EFFECT OF VARIABLE TRANSMISSION DELAYS WITH A PREDICTION CUE ON OPERATOR PERFORMANCE IN A SIMPLIFIED SIMULATED DOCKING TASK

by

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(ABSTRACT)

Two principal issues were investigated in this experiment: (1) to determine if the performance of an operator controlling a simulated space vehicle was affected by variable transmission delays; and (2) to determine if an approximate predictor cue enhanced the operator's ability to control the vehicle. The study employed two independent variables, delay variability and prediction. There were four levels, or ranges, of delay variability; 2.50 ± 0.00, 2.50 ± 0.25, 2.50 ± 0.50, and 2.50 ± 1.00 s, and two levels of prediction, with and without prediction. The amount of fuel used to complete the task, the time to complete the task, error score (weighted deviations from the desired flight path), and a Cooper-Harper subjective rating were the dependent measures used to gauge the performance of the operator. Each of the eight treatment combinations contained three trials for the 12 operators to perform. The results of this experiment indicate that the greater the delay variability, the greater is the amount of fuel used for each task and the greater is the perceived difficulty. Prediction did not significantly enhance the operator's ability to control the vehicle. This result is probably due to one of two reasons: (1) the task itself was too easy; thus, the predictor did not assist the operators in completing the task, or (2) since the predictor was not completely accurate, the operators may have lacked confidence in its ability to improve their performance. Consequently, this result suggests that a predictor cue may not be useful for this type of situation. Recommendations are suggested for further research efforts associated with predictors used in conjunction with variable delay conditions.

ACKNOWLEDGMENTS

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To my parents, family, and special friends go my greatest thanks for their love and friendship. For without them, none of this would be possible.

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INTRODUCTION

Background

The National Aeronautics and Space Administration (NASA) will be adding another element to its Space Transportation System (STS) late in this decade. It will be a teleoperated vehicle called the Orbital Maneuvering Vehicle (OMV). The OMV will be brought to low earth orbit inside the cargo bay of one of the STS's Space Shuttles. It will be deployed, activated, and brought under control by an operator located at a Payload Operations Control Center (POCC) on earth.

The purpose of this vehicle is to enhance the Space Shuttle's, and later the Space Station's, capabilities or "sphere of influence" by going to altitudes and/or inclinations that are outside their performance envelopes. For early missions the OMV will be employed as a reusable upper stage booster delivering satellites from the Space Shuttle to their assigned orbits. Later, enhancements will enable the OMV to retrieve a satellite from its orbit, bring it back to the Space Shuttle (and by now the Space Station) for on-orbit repair, and return the satellite to its original orbit. Eventually, with the aid of an attached servicer unit, the OMV will be performing on-orbit repairs itself.

Since the OMV will be controlled from an earth-based POCC, long communication delays between the time the operator makes a control input and the time when he or she sees the results will be encountered due to the use of current communication systems. In addition, there will be some unknown variability around a predicted average delay that is discussed in depth later in the Experimental Design section.

Research Objectives

Two specific issues were addressed in this study. The first was to determine the effects of the delay variability on the operator's ability to control this dynamic vehicle during a simple docking task. The second was to assess the impact of a predictive cue on the operator's performance.

LITERATURE REVIEW

Time Delay Studies

The concern over the effects of transmission time delays on teleoperated vehicles appeared in the NASA's space program in the early 1960s. Unmanned vehicles were being planned for use in space exploration and the effects of these transmission delays were of concern.

An early study that dealt with the effect of transmission time delays was conducted by Sheridan and Ferrell (1963). These experimenters used a simple master-slave servo-controlled manipulator with two degrees of freedom (DOF) to determine how the time delay affected completion time of a simple manipulative task. They used time delays of 0.0, 1.0, 2.1, and 3.2 seconds and found that the subjects, without prior coaching, developed a move-and-wait strategy to compensate for the delays to maintain control of the vehicle. The strategy involved making open-loop commands, waiting until the remote hand had responded, and repeating this process until the objectives of the task had been achieved. The data indicated that a linear relationship existed between the task difficulty rating (the logarithm of movement time over terminal tolerance distance) and the logarithm of the completion time. A linear relationship also existed between the task completion time and the length of the time delay (Sheridan, 1963).

A follow-up study conducted by Ferrell (1965), using the same manipulator, had as two of its objectives to determine: (1) if operators would again independently adopt the move-and-wait strategy and (2) if similar linear relationships among completion time, task difficulty rating, and length of time delay would be obtained with a more complex manipulation task. Ferrell found that six of the seven subjects adopted the move-and-wait strategy and that similar trends between factors, as reported in the earlier study, were obtained for the more complex task.

He also found that the operators used-the-move and wait strategy so consistently that the completion times for both the simple and complex tasks were predictable given the amount of delay time, completion time without the delay, and the number of open-loop moves required when there was no delay.

A later study conducted by Black (1970) examined transmission time delay effects on the performance of manipulator tasks with a six DOF master-slave manipulator.

Using a 3.5-second time delay, the study confirmed that six DOF manipulation was possible and effective with a move and wait strategy that again was independently adopted by the subjects. The results showed that the delay most affected those portions of the task requiring the greatest precision.

These findings also substantiate those by Ferrell that a linear relationship exists between the time delay of the task and the average completion time. Unfortunately, an index of difficulty was not calculated due to the nature of the task. Therefore, no comparison could be made to Ferrell's conclusions concerning delay time and task difficulty.

In a recent study, Pennington (1983) confirmed Ferrell's and Sheridan's results for the task completion time and time delay linear relationship using a manipulator arm with five DOF controlled by a rotational hand controller and a joint matrix switch for the translational control. The subjects for this experiment again adopted the move-and-wait strategy, but it was found that the various time delays (0.00, 0.25, 0.50, 1.00, and 2.00 s) had no effect on the alignment accuracy of a peg-in-hole task used in this experiment.

