fly on the IML-1. Currently, MWPE is scheduled on the IML-1 mission and hopefully it will not be rescheduled or dropped.

Ms. Calla and Mr. Plaza coordinate and communicate with the mission managers from MSFC. The JSC and MSFC interface is largely dependent on paperwork. The Spacelab Payload Accommodation Handbook (SPAH), the Operations and Integration Agreement (O&IA) and the Interface Integration Agreement (IIA) are typical experiment documentation which the managers at JSC and MSFC approve and finalize. As you can imagine, many of the inputs for the documents come for the principal investigators. In addition to paperwork, that hardware mock-up and integration for IML-1 took place at MSFC in the Payload Crew Training Complex (PCTC). A full size mock-up including storage containers, workstations, video, and audio capabilities which are similar to those in Spacelab is located in the PCTC.

There is also a link to the Kennedy Space Center (KSC). KSC is the primary launch and landing site for the Space Shuttle. The final checkout, integration, and loading of Shuttle payloads is done at KSC. KSC is responsible for off-line facility requirements and a final science verification. Off-line facility requirements include arranging for and attending to the needs of the PIs. The final science verification performed at KSC entails going through the experiment from start to finish and making sure everything is operational. Once the experiment passes the final science verification it is received at the Operations and Checkout (O&C) building. Following inspection and laboratory preparations, all experiments on IML-1 are brought together to form a functioning payload unit. After the integration in the O&C is complete, the payload is transported to the Obiter Processing Facility for integration with the Space Shuttle Vehicle. The Shuttle is then towed to the Vehicle Assembly Building (VAB) and mated with the external tank and solid rocket boosters. Finally, the Shuttle is moved to the launch pad for take-off. (NASA-STS Investigator's Guide, 1984.)

In the end, all of these participants will have enabled MWPE to fly in space. MIT personnel formulate and carry out the scientific research. PSI's crucial input and co-investigator participation helped shape and finalize MWPE. Key personal from NASA HQ in Washington, D.C. initially endorsed MWPE. JSC is the NASA center in charge of management and flight qualification of MWPE. MSFC is the NASA center which coordinates the Space Shuttle missions and hosts the mock-up reviews. KSC has the Space Shuttle launch facilities and conducts final payload integration of experiments. MWPE has been shaped by people across the entire nation, with scientific inputs coming from people in New England to Texas to California (See Figure 7.1).

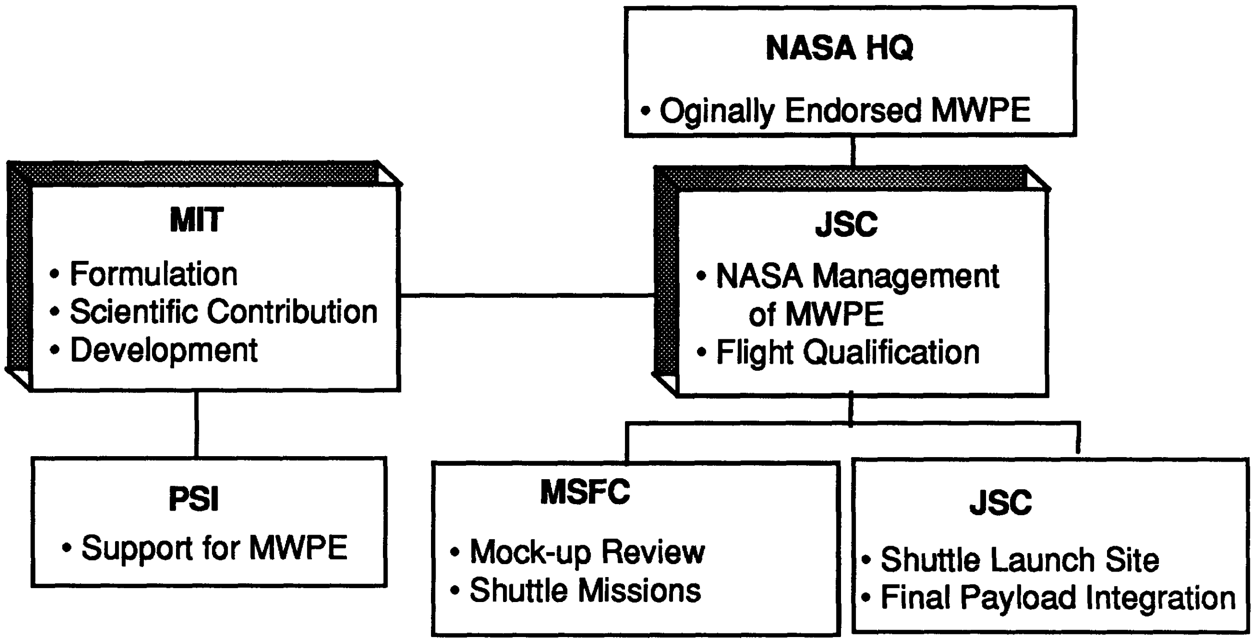


Figure 7.1 MWPE participant primary responsibilities flowchart.

7.2 MWPE Dynamic Schedule from Genesis to Flight

The MWPE master schedule (See Figure 7.2) is explained in this section. The first section gives the launch schedule chronology and the second section gives the development and management schedule. MWPE scheduling and timeline from genesis to flight has been reconfigured countless times and the master schedule illustrates the busy and chaotic MWPE schedule. The ideas, participants, and bureaucracy that have shaped MWPE create the arena for the policy analysis.

7.2.1 The Launch Schedule Chronology

The rescheduling of flights and experiments produces aggravation and chaos among astronauts, PIs, project engineers and managers, and everyone else associated with space flights. After its inception, MWPE was scheduled to fly on EOM-1. EOM-1 was originally slated for an April 1985 launch date. By the time MWPE became a manifest experiment on EOM-1 the mission had been rescheduled to an August 1986 launch date. In light of the schedule delays, EOM-1 was combined with EOM-2 and the mission became EOM 1/2. A final schedule slip of one month targeted EOM 1/2 for a late September 1986 launch. Please see Figure 7.2 - MWPE Master Schedule for the timeline which is described in the remainder of this section.

