Memory Processes and Motor Control in Extreme Environments

Dava J. Newman and Corinna E. Lathan

***Abstract*—Cognitive-performance and motor-performance activities in multi-task, high-workload environments were assessed during astronaut performance in space flight and in isolation. Data was collected in microgravity on the International Microgravity Laboratory (IML) space shuttle mission (STS-42), and the Canadian Astronaut Program Space Unit Life Simulation (CAPSULS) mission offered an ideal opportunity to collect data for individuals in extreme isolation to complement the space flight data using similar hardware, software, and experimental protocols. The mental workload and performance experiment (MWPE) was performed during the IML-1 space flight mission, and the memory processes and motor control (MEMO) experiment was performed during the CAPSULS isolation mission. In both experiments, short-term exhaustive memory and fine motor control associated with human–computer interaction was studied. Memory processes were assessed using a Sternberg-like exhaustive memory search containing 1, 2, 4, or 7 letters. Fine motor control was assessed using velocity-controlled (joystick) and position-controlled (trackball) computer input devices to acquire targets as displayed on a computer screen. Subjects repeated the tasks under two conditions that tested perceptual motor adaptation strategies: 1) During adaptation to the microgravity environment; and 2) While wearing left–right reversing prism goggles during the CAPSULS mission. Both conditions significantly degraded motor performance but not cognitive performance. The data collected during both the MEMO experiment and the MWPE experiments enhance the knowledge base of human interface technology for human performance in extreme environments.**

***Index Terms*—Adaptive control, biological motor systems, cognitive science, computer interface factors, extraterrestrial exploration, human factors, telerobotics.**

I. INTRODUCTION

THE mental workload and performance experiment (MWPE) was developed to look at human performance during space flight. The MWPE flew on the International Microgravity Laboratory-1 (IML-1) space shuttle mission in January, 1992 [1], [2]. The general motivation for developing the MWPE was to investigate the performance of a human operator engaged in high-workload tasks during space flight. One of the driving factors was the recognition that as missions get longer and tasks become more automated and computer controlled, the role of the human operator changes. Perceptual and cognitive capabilities and limitations of humans are becoming driving criteria for system design of the human-machine interface (HMI).

Human performance has many aspects that are difficult to measure and distinguish from one another. Space station operations, however, will put particular emphasis on astronauts' interaction with the station's many computer control systems. The MWPE was therefore designed to focus on motor and cognitive skills associated with such interactions, specifically, computer cursor control and short-term memory. Though narrowly focused, the experiment serves as a prototype for further investigations to pursue broader, multidimensional measures of in-space performance. The MWPE performance assessment test is based on the Fittsberg Task, a combination of Fitts's Law and Sternberg Tasks, which combines tests of short-term memory and motor control [3]–[5].

The first goal of these experiments was to quantify short-term memory performance as well as motor control associated with human/computer tasks for planning and commanding in extreme environments; environments characterized by high workloads leading to high stress and fatigue. Such environments include outer space, polar region stations, and oil rigs. The second goal of the MWPE was to assess human performance while performing interactive computer tasks that require perceptual-motor, or more generally, sensorimotor adaptation. This goal involves decoupling the workload and stress of microgravity from the alterations in the astronauts normal sensorimotor functioning. In the case of space flight, this altered functioning is unwanted and usually degrades performance. However, in many situations, such as in performing a teleoperator task, the sensorimotor transformations are expected to enhance performance. For example, manipulation of a large robot arm would be impossible without a control interface that enhanced the forces initiated by the human operator. In either case, knowledge of human performance with normal sensorimotor loops is needed. We begin to address this issue in the memory processes and motor control (MEMO) experiment, which provides an initial look at multitask performance under induced sensorimotor transformation.

A. Experiment 1: Mental Workload and Performance Experiment

Space flight places astronauts in a very stressful working environment as well as inducing substantial changes in physiological functioning due to microgravity. The MWPE was designed to assess the influence of the space flight environment on astronaut productivity, particularly for computer-interaction tasks, by measuring cognitive and motor performance during

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Manuscript received December 22, 1997; revised November 23, 1998. This work was supported in part by NASA Grants NAG 9-125 and NAG 5-4928. The Canadian Space Agency supported travel to the DCIEM facility in Toronto, Ont., Canada.

D. J. Newman is with the Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA 02139 USA (e-mail: dnewman@mit.edu).

C. E. Lathan is with the Biomedical Engineering Program, Catholic University of America, Washington, DC 20664 USA.

Publisher Item Identifier S 1094-6977(99)05321-3.

a dual, computer-based, memorization and target acquisition task. The MWPE experiment flew on the eight day, ten hour IML-1 space shuttle mission (known as STS-42), which was launched on January 22, 1992 [1], [2]. Four astronaut test subjects each performed four interactive experiment sessions during the course of the flight, along with three sessions both preflight and postflight.