Except for Pennington's (1983) study, all of the above studies used some type of manipulator system operated by a master-slave controlling mechanism. The only known studies that have involved transmission time delay effects on the control of a teleoperated, free-flying spacecraft were conducted by Martin Marietta Aerospace, Denver Division. Part of the then-called Teleoperator Maneuvering System (now OMV) study involved the simulation of a task controlling the OMV with various constant time delays (0.0, 1.0, 1.5, 2.0 s) during the final approach of a docking maneuver to a cooperative, stable target (an Apollo stand-off cross). The vehicle was controlled by two 3-DOF hand controllers, one for translation and the other for rotation. Both were spring centered devices. The control mode used for both hand controllers was an acceleration mode. In operation, if the hand controller was moved out of center detent, the appropriate thruster engines would fire, causing the vehicle to accelerate. When the hand controller was released and returned to the center, the thrusters would stop firing and the vehicle would then coast at a constant velocity.

To simplify this docking task, the Martin Marietta pilots maneuvered the vehicle to the proper approach attitude, nulled all rotation rates using a gyro controlled attitude hold system, and flew the OMV to the target with only the translational hand controller to the target. This reduced the simulation from a 6-DOF task to a 3-DOF (translation only) task. With the exception of some Apollo-Soyuz "fly-around" maneuvers and a few other past docking experiments, all actual spacecraft docking maneuvers to date have used this technique (Martin Marietta, 1982).

The results of these experiments demonstrated that the vehicle is controllable with each of the simulated delays, but that pilot behavior varied with the amount of delay. The longer the delay time the slower the pilots flew; therefore, the completion times increased. The amount of delay also had an effect on the quantity of propellant consumed. With the longer delays, the pilot's control inputs were smaller in magnitude and their actions more deliberate, thus decreasing the amount of propellant consumed (Martin Marietta, 1982). It was noted by this author that the pilots in this experiment also used the move-and-wait strategy to compensate for the delays. Although no trend was found, it did appear that the docking accuracy was not affected by the time delays. One final result of the study was that, with the 2.0-s time delay, the operator was sometimes unable to observe the results of an input before having to command another input in the opposite direction to stop the initial input. This usually occurred when the operator desired to make fine adjustments to the vehicle's motion (Martin Marietta, 1982).

Causes of time delay. The reasons for the expected time delay are primarily due to signal processing delays and signal transmission travel times (Walsh, 1975). Figure 1 depicts the communication path that will be used to control the OMV when in operation (Martin Marietta, 1982). The transmission delays will be caused by the use of the domestic satellites (DOMSAT) and the Tracking and Data Relay Satellites (TDRS) located in geosynchronous orbit 35,800 km (22,300 miles) above the earth's surface. Each use of these relay satellites takes approximately 250 ms for a signal to travel from the earth to the satellite and return to the earth. Since a total of four satellite relays will be used, a combined total of approximately 1.0 s of delay just for signal propagation is expected.

The other source of delay is the result of processing the signal at the various points in the communication link. The command that the operator puts into the system to move the OMV must first be converted into signal form at the POCC. This signal is then sent to a NASA Communications System (NASCOM) center where it is converted into their block format (usually entailing some buffering) and then sent to the TDRS communications center via a DOMSAT. Here it is reformatted again to conform to the TDRS system and then sent to the OMV in low earth orbit via a TDRS satellite.

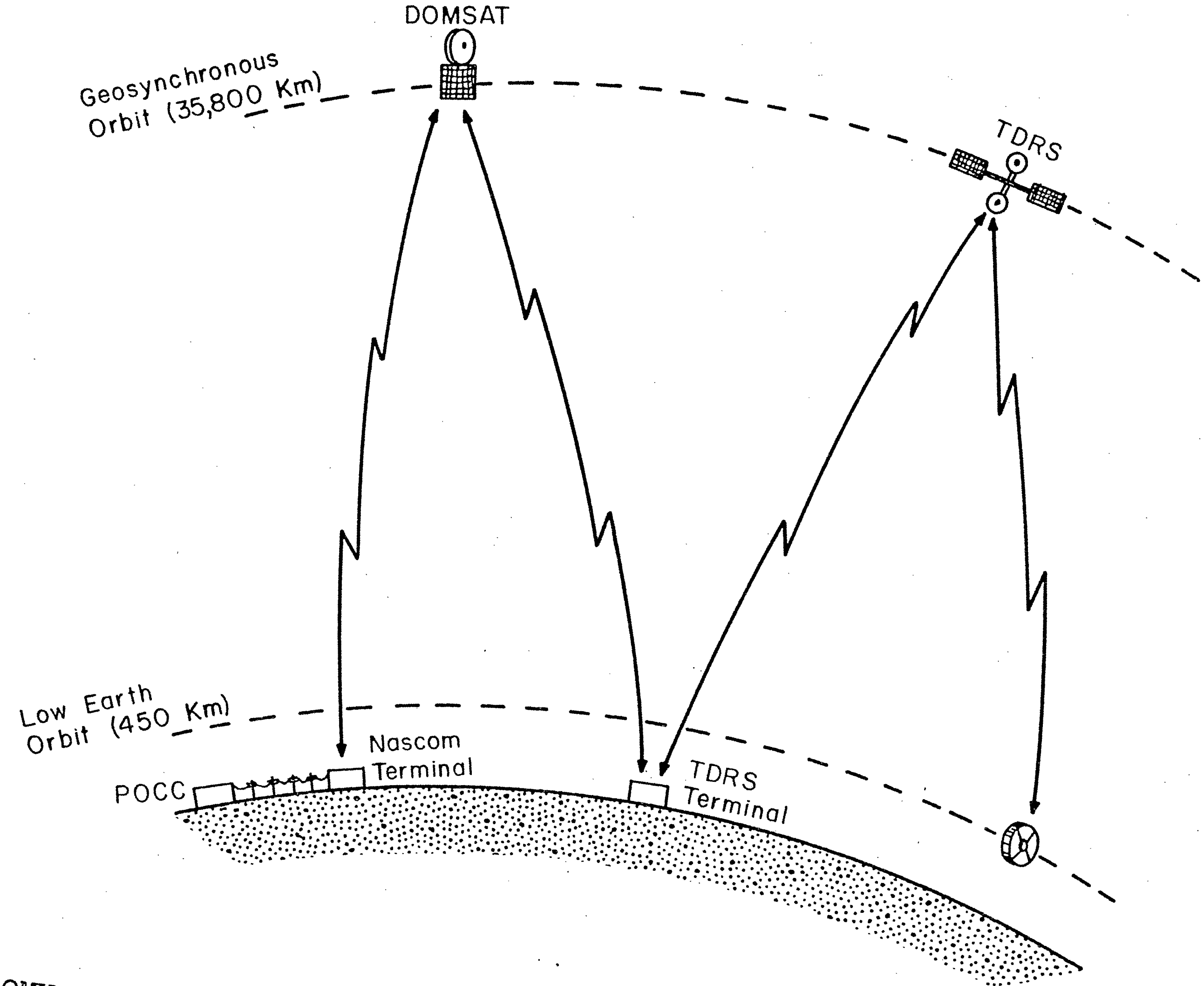


Figure 1: OMV communication path

This path is repeated for the return link with some additional delay resulting from onboard processing at the OMV. It is because of the cumulative effect of the signal conversions, buffering, and formatting that the additional time delay occurs.