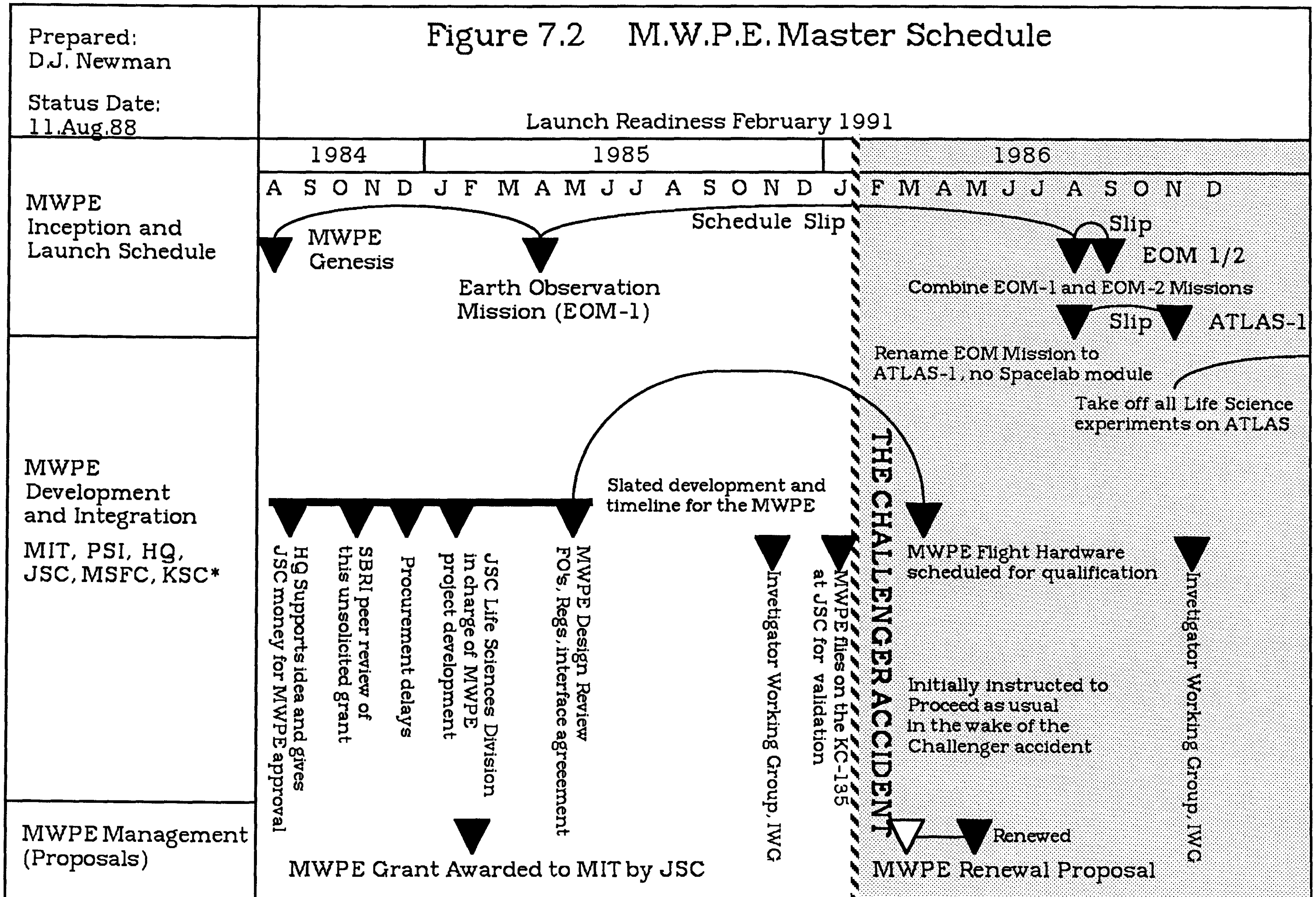
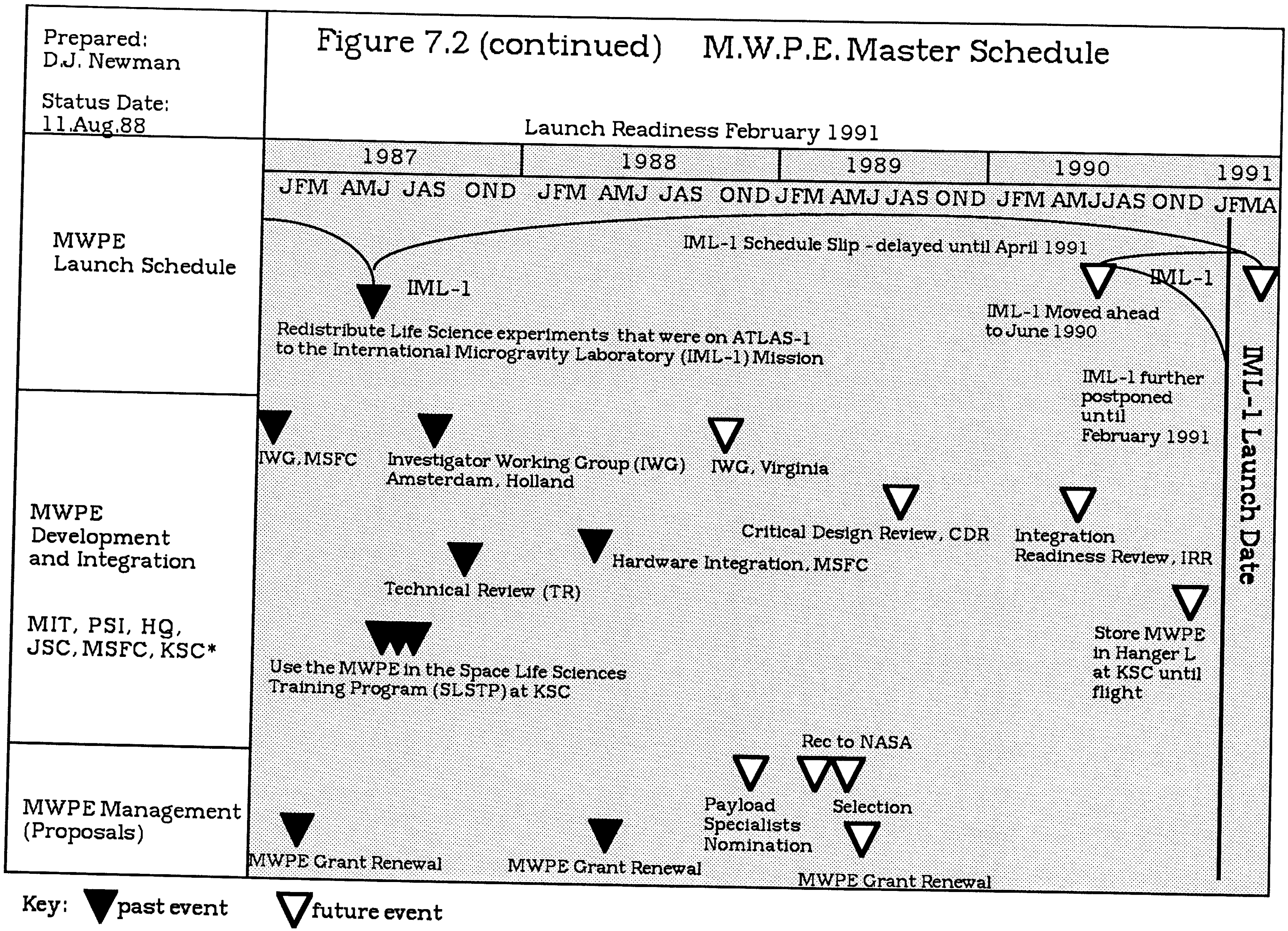


Figure 7.2 M.W.P.E. Master Schedule

* MIT-Massachusetts Institute of Technology, PSI-Payload Systems, Inc., NASA-HQ (Headquarters, Washington D.C.) JSC-Johnson Space Center (Houston, TX), MSFC-Marshall Space Flight Center (Hunstville, AL) KSC-Kennedy Space Center (Cape Canaveral, FL)


Prepared:
D.J. Newman
Status Date:
11.Aug.88
Figure 7.2 (continued) M.W.P.E. Master Schedule
Launch Readiness February 1991
1987
1988
1989
1990
1991
JFM AMJ JAS OND JFM AMJ JAS OND JFM AMJ JAS OND JFM AMJJAS OND JFMA
MWPE
Launch Schedule
IML-1
Redistribute Life Science experiments that were on ATLAS-1
to the International Microgravity Laboratory (IML-1) Mission
IML-1 Schedule Slip - delayed until April 1991
IML-1
IML-1 Moved ahead
to June 1990
IML-1 further
postponed
until
February 1991
IML-1 Launch Date
MWPE
Development
and Integration
MIT, PSI, HQ,
JSC, MSFC, KSC*
IWG, MSFC
Investigator Working Group (IWG)
Amsterdam, Holland
IWG, Virginia
Critical Design Review, CDR
Integration
Readiness Review, IRR
Technical Review (TR)
Hardware Integration, MSFC
Use the MWPE in the Space Life Sciences
Training Program (SLSTP) at KSC
Store MWPE
in Hanger L
at KSC until
flight
MWPE Management
(Proposals)
Rec to NASA
Payload
Specialists
Nomination
Selection
MWPE Grant Renewal
MWPE Grant Renewal
MWPE Grant Renewal
Key:
past event
future event

The loss of the Challenger and crew on January 28, 1986 has shaped, shocked, and stagnated the American space program more than any other single incident. Immediately following the accident, the PIs were told to operate as usual until further notices about schedules and programs were implemented. Everyone and "everything was in a holding pattern for a few months" (Lichtenberg). NASA went through changes in administration and management following the Challenger accident.