B. Experiment 2: Memory Processes and Motor Control

The MWPE was enhanced for the CAPSULS mission and was renamed the MEMO experiment. This mission studied four Canadian astronauts during seven days of isolation at the Defense and Civil Institute of Environmental Engineering, Toronto, Canada [2]. The CAPSULS seven-day isolation mission offered an ideal opportunity to collect human-performance data for individuals in extreme isolation to complement the data collected in space on the IML-1 mission using a similar protocol and ground hardware. The CAPSULS experiment duplicated the space flight workload and conditions of isolation without the physiological changes due to exposure to microgravity. The experiment then evaluated operator performance on the same short-term memory and fine motor control tasks that were performed for the MWPE. The MEMO experiment then examined human performance when a sensorimotor transformation was deliberately induced in order to evaluate the limitations of different human operator control strategies. Specifically, our subjects wore left–right reversing prism goggles for approximately one third of the trials.

C. Models of Performance: Reaction Time and Movement Time

Traditionally, human memory is studied upon failure, but Sternberg proposed an alternative approach to studying memory. He studied "successful memory" that was almost free of errors [4]. According to his approach, 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. The reaction time measurement RT is the period of time from the onset of the test stimulus (presentation of memorized letters and targets) to the initiation of computer cursor movement. Sternberg's classical model suggests that RT increases approximately linearly with response entropy H, which is the amount of information needed to uniquely specify the single correct letter out of a memory set of size n assuming equal probability of any of the memory set letters being the correct choice. The classical response entropy and reaction-time models, given by (1) and (2), respectively, are

$$H = \log_2(n) \tag{1}$$

$$RT = a + b\log_2(n) \tag{2}$$

where a is a constant associated with a cognitive overhead for mental processing, and the slope of reaction time increases at a rate b with each additional bit of memory-set information content. Sternberg's experiments yielded a slope $b = 38$ ms/bit and an overhead of approximately $a = 400$ ms [4].

In our experiments, selection of a response is based upon the Sternberg exhaustive memory search task and response execution (or target acquisition), and it is also based upon Fitts's paradigm of motor control. It should be noted that the MWPE/MEMO experiment software alters the classical model for reaction time (2) to the linear expression in (3), modeling RT as a linear function of the number of letters in the memory set. This enhancement was incorporated into the experimental protocol to reflect recent findings in cognitive performance [6].

$$RT = a + b(n) \tag{3}$$

where a and b are constants associated with a cognitive overhead and the slope of the RT line for mental processing, respectively. The variable n represents the number of letters in the memory set.

Motor control, as measured by movement time MT, received experimental emphasis for the connection between the human motor system and information capacity in the early 1960's [3]. In 1954, Fitts reasoned that the distance D of a human movement and the width W of the target being acquired defined an index of task difficulty ID, again expressed in bits of information according to the logarithmic representation

$$ID = \log_2\left(\frac{2D}{W}\right). \tag{4}$$

Fitts's Law predicts MT to be a linear function of index of difficulty. Fitts defines target acquisition movement time according to the time it takes the subject to reach a target, and represents this by the following equation:

$$MT = c + d\log_2\left(\frac{2D}{W}\right) \tag{5}$$

where c and d are constants. It seems logical that MT increases if the movement distance increases or target width decreases, as under these prescribed conditions the target becomes further away and smaller, respectively.

II. METHODS

A. The "Fittsberg" Task

We used the Fittsberg experimental paradigm [5], which theoretically provides independent control and measurement of two tasks: response selection and response execution, where the former represents a cognitive task and the latter represents a neuromuscular task. The selection of a (binary) response is based upon the Sternberg memory search task [4], in which the subject is required to determine if a displayed item is a member of a previously memorized set, and target acquisition is based on Fitts's paradigm [3] to examine the control and accuracy of movement. Subjects were required to manually acquire a target of a certain size and distance away from an initial cursor position as quickly and as accurately as possible using a computer input device. The Fittsberg paradigm is illustrated in the three computer screens presented in Fig. 1.

From the time the targets appear on the computer screen to the time it takes the subject to identify the letter is the RT, a measure of short-term memory. From the time the subject starts to move the cursor on the screen via the computer device to the time he or she reaches the target is the MT, a classical measure of motor control. For each memory set, eight test

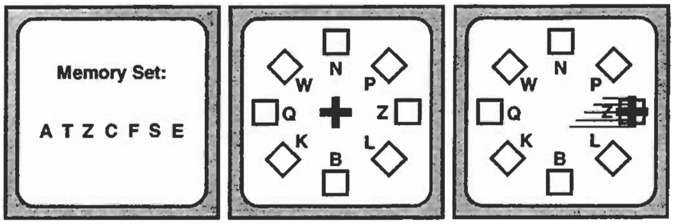


Fig. 1. The basic paradigm was the same for the MWPE and the MEMO experiment. (a) The subject was presented with a memory set consisting of one to seven letters, which they were asked to memorize. The subject pressed return on the keyboard to indicate the end of the memorization time. (b) The subject was then immediately presented with a test stimulus with a cursor in the center. Only one of the letters from the memory set was presented, the letter Z in this case. (c) As soon as the subject spotted the letter, the subject moved the cursor to that location. Once the location was reached, a new test stimulus appeared immediately.

stimuli were presented, while 12 memory sets were presented for each device.