This additional delay will account for an average of 1.5 s of delay with some unknown variability about this mean. The variability has been estimated to be as little as $\pm$ 0.25 s (T. Rasser, Martin Marietta Company, personal communication, November 11, 1984) and as high as $\pm$ 1.0 s (N. Schields, Essex Corporation, personal communication, January 24, 1985).

Not only is the physical quantity of the variability unknown, but the rate of variation is also not known (H. Watters, Marshall Space Flight Center, personal communication, March 1, 1985). Since the OMV will not be the only user of the aforementioned communication systems, it will have to compete for the processing capability and bandwidth space. The delay variability could theoretically be a negligible quantity and be very slow to change over time, thus resulting in a nearly constant time delay. A constant time delay for this type of vehicle has been demonstrated to be controllable by the Martin Marietta (1982) studies. More than likely there will be several users of the communication systems, thereby resulting in significant variability in the delay and causing it to change frequently during a mission. This latter type of delay variability will be one of the two issues studied in this research.

Prediction

A prediction instrument presents information about the future to an operator of a manually controlled vehicle. This typically is accomplished by using current vehicular information and extrapolating it into the future with the aid of a fast-time model of the vehicle to predict some future state or by sensing the surrounding environment and providing information about some future position. These types of instruments are typically visual displays and are particularly helpful in dynamic situations, such as high-speed piloted aircraft, submarines, and space vehicles. They have also been helpful in controlling manipulators if the operator is experiencing a significant time delay (Johnson and Corliss, 1971).

Military aircraft have been equipped with predictor displays to aid the pilot during particular phases of flight. An example is high-speed, low-level flight (terrain following/terrain avoidance) in which the pilot is provided information about the elevation of the terrain along the intended flight path using forward-looking radar. (Brinkley and Sharp, 1977). Studies have also demonstrated the effectiveness of predictor displays aboard submarines. These were used to assist the operator in avoiding potential collision situations (Kelly, 1968).

The effectiveness of predictors has also been demonstrated by NASA and Air Force studies during simulated and actual orbital rendezvous using fast-time models for prediction and for teleoperators in a time-delayed situation (Johnson and Corliss, 1971).

Akin, Howard, and Oliveria (1983) and Ferrell (1963) have discussed the application of a predictor to a delayed teleoperator task and have argued that a move-and-wait strategy would not be necessary for any type of time delayed task if the accuracy of the predictor cue were sufficient.

The key factor when using predictive displays is the accuracy. Obviously, the better the predictor's accuracy, the easier is the task to control the system. The more complex the overall system dynamics are, the greater will be the difficulty in developing the mathematical model to describe that system to generate future states.

In the OMV's case, the vehicle dynamics are accurately known, but the communications link is not. The current time delay estimate is on the order of 2.5 s with up to $\pm$ 1 s variability. In the discussions with N. Schields of Essex Corporation, it was felt that the distribution of the variability between 1.5 and 3.5 s would be similar to a normal distribution with the mean at 2.5 s as a first approximation. Since 2.5 s was the best estimate of the length of the transmission delay, the predictor would be displayed at a point 2.5 s into the future for each of the variable delays. This prediction method had an effect of decreasing the predictor's accuracy as the variability increases.

To generate a visual display to represent accurately the scene to the best of the equipment's ability, a diagrammatic classification scheme for man-machine system displays developed by Wierwille (1964) was used. Given the requirements of this study, an intermediate form of display was recommended. This type of display is useful in overcoming pure time delays by presenting future input and output information to allow the operator to take corrective action to compensate for the delay.

In summary, an intermediate display that would meet the needs of this research will contain the following elements.

1. Present system input

2. Future system input (desired path)

3. Present system output

4. Future system output

Pertinent literature indicates that a simplified teleoperated simulation can accurately predict the results of higher fidelity simulations. An example of this prediction is Black's (1970) 6-DOF experimental results confirming Ferrell's (1965) 2-DOF experimental results. With this in mind, the present study used a 2-DOF simulation to provide a preliminary look at the effects of delay variability and prediction on operator performance. This study was conducted such that the applicability of significant results should be transferable, at least in part, to higher fidelity simulations.

Using this approach, the prediction technique was also simplified for this study. Previous studies have developed a large number of prediction techniques for a broad range of applications, but for this study all that was needed was an indication of the system output at some future time as recommended by Wierwille (1964). Therefore a simple character was chosen to be used as the predictor cue.

METHODS FOR THE EXPERIMENT

Apparatus

An International Business Machine (IBM) Personal Computer (PC) was used to perform this research. The PC was equipped with 256K random access memory (RAM), two 360 kilobyte disk drives, and an internal clock. An IBM red-green-blue color graphics monitor was used in its medium-resolution text mode. This configured the monitor with a resolution of 320 x 200 pixels. The screen width of this monitor was 26.5 cm horizontal by 19.2 cm vertical. Connected to the input/output (I/O) port was an interface system (Metrabyte PIO12) containing a parallel digital input port (as well as other input and output devices). A hand controller was connected to the input port.

The hand controller was a pistol grip, two axis, spring centered device modified from a surplus antenna side-arm controller. In the positive and negative directions for each axes were two detent positions. Only the first detent was used in this experiment. To reach this first detent position in either direction for both axis, the hand control needed to be moved through an angular distance of 25 degrees from the vertical or neutral position. This required approximately 0.0077 joules (0.0104 ft-lb) of energy. Moving to the first detent position produced a constant acceleration of the simulated vehicle. This acceleration ceased when the stick was returned to the neutral position.