Meanwhile, EOM 1/2 was renamed to the ATLAS-1 mission. The Spacelab module was not scheduled to fly on ATLAS-1 flight which caused grave complications for all of the life science experiments that were specifically designed for the Spacelab module (including MWPE). The complications resulted in MIT and JSC quickly trying to adapt MWPE to the Shuttle mid-deck, rather than the Spacelab module, so it would not be removed from the flight. Crushing news for MWPE came in late 1986 when NASA revealed that *all* life science experiments would be removed from the ATLAS-1 mission.

By late summer of 1986 the word was out that it would be a long time until the Shuttle fleet would be permitted to fly. The entire Shuttle fleet, which consists of four Orbiters, was grounded. A one year delay seems like an eternity to a PI and even longer to a research assistant who is writing a thesis, but a three to five year delay was unthinkable. The first tentative flight schedules were released in early 1987 and it appeared that MWPE had a chance to fly on the International Microgravity Laboratory (IML-1) mission. The IML-1 mission was scheduled (more of a guesstimate) for an April 1991 launch. IML-1 is scheduled to have a seven person crew.

In 1988, two years after the Challenger accident, the low morale of NASA workers I witnessed at KSC in the summer of 1987 seems to be dissipating in light of the projected Shuttle launches for the summer of 1988. The awe, energy, and excitement surrounding a Shuttle launch is contagious. A pleasant surprise happened at the mock-up review at MSFC in April 1988. The IML-1 launch date was pushed up to June of 1990 from April 1991. From April to July work continued in anticipation of a June 1990 IML-1 launch date, but a problem with the oxidizer leak in the left Orbital Maneuvering System (OMS) pod in July of 1988 has once again delayed the entire Shuttle launch schedule. IML-1 slipped back to a February 1991 launch date. Further delays are anticipated due to a lack of fuel for the Shuttle resulting from a recent explosion at a fuel plant. Hopefully a positive attitude about the American space program will prevail.

7.2.2 MWPE Development and Management

In the space experiment process, the paperwork starts as soon as the grant goes into effect, if not sooner. The second category of Figure 7.2 highlights MWPE development and I will detail some of the events. The original deadline for MWPE functional objectives (FOs), requirements, and interface agreement documents was July of 1985. Preliminary requirements and objectives were outlined by this time, but initial schedule delays yielded buffer time for the completion of the paperwork. Both MIT and JSC prepare sections of the documentation for MWPE.

Jess Fordyce, a graduate student at MIT, developed MWPE software on the GRiD microcomputer and it was fully operational by Spring of 1986. Two graphic input devices, the joystick and trackball, were built to supplement the computer keyboard arrows. The hardware for MWPE was chosen in hopes that it would be easy to flight qualify. As previously mentioned, the GRiD microcomputer is the only space flight qualified microcomputer, so it was slated for MWPE development. Conventional input devices which were thought to be easy to flight qualify were selected for the experiment. MIT purchased ground hardware that was suitable for MWPE development and ground-based experimentation, but not qualified to fly on the Shuttle. JSC has a duplicate set of MWPE hardware, but it is modified to pass flight qualification. Flight hardware is approximately an order of magnitude more expensive than the hardware used for ground-based experiments. The flight qualified GRiD Compass microcomputer has a titanium casing and the computer is rated to withstand up to 30 Gs.

Once the software was operational, ground-based tests were run at MIT to establish baseline data for MWPE. The initial baseline data was analyzed by the Spring of 1986. MWPE flew on the KC-135 at JSC for experiment validation in zero gravity in early 1986. The experimental protocol was checked, but there was insufficient time in zero gravity to yield much data. (The KC-135 produces twenty-five to thirty seconds of weightlessness for each parabola it flies while a typical MWPE session takes thirty minutes.)

The development phase of space experiments also includes attending many meetings. PIs attend meetings for the following: the investigator working group (IWG), the mock-up review, the critical design review (CDR), science qualifications, and crew training. There is at least one IWG a year. The IWG allows the PIs to get together and review the science and ground-based results of their experiments with each other. The IWG establishes a Spacelab user's group for NASA. Many conflicts which could result in future problems are resolved at the IWG because PIs get guidance from other PIs encountering similar problems. As seen on the master schedule, an IWG took place at MSFC in January of 1987 and it was followed by an IWG in Amsterdam, Holland in October of that year. There was an IWG scheduled for October of 1988 in Virginia which as of August 5, 1988 has been postponed until further notice.

The Critical Design Review, a review of all experimental designs, is slated for August of 1989. A design review board comprised of JSC and MSFC managers reviews the science and hardware of experiments with the PIs. MWPE passed the CDR for the EOM 1/2 mission in December of 1985. However, MWPE is subjected to another CDR for the IML-1 mission in August of 1989. We anticipate that MWPE will once again pass the CDR.

The mock-up review for IML-1 occurred in April of 1988 at MSFC. The PIs bring their experiments to the mock-up to verify the experiments' size and operational procedures. The PIs are shown the light levels, video links, and audio capabilities which are available in Spacelab. Also, a board of reviewers from MSFC was present to ask the PIs and project engineers questions. I represented the PI team in Huntsville and gave the science overview of MWPE, while Mr. Plaza and Ms. Calla reviewed the equipment certification.

In addition to the science review that was given at the mock-up, a science review using the flight hardware will be scheduled at JSC for early 1989. A final routine science verification will take place at KSC a few months before the flight. Crew training for MWPE will take place at JSC for one week, but it is currently unscheduled because the crew for IML-1 has not been chosen. The crew will most likely be chosen in the fall on 1988 and crew training will get underway in early 1989. The PIs from MIT and PSI will train the astronauts at JSC on the flight hardware.

The MWPE grant proposal comes up for renewal every year. The NASA attitude has been to continue supporting experiments which are manifest on Shuttle flights. However, continued support ranges from grants which exclude new science research and barely cover operating costs to grants which receive 100% renewal support. MWPE has received continued support on a stable level, probably because it is a small grant. The renewal grants enable MWPE to go through development and protocol changes and enhancements in order to make it more robust for space flight.

In this section I have tried to present the dynamic schedule of MWPE. *Dynamic* is the key word, it seems as though we receive a phone call at least once a month from our project engineer at JSC informing us that MWPE has been delayed or a meeting has been postponed. The master schedule contains three divisions, launch schedule, development, and management. The cluttered interactions of deadlines are illustrated on the master schedule.

7.3 Recommendations and a Course of Action for MWPE

7.3.1 Space Policy at the National Level

American space policy has short-term horizons rather than long-term horizons. The question is "can long-term goals, goals 20 to 30 years in the future (i.e. a human mission to Mars), be accomplished with our existing system?" The level of commitment to space changes with each presidential administration and legislature. The emphasis on military or civilian space efforts is also dependent upon the political tides inherent in 2, 4, and 6 year terms in office. Our repeated pattern of focusing all our efforts on one space program or project seems to have crippling effects. Does our political system need change?