The specific process of the interactive experiment was as follows. At the beginning of each experimental run, the astronaut subject was directed to prepare to use one of the two computer input devices, the trackball or the joystick. When the subject connected the designated device to the computer, he or she was presented with a "memory set" of one to seven characters to be memorized and used for the upcoming series of tests. Specifically, four memory set sizes comprised of one, two, four, and seven letters were used in the astronaut tests and were chosen to present the astronauts with a wide range of workload.

After memorizing the memory set, the subject pressed the enter key and was then presented with a "target set" of eight characters, or probe items, arranged in a circle, or a clock face pattern. Exactly one of these eight characters matched a member of the memory set. The subject was required to choose that one and designate it by moving the cursor from the center of the screen to the corresponding target square using the currently selected computer input device.

The difficulty of selecting the chosen character was varied by changing the size of the target square associated with the target characters and by changing the diameter of the circle they were arranged in, both of which influenced the Fitts's law index of difficulty ID. The time elapsed from beginning cursor motion (the end of the RT period) to settling within the correct target square (remaining at least 400 ms) was recorded as the MT. Three possible indices of difficulty were used: $ID = 2$, $ID = 3$, and $ID = 4$ bits of information [recall (3)]. The three ID values correspond to small, closely-spaced targets [$W = 5$ pixels, $D = 20$ pixels, $\log_2(8)$], large, widely-spaced targets [$W = 10$ pixels, $D = 30$ pixels, $\log_2(6)$], and small, widely-spaced targets [$W = 5$ pixels, $D = 30$ pixels, $\log_2(12)$], where distance D refers to the distance between the center of the screen and the target location and width W refers to the number of pixels spanned by a particular target.

The following is a summary of parameters measured.

Dependent Variables:

1) Short-term memory is assessed by reaction time (RT).
2) Motor performance is measured by movement time (MT).

Independent Variables:

1) Four memory set difficulties (one, two, four, and seven letters).
2) Three target acquisition index of difficulties (including target size and distance from the initial cursor position).
3) Graphic input devices (e.g., joystick, trackball,): The trackball provided direct control of the cursor position so that the rotation of the trackball corresponded to thecursor motion. The joystick, on the other hand, controlled the rate of the cursor's motion, making it more challenging to control.
4) Direction of Target Acquisition: The direction (from the center of the screen) of the target to be acquired was recorded to provide information on whether location of a target on the computer screen significantly affects the length of cursor movement. The eight target directions included the cardinal directions north, south, east, and west, and the diagonal directions northeast, southeast, southwest, and northwest.

B. Equipment

The MWPE was conducted using a payload general support computer (PGSC), which is a GRiD Corporation, Fremont, CA, Model 1530 laptop computer specially modified to be used on the space shuttle. The PGSC computer has a specially fitted electro-luminescent display. The PGSC computer is approximately compatible with the IBM-PC 386 desktop computer. The GRiD 1530 microcomputer was used to present the experimental paradigm and collect the data for both the MWPE and the MEMO experiment.

In order to provide the subjects with a variety of computer input devices, a trackball and joystick were purchased from Measurement Systems Corporation, Norwalk, CT, by NASA and qualified for flight use. The trackball has no dependence on gravity for normal functioning and, in fact, can be used in Earth gravity in any orientation. The trackball provided direct control of the cursor position so that the rotation of the trackball corresponded to the cursor motion. The joystick, on the other hand, controlled the rate of the cursor's motion. For both the MEMO and MWPE tasks, the subjects used either the position-control device (trackball) or the rate-control device (joystick) to perform the experiment. The computer and input devices are shown in Fig. 2.

The test program was designed to be fully automated, so that the subjects were prompted through the entire testing process once they began the Fittsberg program. This minimized the need for extensive operational training, which is extremely useful when conducting a space flight experiment using the space shuttle. The training time that was available was dedicated to achieving skill at the Fittsberg task to minimize training effects during actual data collection.

Finally, during the MEMO experiment only, the subjects repeated the task wearing left–right reversing prisms to induce a sensorimotor transformation. In other words, while wearing the reversing prisms, when the subject moved the joystick to the left, the cursor was seen to move to the right.