A trial began when the space bar on the keyboard was depressed by the experimenter after the subject indicated that he or she was ready to start. At the end of each trial the dependent measures were displayed on the screen and recorded by the experimenter.

Subjects

For this study 12 volunteer subjects were used, 6 males and 6 females. The subjects were screened initially using a vision test as described later.

Subjects were paid $3.50 per hour for their time spent in the experiment.

Experimental Design

The experimental design was a 4 x 2 complete factorial design, as shown in Figure 2. The within-subject design was chosen to minimize the number of subjects required to obtain a level of proficiency in controlling the vehicle.

Prediction	±0.00	±0.25	±0.50	±1.00
With	S_{1-12}	S_{1-12}	S_{1-12}	S_{1-12}
Without	S_{1-12}	S_{1-12}	S_{1-12}	S_{1-12}

Delay Variability Ranges (Second)

Figure 2: Experimental design

The two factors in this design were prediction and delay variability. The first factor, prediction, had two levels: with and without prediction. The second factor, delay variability, had four levels: 2.50 ± 0.00, 2.50 ± 0.25, 2.50 ± 0.50, and 2.50 ± 1.00 s. Each of these levels represented a range of time within which the variable delays were selected. Since both factors were within-subject variables, each subject received all eight treatment combinations in the design. Each of these treatment combinations was repeated three times. Therefore, each subject performed a total of 24 trials in an effort to minimize subject variability.

To minimize differential transfer effects both factors were counterbalanced. Prediction was counterbalanced across the design by presenting the predictive condition randomly to six of the subjects first and the non-predictive condition to the remaining six. The four levels of delay variability were counterbalanced with two balanced Latin squares, used one and a half times each, for each group of six subjects. These methods reduced the chance of an order effect confounding the results.

Delay variability. The delay variabilities were developed using a two-step process: (1) generating the varying delays that the subjects would experience during each trial, and (2) generating the length of time that each particular delay would be experienced by the subjects.

The first step consisted of determining the varying delays a subject would experience during a trial. The first level of delay variability was 2.50 ± 0.00 s. This was simply a constant delay of 2.50 s. The second level of delay variability was 2.50 ± 0.25 s. This meant that the subjects could expect to experience a time delay ranging from 2.25 to 2.75 s. Due to software implementation, only three delay values were used within this range; 2.25, 2.50, and 2.75 s. In discussions with N. Schields, he suggested that for a first approximation, each delay variability range should be normally distributed around the 2.5-s delay mean. Instead, a more conservative approach using a uniform distribution around the 2.5-s mean was used for this experiment. If a Gaussian distribution were to have been used, the extreme delay values for each range, assuming they were located three standard deviations from the mean in either direction, would have been experienced by the subjects during a task approximately 2% of the time. With a uniform distribution, these extreme values had the same probability of being experienced by the subjects as the mean delay. This approach allowed for more frequent testing of these extreme values. A random number generator was used to generate three uniform distributions containing these values. Three distributions were generated since each delay variability was to be tested three times.

The third level of delay variability was 2.50 $\pm$ 0.50 s. The possible delays that a subject would experience in this range were 2.00, 2.25, 2.50, 2.75, and 3.00 s. Again three uniform distributions were generated for this level of delay variability. This procedure was repeated again for the last level of delay variability, 2.50 $\pm$ 1.00 s. This produced a total of 12 delay distributions. The subjects were exposed to each of these distributions twice, once with the predictor and once without, bringing the total number of trials the subjects were asked to perform to 24.

The second step consisted of determining the length of time that a particular delay would be experienced by the subjects. This step generated what will be subsequently referred to as a delay profile. Each delay profile consisted of randomly changing lengths of time ranging between one and five seconds. This range was chosen based on discussions with T. Rasser of Martin Marietta and the experimenter's own judgement. These randomly changing lengths of time were used to vary the subject's exposure to the time delays for each level of delay variability. In total, 24 delay profiles were generated. As stated previously, each subject was assigned to a different ordered set of 24 trials with the use of balanced Latin squares. The delay profile order, on the other hand, was the same for all subjects regardless of trial order. This procedure resulted in presenting each subject with a different set of 24 delay profiles and delay variabilities. The purpose of this procedure was to control for order effects by counterbalancing the presentation order of the trials across the delay profiles.

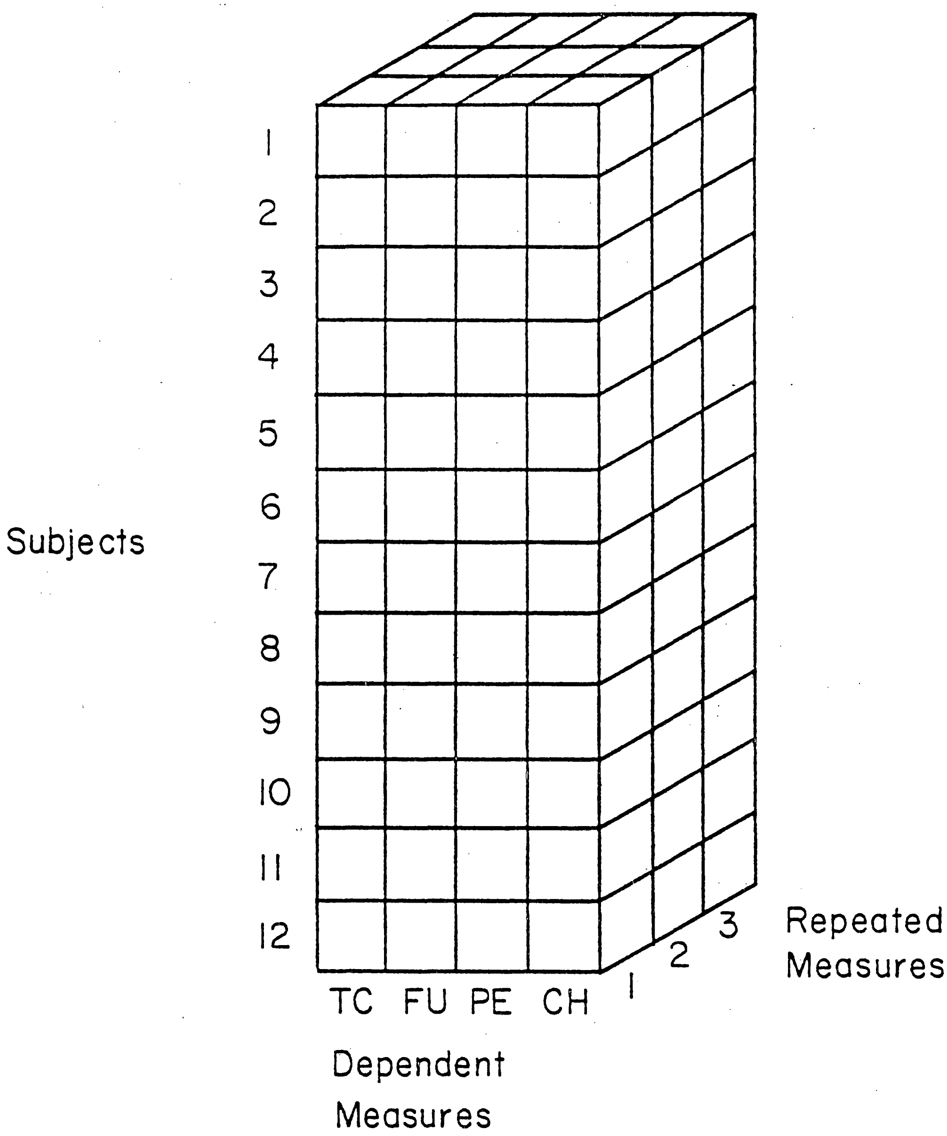
Independent and Dependent variables. The independent variables for this study were:

1. Delay variability
2. Prediction
3. Repeated Measures
4. Gender

For each of the cells in Figure 2, four dependent measures were recorded. These were:

1. Task completion time
2. Fuel usage
3. Weighted position error
4. Cooper-Harper rating

This cell design is shown in Figure 3.



Legend:

TC - Task Completion Time
FU - Fuel Used
PE - Position Error
CH - Cooper-Harper Rating

Figure 3: Cell design

Fuel usage was included in this experiment to measure task difficulty for two reasons. First, it was felt that fuel usage is more sensitive to the differences in the subject's techniques for controlling the vehicle. Two subjects may require the same amount of time to complete a run or may assign a similar subjective rating, but may use very different techniques. For instance, one subject may use a few and very small control inputs and wait while the vehicle translates slowly to the target while another uses many control inputs with greater thrust, thus requiring a greater amount of "jockeying" around the target. Even though they both may require the same time to complete the task, there is a difference in the fuel used. Second, during actual flight operations, the amount of fuel used will be a critical issue. The more fuel a spacecraft uses, the sooner it must be refueled. Using too much fuel to accomplish a task could jeopardize the successful completion of a mission. This was almost the case during the Solar Maximum Satellite repair mission on the Space Shuttle mission 41-C (Covault, 1984). The small amount of extra propellant remaining in the forward reaction control system of the Space Shuttle allowed for one final attempt to rescue the satellite after the first attempt failed. Fortunately this last attempt was successful.

As shown in Figure 4, the flight envelope was divided into three zones, each with a different weighting value. The subject was asked to fly to the flight path from the initial starting position and remain flying along this path until the vehicle reached the task completion box with a minimum amount of fuel expended (the requirement to end each trial is explained in the next section).

A weighted position error was calculated by summing an error score that was generated each 250 ms. The error score was calculated by multiplying the distance the vehicle was from the flight path by the weighting value assigned to the appropriate zone occupied by the vehicle: for Zone 1 the weighting value was 1, for Zone 2 it was 2, and for Zone 3 it was 4. The rationale used to generate this error score was based on the fact that the closer the vehicle was to the target, the more critical the deviations from the flight path. This error paradigm was adapted from an aircraft approach and landing study developed by Hyatt and Deberg (1974).

Error score and fuel usage were related such that when one was minimized it was usually at the expense of increasing the other. When the subjects had to make this trade-off they were instructed to minimize fuel usage.

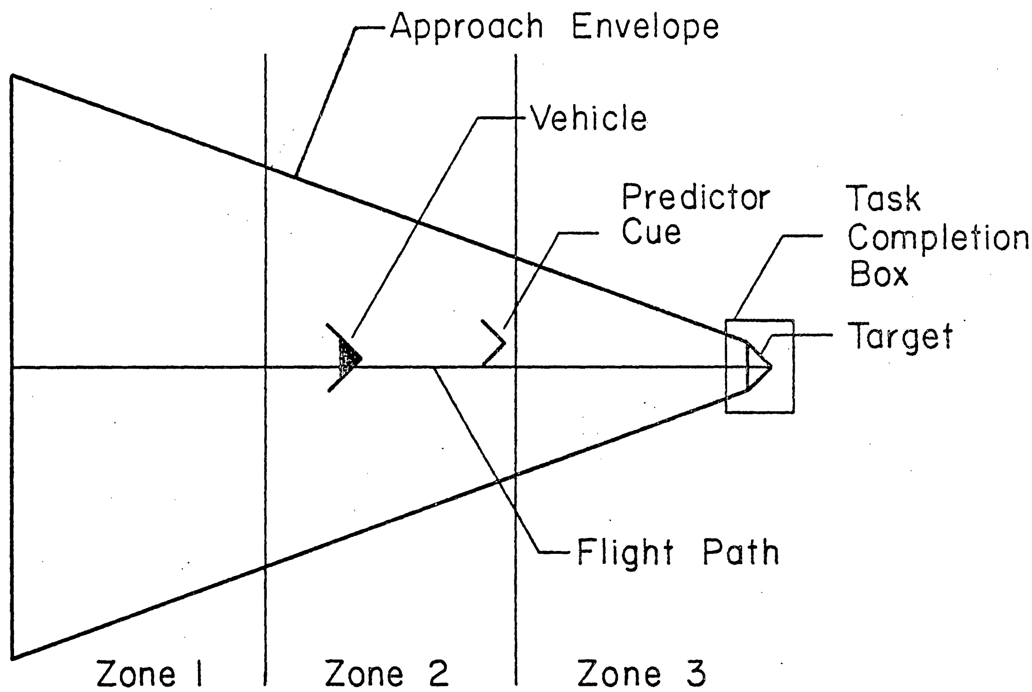


Figure 4: Flight path display

The Cooper-Harper rating scale was used to obtain subjective ratings of the task difficulty. This scale is described in Appendix D.