The Soviets have committed to a long-term space program. The most notable element of Soviet space policy is persistence. After being beaten to the moon, the Soviets continued their space R & D with limited, but increasing success. By 1966 Americans had flown 437 spacecraft compared to 197 for the Soviets, but the Soviets were persistent. "In 1973 the USSR placed 124 spacecraft in orbit or beyond (one every three days) to just 23 for the Americans" (OTA report, 1984) and the score was reversed. The Soviets have continued high level space spending throughout the 1970s and 1980s.

The Soviet theory was to routinize earth orbit operations for manned spaceflight. Soviet Soyuz and Salyut space stations orbited the earth in the1970s. The presence of Salyut VI in the late 1970s and the MIR space station in the 1980s exemplify the Soviets accomplishments in manned orbital operations. The Soviets have a well established space program consisting of space stations, launch vehicles, and a long-term policy which insists on a manned mission to Mars and permanent presence in space. Soviet persistence and planning has produced a space program with routine access to space.

The democratic ideals which cause America's strength, legitimacy, and attraction also cause obstacles for establishing a national space policy. Our individual freedoms and freedom of choice are nearly taken for granted. Our democratic state changes administrations almost every four years and federal funding is appropriated under a yearly budget. We seek these liberties, but they are often the constraints which produce a sporadically funded space program.

The American space program should be a major national issue. The Space Age has been one of the greatest technology drivers in history. Technology has been the yardstick to measure the political power of states in the modern world. I believe a national commitment to space should support a space station, international cooperation in space, commercial space efforts, and an expansion of launch capabilities. President Reagan's *National Space Policy* was formulated in early 1988 and it suggested much of the above. The policy is currently no more than words on paper and with the changing of administrations this year, the policy will likely remain just that, words on paper.

Not to be pessimistic, the first of four steps to establishing a rejuvenated national space policy is words on paper. The words of the National Space Policy reflect countless hours of negotiations between the White House, DoD, NASA, Legislators, and the Commerce Department. The fate of the National Space Policy will be partially determined by the next administration. The second step to establishing a commitment to long-term space goals is the President's budget request. The administration's commitment to an announced policy is reflected in the funds sought for the policy. The third step involves Congress. Congress mutilates budget requests, but that is what we elect them to do. The forth input into the system should come from the people, space advocates themselves.

Scientists and engineers along with science fiction buffs can demand that America forge ahead with a national commitment to space. Congress is a reactionary body that responds to constituents, so a major responsibility in establishing American space policy rests with supporters of the space program. "The scientific and engineering community are the space program's natural constituents" (Forman, 1988). A national commitment to space would assure a space budget regardless of administration.

In the 1960s, Apollo was the American space project. Then the Space Shuttle became the American space project of the 1970s and its longevity has extended over two decades as the primary space project. A space station or a human mission to Mars may be the next American space project, but do we want to continue this "single major project" trend? It seems as though a carefully planned, long-term horizon, space policy would most benefit the American space program. Clearly, two ingredients of a long-term space horizon that need to be developed are necessary infrastructure to support space habitation and the facilities to conduct science experiments and observations on a continual basis.

There are two options for acquiring long-term space infrastructure. The first option is similar to the acquisition of the Space Shuttle. Vast quantities of publicly funded new technologies would be developed. NASA specifies the engineering requirements and manages the technology provided by contractors. The international participation would be limited. I suggest a second and different course be taken. (These procurement options were highlighted in an OTA report, 1984.) Already existing technology should be used for initial operating capability. Private industry would be encouraged to develop their own resources and NASA would lease or buy the technology on a competitive basis. Collaboration agreements would be negotiated with countries and partners would share in the benefits. More challenging new space technologies would be pursued by NASA R & D efforts (i.e. reusable orbital transfer vehicles).

A few methods to help reduce the cost of the infrastructure are suggested. NASA should challenge industry by requiring engineering performance of space systems, rather than issuing detailed engineering specifications and managing the process in detail. Additional costs would be reduced by using already developed, tested, and paid-for technology. International collaboration and cost-sharing efforts may prove to be cost effective.

7.3.2 MWPE Case Study

MWPE was a rushed experiment which resulted in good and bad attributes. The concept for MWPE only took two weeks to develop, so not all details had a chance to be ideally thought out. On the other hand, MWPE is a manifest experiment today because it was quick and simple and got pushed through the system in a hurry.

The rigidity of the entire experimental system is a big downfall. Once the hardware and software for an experiment are approved for flight, it is next to impossible to make changes. MWPE has at least five 200 page documents which delineate the specifications for the experiment. Certifying an experiment requires numerous people, hours, and paperwork. Currently the system is very inflexible with no room for enhancement of experiments. This system would be fine if the flights went on time and experimental turnover was quick, but the system is unacceptable in view of the five year delay for a Shuttle flight.

The rigid space flight system is necessary for safety measures and reliability, but a streamlined system is sought. One way to combat the inflexible system is with ground-based enhancements. In the case of MWPE, experimental protocol revisions will allow the ground software to be much more flexible and robust than the flight software. Many additional experimental conditions will be investigated in future ground-based experiments. An expanded database will supplement the prescribed flight data.

The crew time is the largest constraint on Space Shuttle flights. There are very few flights a year, therefore, the astronauts are burdened with numerous tasks and cannot dedicate much time to any one task. The astronauts must follow a very regimented schedule during a mission. Ironically, we lobby for MWPE to be flown (adding to the astronaut's overscheduled day) because it attempts to assess workload and performance measurements. Once the Shuttle is back on a regular schedule the backlog of experiments will slowly dissipate.

Restructuring the flight experiment system would yield shorter timelines for experiments. The approval procedure of an experiment could be shortened by limiting the bureaucracy. Centralized management from NASA HQ would streamline procedures because the bureaucracy of the NASA centers could be reduced. The time from inception of an experiment to flight should be shortened. Higher demands should be placed on researchers and NASA centers (i.e. 2 years, rather than 10 years) for experimental turnover. Repetitious experiment procedures should be eliminated. For example, MWPE science verifications at JSC and KSC are sufficient. The additional science verification at MSFC is costly and time consuming and could be eliminated. The time-lag for MWPE has not been at the development stage, but rather at the flight stage. A once inexpensive experiment, MWPE is becoming more costly with each flight delay.

The space station and necessary infrastructure suggested in the last section would provide investigators with a more realistic laboratory setting and eventually repetitious streamlined procedures would reduce the costs of experiments. Science and creativity are restricted in the present inflexible system of adhering to NASA specifications. Ideally, scientists on the ground would be allowed to interact with the astronauts performing the experiments on the space station. The creativity and innovation of an efficient laboratory experiment could be attained.

A few alternatives were suggested, but many more need to be investigated and put into action. The rigidity of the flight experiment system which MWPE is subjected to is combatted by enhancing the ground-based experiments which will compliment flight data. Centralized management on NASA's part to assure performance of an experiment, rather than detailing engineering specifications and managing those efforts would provide a shorter, more coherent timeline. Space station laboratory facilities are necessary for life science experiments, such as MWPE, to be executed in a more flexible realistic setting.

For all that has been - Thanks!
To all that shall be - Yes!
- Dag Hammarskjold

APPENDIX A

Instructions for MWPE Graphic Input Device Experiment
(from Fordyce, 1986)

INSTRUCTIONS FOR GRAPHIC INPUT DEVICE EXPERIMENT

The graphic input device experiment is designed to evaluate your performance using three different devices to move a cursor on a screen. By performing these experiments, you will help to establish a baseline data set used to see which device (joystick, keyboard, or trackball) is best suited for the cursor movement task in terms of speed, accuracy, and ease of use.