Fig. 2. GRiD Corporation Model 1530 laptop computer specially modified for use on the space shuttle is shown on the left. The Measurement Systems Corporation joystick and trackball are shown on the right.

C. Data Collection and Analysis

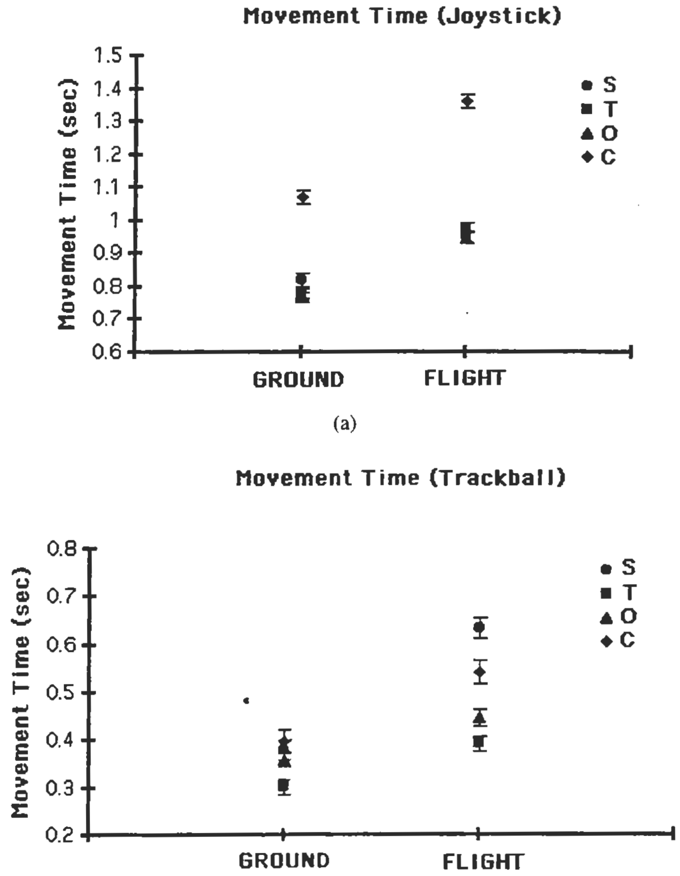
Data collection for the MWPE took place with each subject performing three sessions preflight all within six days of the launch: four sessions in-flight on flight days two through six and three sessions after returning from flight on landing day $R+0, R+1, R+2, R+4$, and $R+5$ ($R =$ Return). The MEMO experiment subjects were tested four days during the eight-day mission. Both MEMO experiment and MWPE subjects were trained during several sessions prior to data collection, and care was taken in the data analysis to ensure that subjects achieved a stable level of performance during training, accounting for learning effects, because the goal of the experiments was to evaluate steady-state performance and not learning effects.

The experimental data from the MWPE and the MEMO experiment were delivered to the investigators soon after the missions, in the form of floppy disks copied from the GRiD computer. The results were analyzed using analysis of variance (ANOVA) tools with the help of the SYSTAT, Evanston, IL, statistical analysis software package. A necessary step in data analysis turned out to be the culling of results that reflected very long reaction or movement times, apparently associated with entirely forgetting the memory set, being interrupted, and/or being pulled away from the experiment (points > 3 standard deviations were culled).

III. RESULTS

A. Performance in Extreme Environments

One of the major results of the MWPE was that all four subjects showed a significant increase ($p < .05$) in movement time MT during space flight as shown in Fig. 3. In other words, a decrease in fine motor control performance was observed in the microgravity environment. This increase in MT was seen for both the joystick [Fig. 3(a)] and trackball [Fig. 3(b)] input devices. In contrast, there were no significant changes in the reaction time of astronauts' performance on the Fittsberg task. There was also no difference in preflight and postflight conditions, so these data were combined to form the "ground" condition.



(a)

(b)