Task scenario. Two conditions were presented to each subject. In the first, the subjects flew the vehicle from a predetermined position off the desired path, with some initial velocity, to the target. The trial was completed when the subject maintained the vehicle within the task completion box for three seconds. The display was that shown in Figure 4, except that the predictor cue was absent. Each subject performed this task three times for each of the four levels of delay variability.

The second condition used the same display as the first and included a predictor cue (as shown in Figure 4) indicating the vehicle's position 2.5 s into the future, assuming the vehicle's velocity was not changed. The task completion requirement was the same as for the first scenario.

Software

This experiment simulated a vehicle in free space during the final phase of docking with a target. The vehicle represented a simplified spacecraft using only two degrees of freedom; translation in the x and z axes. The vehicle's dynamics were derived from the kinematic equations of motion for straight line motion with constant acceleration (Halliday and Resnick, 1974):

$$V = V_o + at, \text{ and} \tag{1}$$

$$d = d_o + 1/2\ (V + V_o)t, \tag{2}$$

where V is the velocity along an axis,

V_o is the initial velocity at $t = 0$,

a is the constant acceleration,

t is the time from $t = 0$,

d_o is the initial starting position, and

d is the displacement after $t = 0$.

These equations were modified to represent the dynamics of a vehicle in free space using an acceleration mode or "bang-bang" control system. First, since the hand controller inputs were read every 250 ms, both equations were used every 250 ms to update the vehicle's motion. The modifications to equation (1) were to let Vo represent the vehicle's velocity subsequent to the previous hand controller input and delete t. Equation (2) was modified by deleting Vo and t. These modifications allowed the vehicle to travel at a constant velocity when there were no inputs from the hand controller and to accelerate when the hand controller was displaced from the center position.

The acceleration for the vehicle in both axes was 1.2 cm/s^2 (8 $pixels/s^2$). Since the hand controller inputs were read every 250 ms, this allowed for a minimum vehicle velocity of 0.3 cm/s (2 pixels/s). These acceleration values were based upon the author's observations of several pilots controlling two types of space vehicle simulators, the OMV simulator and the Manned Maneuvering Unit simulator, and the author's own limited experience operating both these simulators. It was noted that small inputs lasting one second or less were used to control these vehicles when fine, slow maneuvers were desired. The dynamics for the vehicle in this experiment gave the subjects the ability to make these types of fine maneuvers.

To introduce a delay in the system a "delay pipeline" was used (W. Wierwille, Virginia Tech, personal communication, June 8, 1985). The pipeline was made up of individual cells that carried an input from the hand controller. The length of the pipeline, represented by the number of cells in the pipeline, changed as the delay changed. Prior to the start of the task all the cells were initialized with zero acceleration commands. Once the task began, all the values were moved to the next positions on the pipeline every 250 ms. The last value on the pipeline was used to control the vehicle and a new input from the hand controller was stored in the first position in the pipeline. This new input then worked its way down the pipeline, advancing one position per 250 ms, until it reached the end of the pipeline where it was used to control the vehicle. The duration of a particular delay and the length of time that a subject was exposed to it were described earlier in the Delay Variability section.

A predictor was used to show the subject where the vehicle would be 2.5 seconds in the future from any given time. The predictor's position was determined using the current position and velocities of the vehicle in the x and z axes and calculating where it would be in 2.5 seconds.

All the software was written in compiled BASIC, version 1.00, written by Microsoft for IBM (IBM, 1982).

Procedures

The experiment was conducted over a period of two days for each subject, requiring approximately three hours of time per subject. On the first day subjects were presented with a series of pretesting, orientation, and training trials which introduced them to the vehicle's control characteristics and the four levels of delay variability. The second day began with training flights and finished with data collection flights. Each of these phases of the experiment (outlined in Table 1) is described in detail below.

Screening. Subjects volunteering to participate in this study were first asked if they played video games more than one hour per week. There are several video games that have control characteristics similar to the vehicle If they played more than an hour per week they were not accepted. If accepted, they were then tested for near visual acuity with a Bausch and Lomb Orthorater. A minimum of 20/20 near visual acuity (with correction where needed) was required.

Pretesting. Before the experiment began, the subjects were asked to read the general instructions for the experiment and the participant's informed consent form found in Appendices A and B, respectively. If a subject wished to participate after reading these documents, he or she signed

TABLE 1

Outline of Procedures for the Experiment.

1. Pretesting Scenarios
   a) Real-time, without prediction

2. Orientation Scenarios
   a) Real-time, without prediction
   b) 2.5 second delay without prediction
   c) 2.5 second delay with prediction

3. Training Scenarios
   a) Scenarios without prediction
      i) 2.5 ± 0.00 second delay
      ii) 2.5 ± 0.25 second delay
      iii) 2.5 ± 0.50 second delay
      iv) 2.5 ± 1.00 second delay
   b) Scenarios with Prediction
      i) 2.5 ± 0.00 second delay
      ii) 2.5 ± 0.25 second delay
      iii) 2.5 ± 0.50 second delay
      iv) 2.5 ± 1.00 second delay

Table 1

Outline of Procedures for the Experiment (con't)

4. Data Collection Scenarios

   a) For subjects 1 to 6

      i) Scenarios with prediction

      ii) Scenarios without prediction

   b) For subjects 7 to 12

      i) Scenarios without prediction

      ii) Scenarios with prediction

the informed consent form. Once the consent form was signed, the subjects were given more detailed instructions (Appendix C). If at any time the subjects needed clarification of the task or had a question, the experimenter was available to answer it.

The subjects were then seated in front of the computer terminal. The display was brought up on the computer screen (see Figure 4) and each component was explained: (1) the vehicle; (2) the approach envelope; (3) the flight path; (4) the target; and (5) the task completion box. The hand controller and the vehicle's dynamics were then described. After all questions were answered, the subjects were asked to practice controlling the vehicle in a real-time scenario without prediction.