The following is an instructive overview of the experimental protocol for the Graphic Input Device Experiment. The steps described below are presented in the same order as they occur during the experimental session.

STEP 1: Power-up

The experimental session begins when the switch on the back of the Grid Compass microcomputer is toggled to the "on" position. This will initiate the "boot" sequence, and present you with the first screen of information consisting of a list of names. An example of such a screen can be seen in Figure 1. In order to select the appropriate name, simply press the up or down arrow keys until the highlighted box surrounds your name. For example, "Tony" is highlighted in Figure 2. Once your name has been highlighted, select it by pressing the code and return keys simultaneously. You may also notice the highlighted box at the bottom of the screen which provides the prompting information.

STEP 2: Determining the input device

After pressing the "code-return" keys to confirm your name you will be presented with a screen that tells you which device you will use for the upcoming trials. For instance, Figure 3 shows what you would see if the trackball were the device you would use next. Here you are instructed to connect the trackball and press "code-return". You will connect the trackball to the serial cord leading into the back of the Grid computer. The connections will be color coded to make the task easy to complete. After pressing the "code-return" keys to confirm that you have connected the trackball you will see the prompt shown in Figure 4, which lets you know that the testing will begin as soon as you press "code-return" once more. If the joystick were the device you would use next, you would follow the same procedure for that device. The keyboard is an integral part of the Grid and does not require a separate connection.

STEP 3: Executing the trials

When you are ready to begin the timed portion of the experiment and have executed the steps outlined above, you should have one hand positioned on the graphic input device to be used for the current block of trials. At this point you will be presented with a screen similar to that shown in Figure 5. Figure 5 lets you know that you must remember the letter "Q" for the current trial block. Since the targets are also shown on the

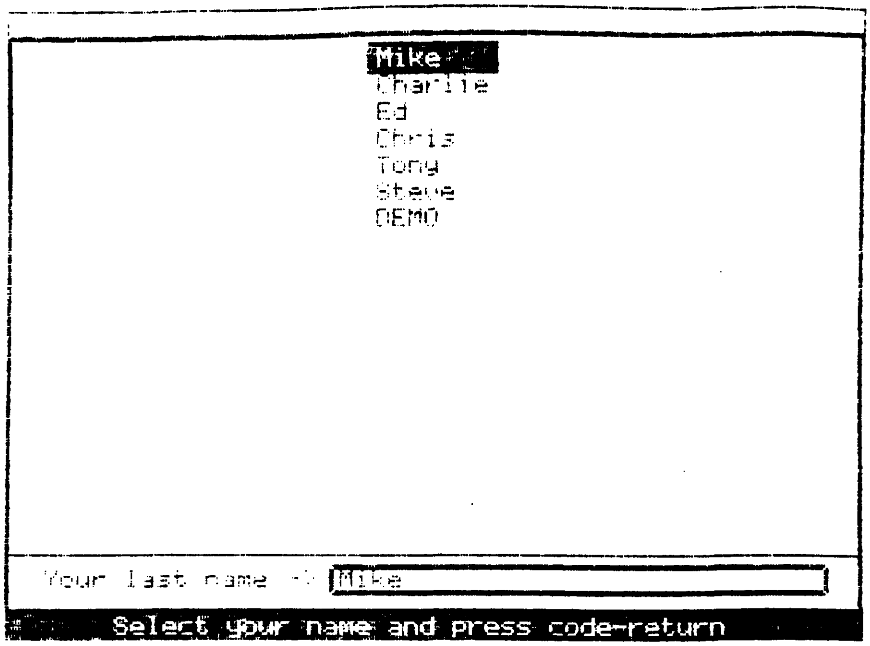


Figure 1

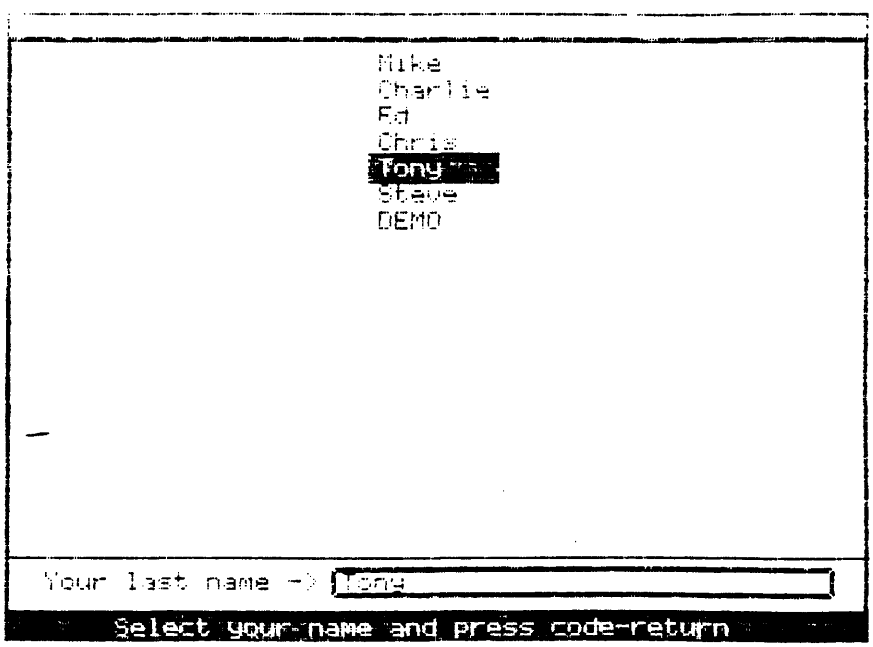


Figure 2

The next device is the TRACKBALL

Connect the TRACKBALL and press code-return.