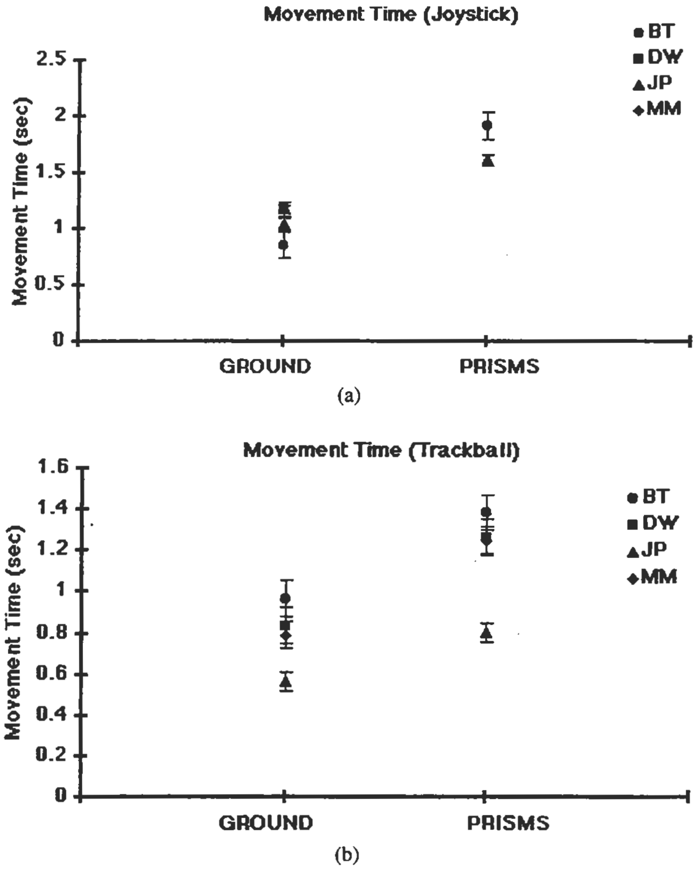
Fig. 3. Performance using both devices decreased (movement times increased) during space flight, but returned to normal upon return. Ground includes both preflight and postflight data sessions. This increase in MT was seen for all subjects in both (a) the joystick input device and (b) the trackball input device ($p < 0.05$). Error bars signify one standard deviation.

The equivalent "ground" condition for the MEMO experiment was the combination of all four experimental sessions (without prisms) during the seven day isolation mission. The sessions, during which the subjects wore prisms, were also combined, and it is termed the "prism" condition.

There was no change in the average MT across sessions during the MEMO experiment in either the ground or prism conditions. However, when a sensorimotor change was induced during the prism wearing condition, there was a significant decrease in overall performance ($p < 0.05$) for all subjects. This increase in MT is shown in Fig. 4 for both the joystick and trackball devices.

B. Control Strategies

Fig. 5(a) shows the MT for the average of the four MWPE subjects for cardinal versus diagonal target directions. Four conditions are compared for each: trackball/ground (TG), joystick/ground (JG), trackball/flight (TF), and joystick/flight (JF). The control strategy using the trackball input device was not affected by target direction. However, the MT's for the joystick conditions was significantly slower for the diagonal directions than for the cardinal directions ($p < 0.05$).



(a)

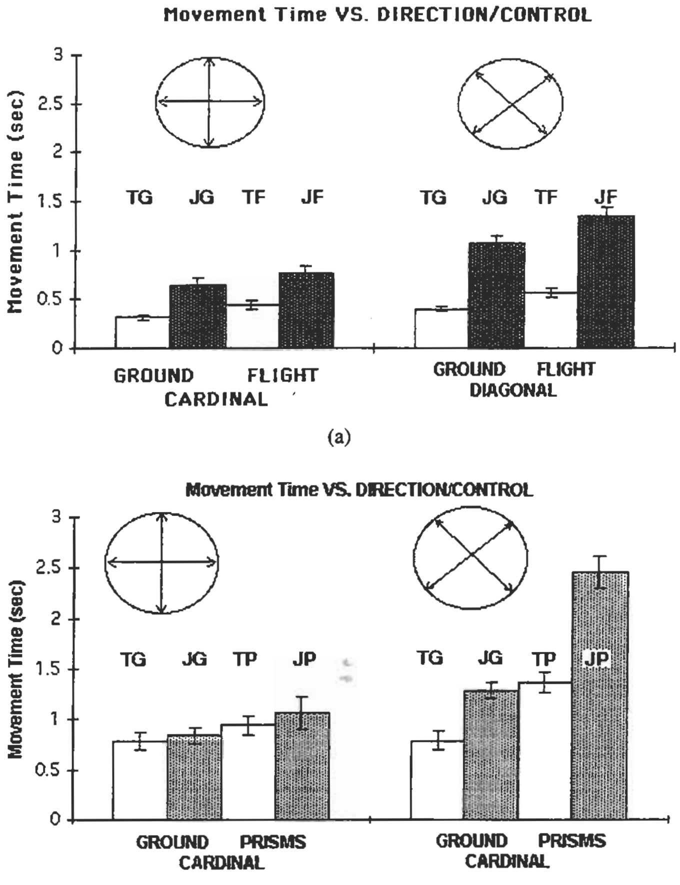
(b)

Fig. 4. Performance using both devices decreased (movement times increased) during the prism-wearing condition as compared to the ground condition, which was the combination of all trials without prisms from the four experimental sessions. This increase in MT was seen for all subjects ($p < 0.05$) in both (a) the joystick input device and (b) the trackball input device. Error bars signify one standard deviation.