This scenario began with the vehicle at the upper left-hand corner of the screen with no initial velocity. The subjects were asked to fly the vehicle from this point to the target and to maintain the vehicle within the task completion box for a total of three seconds. Each subject was asked to perform the task using fewer than 12 units of fuel. They were allowed to repeat the scenario until this performance criterion was met. Subjects unable to master the task within 15 minutes were to be paid for their time and dismissed. If, however, the subjects mastered the pretesting scenario they were requested to begin the Orientation and Training phases of the experiment. These phases exposed the subjects to the simulated transmission delays and the use of the predictor. All subjects who attempted this pretesting task were able to meet the previously described performance criterion. This procedure was employed in an effort to secure a homogeneous set of subjects who were able to acquire the skill to fly the vehicle proficiently in a relatively short period of time.

Orientation. The first orientation scenario required the subjects to fly the vehicle in a real-time, non-prediction condition for approximately 10 minutes. This scenario provided the subjects with the opportunity to get a better feel for the vehicle's control system. The second orientation scenario introduced the subjects to a constant 2.5-s delay between the time a hand controller input was made and the time the vehicle moved. All the subjects reported that they felt comfortable with the constant delay and were able to maintain good control of the vehicle after approximately 15 minutes of practice.

The third orientation task presented the subjects with a scenario using both a 2.5-s delay and a predictor showing the subjects where the vehicle would be 2.5-s in the future. All the subjects reported they felt comfortable with the predictor after about 15 minutes of practice. The subjects were then given a short break.

Training. After the break, the training phase began. The subjects were first asked to read the instructions explaining how the Cooper-Harper rating scale was to be used for this experiment (Appendix D). They were instructed to practice using it on the two groups of training scenarios that were to be performed that day.

The first group of four training scenarios introduced the subjects to the four levels of variability (±0.00, ±0.25, ±0.50, and ±1.00 s) around a 2.5-s mean delay. The subjects practiced each scenario for approximately five minutes. This gave the subjects two to three practice trials per level of variability. Upon completion of each trial, the subjects were asked to rate the trial using the Cooper-Harper scale.

The second group of four scenarios gave the subjects experience controlling the vehicle across the four levels of variability with the use of the predictor. Again, the subjects practiced each scenario for approximately five minutes.

Each of the eight training scenarios began with the vehicle in a different position on the left side of the screen and with different initial velocities in the x and z axes. The subjects were again reminded before they began to practice to minimize the fuel used for each scenario.

After completing these training scenarios, the subjects were asked if they would like to repeat any of the scenarios they had flown that day. If a subject did request more practice, it consisted of no more than three trials.

Data collection. The second day began with the subjects practicing the orientation scenarios. They were instructed to fly each one until they could perform it with a fuel expenditure of eight fuel units or less on two consecutive trials.

As stated before, the 12 subjects were randomly divided into two groups for data collection purposes; Group One received the scenarios without the predictor first and Group Two received the scenarios with the predictor first. For the subjects who performed the scenarios without the predictor first, additional practice using the training scenarios without the predictor began. Each of the four scenarios was practiced two or three times. Once the subject completed these practice tasks, the training was completed for the nonpredictor scenarios.

The subject then received the data collection trials without the predictor that were described in the Delay Variability section. Each trial began with one of two equally difficult initial conditions: (1) the vehicle placed 6 cm above the flight path with Vx = 0.15 cm/s (2 pixels/s) and Vz = - 0.3 cm/s (4 pixels/s), or (2) the vehicle placed 6 cm below the flight path with Vx = 0.15 cm/s and Vz = 0.3 cm/s. Upon completion of each trial the dependent measures were recorded by the experimenter. The software displayed the weighted position errors and the fuel used, and prompted the subject to use the Cooper-Harper scale to give a rating for that task.

The predictive trials were performed next. The subjects were given the four training scenarios with the predictive cue. Each scenario was again practiced two or three times. Once the subjects completed these practice trials, they were given the data collection prediction trials. The dependent measures were again recorded after these trials. The procedure was reversed for the subjects in Group Two.

Debriefing. The subjects were debriefed after the experiment was complete, with the experimenter noting any comments made about the experiment in general or about the tasks specifically.

RESULTS

Data Analysis

Of the 288 total observations, nine were deleted from the data set prior to statistical analyses. These data points were deleted because the subject performance was confounded in these cases in one of two ways: (1) the subject inadvertently activated the hand controller, or (2) the vehicle was flown to the edge of the display thus nulling the vehicle's velocity.

The General Linear Model (GLM) procedure in the Statistical Analysis System (SAS) computer software was used to preform all the analyses in this experiment (SAS Institute, 1982). GLM performed the multivariate analysis of variance (MANOVA) and the analysis of variance (ANOVA) for models with missing data by adjusting for the remaining effects of the factors resulting from the unbalanced design using the Type III sums of squares (Freund and Littell, 1981).

A MANOVA was first performed to determine if the independent variables (prediction, delay variability, repeated measures, and gender) significantly affected the dependent variables as a group. A MANOVA was chosen to prevent excessive alpha (Type 1) error that would have resulted by performing separate univariate ANOVA procedures (Tabachnick and Fidell, 1983). The results presented in Table 2 are based upon the $\underline{F}$-approximation $\underline{F}$-values and degrees of freedom from Wilks' criterion tests. An alpha level of 0.05 was used to select significant effects in this and all subsequent analyses.

From the multivariate analysis, delay variability and repeated measures main effects were found to be significant. Surprisingly, prediction did not significantly affect the subjects' performance. The entire analysis, with all the main effects and interactions, could not be performed since it required more degrees-of-freedom than were available in the model. Therefore, the third order interaction between delay variability, repeated measures, and prediction, the single fourth order interaction, and their their mutual error term were not included in the analysis.

Based upon the results of the MANOVA, four ANOVAs, one for each of the four dependent measures, were performed using delay variability and repeated measures as the independent variables. These results indicated that both fuel usage and Cooper-Harper ratings were significantly affected by delay variability and error score and task

TABLE 2

Two-Way MANOVA Summary for Effects of the Independent Variables on the Dependent Variables.