Figure 3

Press code-return to begin testing

Figure 4

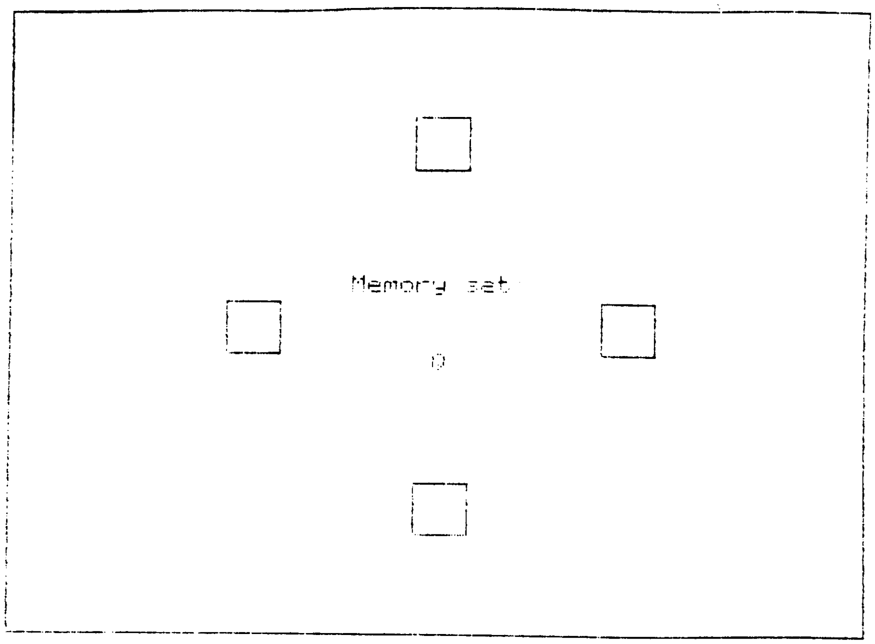


Figure 5

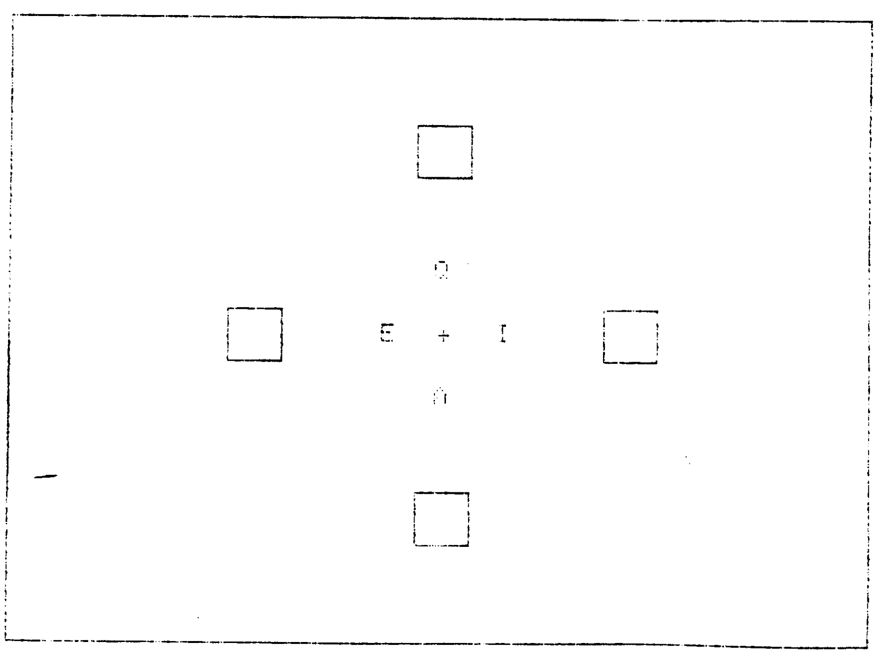


Figure 6

screen, you know their size and location prior to the first trial. After 5 seconds, the prompt shown in Figure 5 will disappear and a screen similar to Figure 6 will replace it. Figure 6 shows four targets, each with a letter corresponding to it. As soon as you determine which letter belongs to the memory set, move the cursor (the plus sign positioned at the center of the screen) into the box located in the same direction as the memory set letter. In this case the letter is "Q". Figure 7 shows that if the cursor is placed in an incorrect box, the box will not light up. Figure 8 shows that the target box corresponding to the memory probe lights up when the cursor is placed within its boundaries. After the target is acquired, the computer will present you with a new screen similar to Figure 6 and you will acquire the approriate targets for the rest of the trial block.

<u>Step 4: Subjective Workload Ratings</u>

After you complete the eighth target acquisition, you will be asked to give your impressions of the workload associated with the task you just completed. Figure 9 shows one of the six workload rating screens you will see. The cursor will initially be positioned halfway between the two endpoints, and you will move the cursor up or down to indicate your judgement of the magnitude of that workload. The cursor is to be moved using the graphic input device used for the trial block. Figure 10 shows that the cursor has been moved. Once the cursor is positioned where you want it, confirm the location and continue by pressing "code-return". This process will be repeated until all six subjective workload measures have been recorded. Upon completion of the sixth workload rating, you will see a prompt to press "code-return" to continue. Then a memory set will be presented for the next trial block and you will repeat the process.

<u>Step 5: Recording the Data</u>

Once all of the trial blocks have been completed for the three devices you will be shown six screens similar to Figure 11. These screens contain the data you generated during your trials, and they are to be photographed as a means of providing backup information in the event that the data files are somehow lost. As each screen is shown, you will photograph it (using a camera we will supply) and then press "code-return" to continue on to the next data screen. After the last screen is photographed, you will see the prompt shown in Figure 12. This lets you know that you are all done, and to turn the computer's power switch off to end the session.