Fig. 5(b) shows the MEMO experiment MT data to compare between control devices and adaptation states. There are two main results. 1) For the cardinal directions, there are no differences in the movement times between devices or adaptation state. 2) In the diagonal target directions, all cases are significantly different from each other ($p < 0.05$). Trackball normal (ground) is no different from the other conditions and has the best motor performance. There is a significant increase in movement time, denoting a decrease in performance, while using the joystick. A further increase in MT is seen for the trackball prism-adapted state, and the longest movement time is seen when using the joystick in the prism-adapted state.

C. Models of Performance

A linear regression model was fit to each subject's reaction time RT and movement time MT data and is reported in Tables I–IV. Index of difficulty, adaptation condition, device, and target direction were all significant variables for the MT responses for both the MWPE and MEMO experiment (data shown only if $p < .05$). Note that for the cases where adaptation is ground or no prism, the device is trackball, and when the direction is cardinal, the regression models reduce to the classic models $MT = A + B * ID$ and $RT = A + B *$ SET_SIZE.



(a)

(b)

Fig. 5. MT for the average of the four subjects for cardinal versus diagonal target directions. Four conditions are compared for each: trackball/ground (TG), joystick/ground (JG), trackball/flight (TF), and joystick/flight (JF). Error bars signify one standard deviation. (a) MWPE. The control strategy using the trackball input device was not affected by target direction. However, the MT's for the joystick conditions were significantly slower for the diagonal directions than the cardinal directions ($p < 0.05$). (b) MEMO experiment. For the cardinal directions, there are no differences in the movement times between devices or adaptation state. In the diagonal target directions, all cases are significantly different from each other ($p < 0.05$).

This analysis is useful, because it shows the relative contributions of the variables to the MT response. Table I shows that for the MWPE, the device condition induced the largest change in the MT, approximately 500 ms, then direction, and then adaptation, with a change of approximately 100 ms. Table II shows that for the MEMO experiment, adaptation, device, and direction all contributed comparably to the MT responses.

Table III shows the RT responses for the MWPE. Surprisingly, device was a significant variable for all four subjects, although it did not affect the response as much as memory set size. Table IV shows the response times for the MEMO experiment. Device and adaptation conditions were both significant for all four subjects, although similar to the MWPE, they did not have as much of an effect as memory set size.

IV. DISCUSSION

With advances in vehicle automation, the role of the human operator has evolved from that of pilot/driver and manual

TABLE I
MOVEMENT TIME RESPONSES FOR THE MWPE

Movement Time (s) = Subject	A	B*ID	C*Adaptation 0=ground 1=flight	D*Device 0=trackball 1=joystick	E*Direction 0=cardinal 1=diagonal
C	*N/A*	0.081	0.024	0.732	0.462
O	0.100	0.039	0.134	0.461	0.308
S	0.173	0.054	0.187	0.383	0.267
T	*N/A*	0.062	0.148	0.538	0.285
AVG	**0.137**	**0.059**	**0.123**	**0.529**	**0.331**

TABLE II
MOVEMENT TIME RESPONSES FOR THE MEMO EXPERIMENT

Movement Time (s) = Subject	A	B*ID	C*Adaptation 0=no prisms 1=prisms	D*Device 0=trackball 1=joystick	E*Direction 0=cardinal 1=diagonal
BT	0.527	*N/A*	0.596	*N/A*	0.466
DW	0.509	*N/A*	0.420	0.346	0.258
JP	*N/A*	0.062	0.377	0.613	0.338
MM	0.328	0.078	0.466	0.373	0.447
AVG	**0.455**	**0.070**	**0.465**	**0.444**	**0.377**

TABLE III
REACTION TIME RESPONSES FOR THE MWPE

Reaction Time (s) = Subject	A	B*Set_Size	C*Device 0=trackball 1=joystick
C	0.399	0.463	0.316
O	*N/A*	0.641	0.180
S	0.384	0.803	0.441
T	0.367	0.464	0.168
AVG	**0.383**	**0.593**	**0.276**

TABLE IV
REACTION TIME RESPONSES FOR THE MEMO EXPERIMENT

Reaction Time (s) = Subject	A	B*Set_Size	C*Adaptation 0=no prisms 1=prisms	D*Device 0=trackball 1=joystick
BT	-0.207	0.516	0.483	0.386
DW	*N/A*	0.350	0.150	0.426
JP	*N/A*	0.470	0.201	0.125
MM	0.191	0.371	0.331	0.278
AVG	**-0.008**	**0.427**	**0.291**	**0.304**

controller to supervisor and decision maker. The projected operational requirements of the International Space Station will necessitate extensive automation and expansion of the supervisory role for its crew members. However, manually-controlled telerobots remain important for activities, which raises issues of astronaut safety in space or during medical applications that require superhuman performance. Manual control issues are important due to a variety of concerns such as whether or not a telerobot might damage the space station structure or whether a telesurgery device will actually improve the surgeon's performance and not put the patient at unacceptable risk.

One of the research questions for the MWPE and the MEMO experiment was to ask how well the astronauts would perform basic cognitive and motor tasks while adapting to the space flight environment. Adaptation to alterations in normal sensorimotor loops has ramifications for any task involving a human–computer interface. An example of a sensorimotor transformation is the act of using a horizontal mouse or joystick to control an arrow on a vertical computer screen. In designing systems for teleoperations or telesurgery, the needed sensorimotor adaptations are much more complicated than the simple 90° transformation just described. Transformations such as amplified gains for microsurgery procedures can be deliberate to improve performance. However, sometimes transformations are unwanted (such as sensorimotor alterations due to the effects of microgravity). How well we can adapt to sensorimotor transformations and perform the required task is an important area of research for space flight as well as ground-based research.

The MWPE design was based on two hypotheses regarding astronaut performance in space. The first was that motor-control adaptation to microgravity, and perhaps other factors such as neurological effects, might result in reduced fine motor-control performance. The second hypothesis of the MWPE was that the combined effects of space flight such as stress, physiological adaptation, and the direct influence of microgravity might cause a degradation in cognitive performance, particularly short-term memory. The experiment therefore also incorporated a subtask focusing on short-term memory. In order to address each of these hypotheses, the MWPE incorporates the dual elements of the Fittsberg experimental paradigm, combining Fitts's test of motor performance with Sternberg's test of cognitive performance. Objective measurements of performance on the two tasks are response selection or reaction time and response execution or movement time, where the former represents a cognitive task and the latter represents a neuromuscular task.

During the MEMO experiment, the subjects performed the Fittsberg task both in the normal viewing condition and again while wearing prisms to induce a left–right reversed sensorimotor transformation. This allowed us to specifically look at the effects of inducing a visuomotor transformation and evaluate operator performance using the trackball or joystick devices. It is worth reporting again that all subjects were trained prior to being tested, so the goal was to evaluate steady-state performance and not learning effects.

A. Performance in Extreme Environments

Motor performance was degraded during space flight. However, distinguishing between changes due to sensorimotor adaptation to the microgravity environment and changes due to the fatigue and high stress of space flight was not possible during the MWPE. However, performing the MEMO experiment during the CAPSULS mission allowed for a distinction between these two hypotheses by performing the same experiment under a similar workload environment without the effects of microgravity.

No changes in fine motor control were observed over the course of the seven-day CAPSULS mission. Therefore, it is likely that the decrease in fine motor control seen during the IML-1 mission was in fact due to changes in sensorimotor loops from exposure to the microgravity environment rather than workload or fatigue.

No significant changes were seen in cognitive performance over the course of either mission as measured by the short-term memory task. None of the four subjects tested on the IML-1 mission reported any symptoms of space motion sickness. We speculate that this may account for their ability to maintain cognitive performance. In the MEMO experiment, all four subjects had a significant increase in RT responses during the prism-wearing condition. This is believed not to be an effect of decreased cognitive performance, but decreased performance due to a harder task. Wearing prisms made it harder to recognize the letters, because they were also reversed. Therefore, RT went up. A more robust experimental design would control for this.

B. Control Strategies

Manual control refers to the closed-loop control of some systems by a human operator through feedback about the desired state of the system. Evaluation of manual control strategies is important for designing human–machine interfaces (HMI's) for fully and partially automated tasks. How to implement controllers for telerobotic applications is dependent upon what we know about the human operator's ability. All of these controllers induce some sort of sensorimotor transformation, so it is important to understand and quantify human performance using different control strategies under different demands of sensorimotor adaptation.

These experiments compare human performance using position control or rate control to execute a radial Fitts motor task [3] under induced sensorimotor transformations. Both position-control and rate-control devices have been used extensively in teleoperations and in the laboratory to model human performance [7]–[15]. Position-based teleoperation uses a remote manipulator that is servocontrolled to follow the operator's position commands. Rate-control devices interpret human hand displacements as velocity commands. The resulting tradeoffs depend upon the task and the device. In order to prescribe and investigate questions for the design of telerobotic systems, we need to know how complicated tasks decompose into more basic tasks, which can then be measured (e.g., when to apply rate control versus position control or how to include force feedback into rate control, which has been shown to improve performance [12], [16]) depending upon stiffness [14], [17], [18].

One objective of the MWPE/MEMO experiment was to consider the effects of sensorimotor transformations on the human operator performance using different control strategies. The experimental paradigm helped to answer the following two questions. 1) How is motor-control performance affected by using a rate-control (joystick) versus a position-control (trackball) device? 2) Is motor control affected by adaptation state (either a normal or prism-adapted sensorimotor state)?