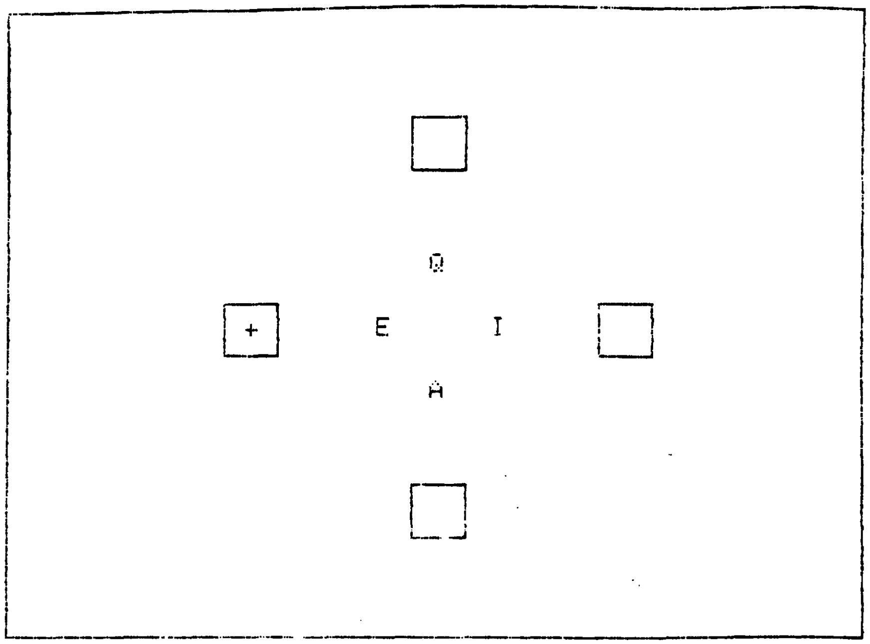


Figure 7

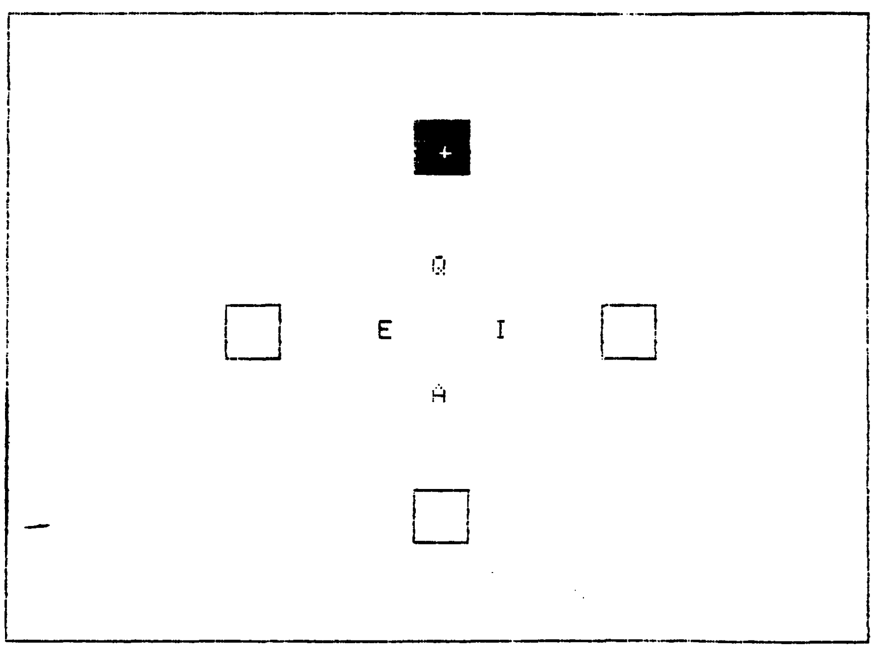


Figure 8

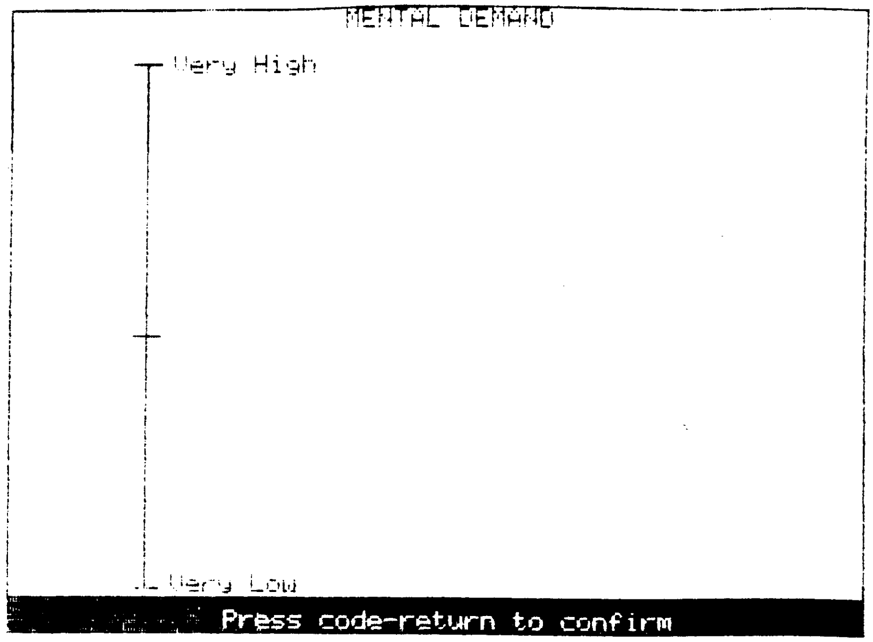


Figure 9

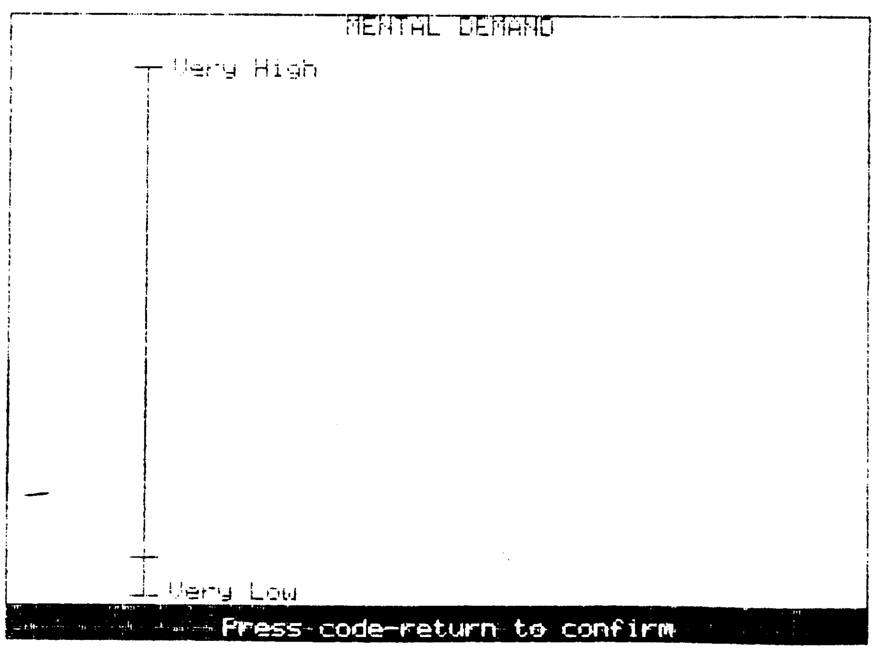


Figure 10

Tony Tuesday 18-Feb-86 2:13

BLOCK 1		BLOCK 2		BLOCK 3		BLOCK 4	
TCE1		TDE4		TCH1		TDH4	
22431314		76568875		43234121		67567865	
823	191	850	338	540	249	2676	657
521	255	504	419	395	383	1019	458
549	119	2567	167	808	407	799	468
424	274	548	700	556	399	1110	317
483	119	1067	394	391	718	851	463
658	119	2056	448	493	778	2495	660
602	161	712	187	410	493	1407	387
570	149	856	198	510	292	1005	441
3		34		3		36	
0		20		0		21	
3		38		4		21	
99		77		99		39	
1		54		2		37	
2		37		7		35	

Photograph and press code-return

Figure 11

This session is now complete.

Turn the computer off to exit.

Figure 12

Abort Contingencies

At some point in the experimental session it may be necessary to use the abort features of the software. You can abort the session at any time by pressing the code and escape keys simultaneously. Figure 13 shows the abort form menu of options available.

The first option is to redo the trial block you are currently executing. This may be necessary if you were distracted for some reason, or forgot the memory set, or any number of reasons. When you select this option, the computer will take you back to the point where you just began the trial block and give you a new memory set. Then you just redo the block.

The second option is to redo the device you are currently using. When this item is selected, the computer will take you back to the point where you connect the device and resume testing from there.

The third option is to abort the device altogether. This means that the remaining trial blocks will be skipped and you will proceed to the next device, if there are any more to be done in the current session.

The last option is to abort the entire session. If this is done, you will not perform any more trials, and the software will advance you to the data screens to be photographed as a backup measure.

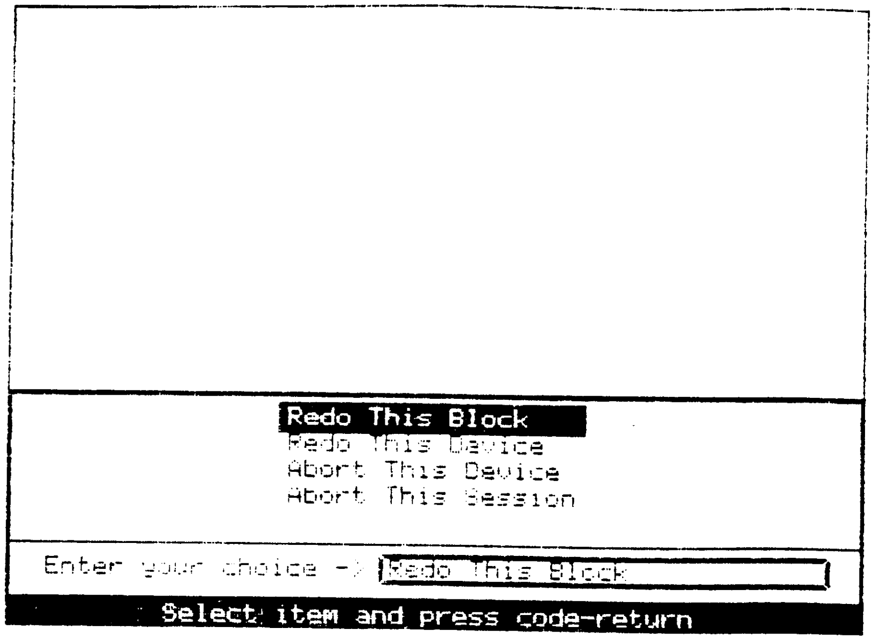

Redo This Block
Redo This Device
Abort This Device
Abort This Session
Enter your choice -> Redo This Block
Select item and press code-return

Figure 13

APPENDIX B

Instructions for NASA Bi-polar Workload Rating Scales

Subjective Rating Scale Descriptions

Subjective Workload Questionnaire

Subject Name: ___Subject 1___

Instructions for NASA Bi-polar Workload Rating Scales

You are about to take part in an experiment designed to evaluate various types of computer graphic input devices. We are interested in assessing both performance and your experiences resulting from different task conditions. In the following paragraphs we will describe the technique to be used to examine your experiences.