1) Control Device: When using the joystick as a rate controller to acquire the targets, movement time was slower in the diagonal directions in both the normal and prism-adapted or microgravity-adapted state. However, when the trackball was used in the position-control mode, movement time was unaffected by target direction in the normal state and in the microgravity-adapted states. However, performance decreased (MT increased) in the diagonal directions (in the prism-adapted state). Remembering that these were left–right reversing prisms, the motor-control performance in the cardinal directions (i.e., up, down, left, right) was unaffected by control mode or adaptation state. However, movement time to the diagonal targets was affected by both control mode and adaptation state.

One of the most interesting results was that both the position-control and rate-control devices had similar relative performances in their prism-adapted state as in the normal condition. In other words, both control devices had a decrease in performance only in the diagonal target directions. This predictability may mean that a human-operator model, developed from results using simple transformations, may be applied to human–computer interface design for more complicated tasks.

2) Sensorimotor Transformation: Sensorimotor integration in systems physiology refers to the process by which the central nervous system converts sensory inputs into a motor output. In almost any HMI, there will be some alteration of our normal sensorimotor loops. Some alterations may be intended to increase performance and some may be a result of noise or technical limitations. There is a need, therefore, to study sensorimotor loop adaptations in order to predict responses of human performance to alterations. Prisms have been used to study perceptual-motor coordination since 1925 when Helmholtz observed that when reaching for an object, subjects could quickly overcome the errors induced by displacing a visual field through wedge prisms (see [19]). Many people have demonstrated that humans are capable of adapting to almost any stable rearrangement of sensory input, although the mechanisms for adaptation vary depending on the particular circumstance.

Since the subjects were trained subjects, steady-state performance was evaluated in both the normal sensorimotor and prism-adapted sensorimotor conditions. One confounding factor was that left–right reversing prisms actually induce different transformations depending upon target direction. The north and south targets are not subject to any transformation, while the east and west targets are subject to the equivalent of a 180° rotational transformation. The diagonal targets are subject to a 90° rotational transformation. The differences in the diagonal and cardinal positions may in fact be due to this phenomenon. If this is true, it is interesting to note that subjects can perform just as well with a 180° transformation (transformation in one axis) as in the normal unaltered condition. However, a 90° rotational transform (transformation in two axes) results in a decrease in performance. In other words, this would imply some transformation threshold that would result in a decrease in human-operator performance if surpassed.

C. Models of Performance

Models of human performance and computer-interface design are important for many applications. Some examples are: establishing a human presence in space, teleoperations, and simulated environment training systems. System design for all of these tasks assumes a knowledge of human performance in the microgravity environment and on earth. Although position-control and rate-control devices have been studied previously, this may be one of the first attempts to look at position-control versus rate-control devices in the context of altered sensorimotor loops to evaluate human/operator performance. The linear regression models indicate that direction and adaptation also play an important role in modeling human performance, not just device. In fact, in the MEMO experiment, direction, adaptation state, and device were all significant contributors.

ACKNOWLEDGMENT

The authors would like to extend a special thank you to the subjects who participated in these experiments.

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Dava J. Newman was born in Helena, MT. She received the B.S. degree in aerospace engineering from the University of Notre Dame, Notre Dame, IN, in 1986, and the S.M. degree in aeronautics and astronautics, the S.M. degree in technology and policy, and the Ph.D. degree in aerospace biomedical engineering from the Massachusetts Institute of Technology (MIT), Cambridge, MA, in 1989 and 1992, respectively.

She is currently an Associate Professor of Aeronautics and Astronautics at MIT. Her main interest is in aerospace bioengineering, specifically in the areas of control and dynamics, biomechanics, human factors engineering, and systems engineering.

Dr. Newman is a member of the American Association of University Women (AAUW), the American Institute of Aeronautics and Astronauts (AIAA), the Aerospace Human Factors Association (AsHFA), the Aerospace Medical Association (AsMA), the American Society for Engineering Education (ASEE), the American Society of Biomechanics, the International Society of Biomechanics (ISB), the KEYS to empowering youth, the OmniSport 2001 organization, Sigma Xi —The Scientific Research Society, the Society of Women Engineers (SWE), the Space Studies Institute (SSI), and the Union of Concerned Scientists (UCS) for Peace. She has been the Principal Investigator on three space flight experiments to study astronaut performance on the space shuttle and Russian MIR Space Station.

Corinna E. Lathan received the B.A. degree in biopsychology and mathematics from Swarthmore College, Swarthmore, PA, in 1988, and the S.M. degree in aeronautics and astronautics and the Ph.D. degree in neuroscience from the Massachusetts Institute of Technology, Cambridge, MA, in 1994 and 1995, respectively.

She is currently an Assistant Professor of Biomedical Engineering, Catholic University of America, Washington, DC. She has appointments at the National Rehabilitation Hospital and the Georgetown University Medical Center. Her interests include human-technology interface design, space human factors, medical applications of virtual reality, rehabilitation engineering, and telemedicine and home care.