In the most general sense we are examining the "workload" incurred while you perform target identification and target acquisition tasks on the GRiD microcomputer using different input devices. Workload is a difficult concept to define precisely, but a simple one to understand generally. The physical workload associated with repeatedly lifting a 100 lb package is greater and more tiring than repeatedly lifting a 50 lb package. There are some tasks that require greater mental workload to perform than others. However, It is not always easy to tell which of the two tasks inflicts more mental workload than the other. Since mental workload occurs in the mind, it is not something you can physically measure with a yardstick. The only effective way to assess mental workload is to ask people to describe what feelings they experience.

The experience of workload is a feeling, and as such, is a particular challenge to collect and evaluate. Simply discussing your experiences in the different task conditions provides some information about the levels of mental workload. Unfortunately, such discussion usually does not provide sufficiently rich information to allow the combination of separate individuals' experiences in a careful statistical evaluation. This can cause grave problems, especially if the different task condition are very close in the amount of mental workload they inflict.

To overcome this problem, we will use a multidimensional set of rating scales to evaluate mental workload. The six workload rating component scales follow. Please read the descriptions carefully. Each component may contribute to what you perceive as workload. If you have any questions about the scales in the table, please ask the experimenter about it. It is extremely important that they are clear to you.

Workload Rating Scales used in MWPE.

TITLE	ENDPOINTS	DESCRIPTIONS
MENTAL DEMAND	Very Low / Very High	How mentally demanding was the task?
PHYSICAL DEMAND	Very Low / Very High	How physically demanding was the task?
TEMPORAL DEMAND	Very Low / Very High	How hurried or rushed was the pace of the ask?
PERFORMANCE	Perfect / Failure	How successful were you in accomplishing the task?
EFFORT	Very Low / Very High	How hard did you have to work to accomplish your level of performance?
FRUSTRATION	Very Low / Very High	How insecure, discouraged, irritated, and annoyed were you?

Subjective Workload Questionnaire

For each of the following pairs of subjective workload ratings, please circle the rating you feel is more important. Refer to the rating scale descriptions of each workload rating item.

mental demand vs. physical demand

physical demand vs. performance

temporal demand vs. frustration

performance vs. mental demand

physical demand vs. temporal demand

effort vs. mental demand

physical demand vs. frustration

effort vs. frustration

temporal demand vs.mental demand

physical demand vs. effort

performance vs. temporal demand

mental demand vs. frustration

temporal demand vs. effort

performance vs. effort

performance vs. frustration

APPENDIX C

Questionnaire

Measurements

Questionnaire / Measurements

Subject Name: ________Subject 1___

1. Height _5' 8"____

2. Age __27____

3. Weight __148 lbs____

4. Gender __M__

5. Do you have much experience with using computer...

	None	A little	Pretty much
Keyboards?			X
Joysticks?		X	
Trackballs?	X		
Mouse devices?		X	

6. Measurements

   A. Forearm-hand length _17 3/4"___

   B. Thumb-tip reach (back against wall) _33"___

   C. Wrist circumference _6 7/16"___

   D. Forearm circumference _10 1/4"___

   E. Hand length _7 1/8"____

   F. Hand breadth _4 1/2"___

   G. Hand circumference _10 1/4"___

Questionnaire / Measurements

Subject Name: Subject 2

1. Height 5'8"
2. Age 27
3. Weight 147 lbs
4. Gender M
5. Do you have much experience with using computer...

	None	A little	Pretty much
Keyboards?			X
Joysticks?		X	
Trackballs?		X	
Mouse devices?			X

6. Measurements

A. Forearm-hand length 18"

B. Thumb-tip reach (back against wall) 32 1/2"

C. Wrist circumference 6 1/2"

D. Forearm circumference 11"

E. Hand length 7 1/4"

F. Hand breadth 4 3/4"

G. Hand circumference 10 1/4"

Questionnaire / Measurements

Subject Name: Subject 3

1. Height 6'
2. Age 22
3. Weight 170 lbs
4. Gender M
5. Do you have much experience with using computer...

	None	A little	Pretty much
Keyboards?			X
Joysticks?			X
Trackballs?		X	
Mouse devices?		X	

6. Measurements

A. Forearm-hand length 18"

B. Thumb-tip reach (back against wall) 33"

C. Wrist circumference 7"

D. Forearm circumference 11"

E. Hand length 7 1/4"

F. Hand breadth 5"

G. Hand circumference 10 3/4"

Questionnaire / Measurements

Subject Name: ________Subject 4___

1. Height _6'_____

2. Age __24____

3. Weight __152 lbs____

4. Gender __M___

5. Do you have much experience with using computer...

	None	A little	Pretty much
Keyboards?			X
Joysticks?	X		
Trackballs?	X		
Mouse devices?		X	

6. Measurements

A. Forearm-hand length _19"___

B. Thumb-tip reach (back against wall) _34 3/4"___

C. Wrist circumference _7"___

D. Forearm circumference _10"___

E. Hand length _7 1/2"____

F. Hand breadth _4 1/4"___

G. Hand circumference _9 1/2"___

Questionnaire / Measurements

Subject Name: Subject 5

1. Height 5' 1"
2. Age 21
3. Weight 101 lbs
4. Gender F
5. Do you have much experience with using computer...

	None	A little	Pretty much
Keyboards?			X
Joysticks?		X	
Trackballs?	X		
Mouse devices?			X

6. Measurements

A. Forearm-hand length 17 1/2"

B. Thumb-tip reach (back against wall) 30 3/8"

C. Wrist circumference 5 5/8"

D. Forearm circumference 8 1/4"

E. Hand length 7 "

F. Hand breadth 3 7/8"

G. Hand circumference 7 3/8"

Questionnaire / Measurements

Subject Name: Subject 6

1. Height 5' 5"
2. Age 24
3. Weight 130 lbs
4. Gender F
5. Do you have much experience with using computer...

	None	A little		Pretty much
Keyboards?				X
Joysticks?			X	
Trackballs?		X		
Mouse devices?	X			

6. Measurements

A. Forearm-hand length 17 1/4"

B. Thumb-tip reach (back against wall) 33 3/4"

C. Wrist circumference 5 5/8"

D. Forearm circumference 8 7/8"

E. Hand length 6 3/4 "

F. Hand breadth 4 1/4"

G. Hand circumference 8 3/4"

Questionnaire / Measurements

Subject Name: Subject 7

1. Height 5' 6"
2. Age 22
3. Weight 136 lbs
4. Gender F
5. Do you have much experience with using computer...

	None	A little	Pretty much
Keyboards?			X
Joysticks?		X	
Trackballs?		X	
Mouse devices?	X		

6. Measurements

   A. Forearm-hand length 17 1/2"

   B. Thumb-tip reach (back against wall) 31"

   C. Wrist circumference 6"

   D. Forearm circumference 10"

   E. Hand length 7 1/8"

   F. Hand breadth 4 1/4"

   G. Hand circumference 9 1/8"

Questionnaire / Measurements

Subject Name: Subject 8

1. Height 5' 6"
2. Age 25
3. Weight 114 lbs
4. Gender F
5. Do you have much experience with using computer...

	None	A little	Pretty much
Keyboards?		X	
Joysticks?		X	
Trackballs?		X	
Mouse devices?		X	

6. Measurements

   A. Forearm-hand length 17 1/2"

   B. Thumb-tip reach (back against wall) 31 1/4"

   C. Wrist circumference 6"

   D. Forearm circumference 8 3/4"

   E. Hand length 7 "

   F. Hand breadth 4 1/4"

   G. Hand circumference 9 1/2"

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