Source	df	U*	F	p
Between-Subject				
Gender (G)	1	0.6103	1.12	0.4199
Subject (S)/G	11	(Error Term for G)		
Within-Subject				
Prediction (P)	1	0.6033	1.15	0.4074
P x G	1	0.7067	0.73	0.6013
P x S/G	11	(Error Term for P, P x G)		
Delay Variability (D)	3	0.3419	2.99	0.0020
D x G	3	0.6037	1.26	0.2641
D x S/G	33	(Error Term for D, D x G)		
Repeated Measures (R)	2	0.0457	15.63	0.0001
R x G	2	0.6219	1.14	0.3634
R x S/G	22	(Error Term for R, R x G)		
P x D	3	0.5890	1.32	0.2247
P x D x G	3	0.3568	1.37	0.1459
P x D x S/G	33	(Error Term for P x D, P x D x G)		

Table 2

Two-Way MANOVA Summary for Effects of the Independent Variables on the Dependent Variables (con't).

Source	df	U*	F	p
D x R	8	0.7497	0.72	0.8308
D x R x G	8	0.7447	0.73	0.8119
D x R x S/G	88	(Error Term for D x R, D x R x G)		
P x R	2	0.8218	0.44	0.8895
P x R x G	2	0.6160	1.16	0.3482
P x R x S/G	22	(Error Term for P x R, P x R x G)		

* where U = Wilks' criterion

completion time were significantly affected by repeated measures. The summary tables for these analyses are presented in Tables 3, 4, 5, and 6.

Effect of Delay Variability. To examine how these two dependent measures were affected by the delay variability, the means are plotted in Figures 5 and 6. Additionally, Newman-Keuls analyses of the treatment means were performed to determine which of the individual delay variabilities had the most effect upon the fuel usage and Cooper-Harper ratings.

The highest level of delay variability ($\pm$1.00 s) produced a significantly greater usage of fuel than did the other three levels. The Newman-Keuls analysis for Cooper-Harper rating resulted in three distinct groups with the highest level of delay variability rated as the most difficult. These analyses are presented in Tables 7 and 8.

For the purpose of these analyses, the Cooper-Harper scale was treated as an interval scale based on the findings by Connor and Wierwille (1983). These experimenters evaluated workload assessment measures and found that the Cooper-Harper rating scale results agreed closely with the two parametric rating scale techniques' results, the Workload Compensation Interference/Technical Effectiveness rating scale and the Multidescriptor rating scale.

TABLE 3

ANOVA Summary for Effects of Delay Variability and Repeated Measures on Fuel Usage.

Source	df	MS	F	p
Between-Subject				
Subject (S)	11	107.04		
Within-Subject				
Delay Variability (D)	3	107.24	5.52	0.0035
D x S	33	19.42		
Repeated Measures (R)	2	3.31	0.26	0.7717
R x S	22	12.63		

TABLE 4

ANOVA Summary for Effects of Delay Variability and Repeated Measures on Error Score.

Source	df	MS	F	p
Between-Subject				
Subject (S)	11	50 864.57		
Within-Subject				
Delay Variability (D)	3	2656.23	0.97	0.4171
D x S	33	2729.29		
Repeated Measures (R)	2	8538.01	3.44	0.500
R x S	22	2480.36		

TABLE 5

ANOVA Summary for Effects of Delay Variability and Repeated Measures on Cooper-Harper Ratings.

Source	df	MS	F	p
Between-Subject				
Subject(S)	11	19.38		
Within-Subject				
Delay Variability (D)	3	15.01	10.91	0.0001
D x S	33	1.37		
Repeated Measures (R)	2	0.08	0.31	0.7342
R x S	22	0.13		

TABLE 6

ANOVA Summary for Effects of Delay Variability and Repeated Measures on Time.

Source	df	MS	F	p
Between-Subject				
Subject (S)	11	0.013		
Within-Subject				
Delay Variability (D)	3	0.025	0.61	0.6141
D x S	33	0.041		
Repeated Measures (R)	2	0.707	84.13	0.0001
R x S	22	0.008		

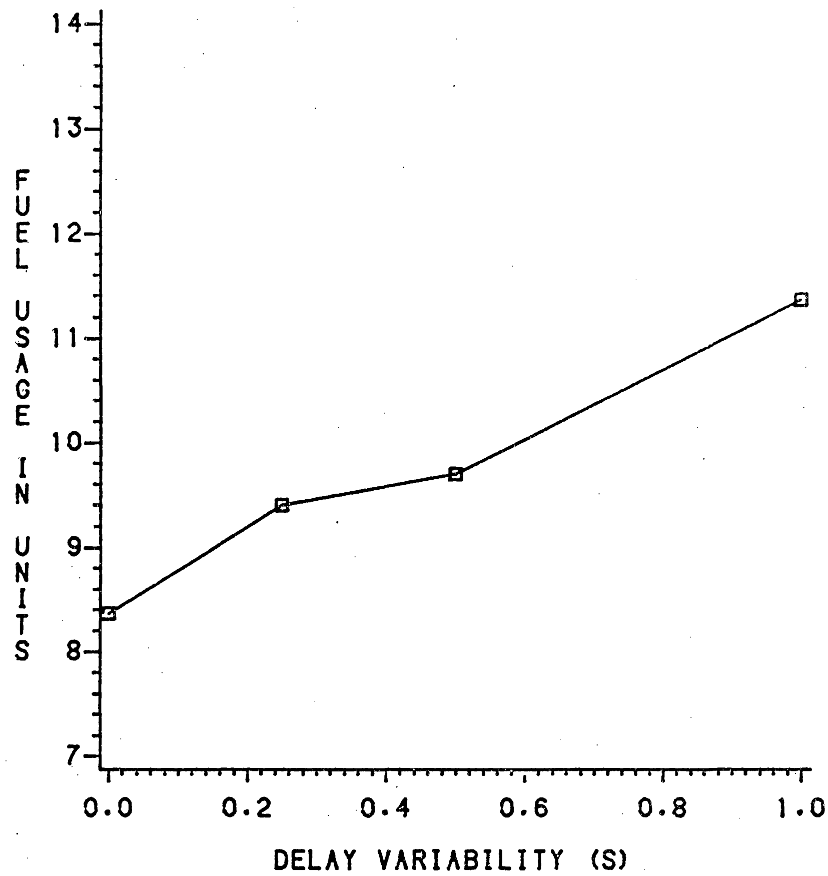


Figure 5: Mean fuel usage vs. delay variability.

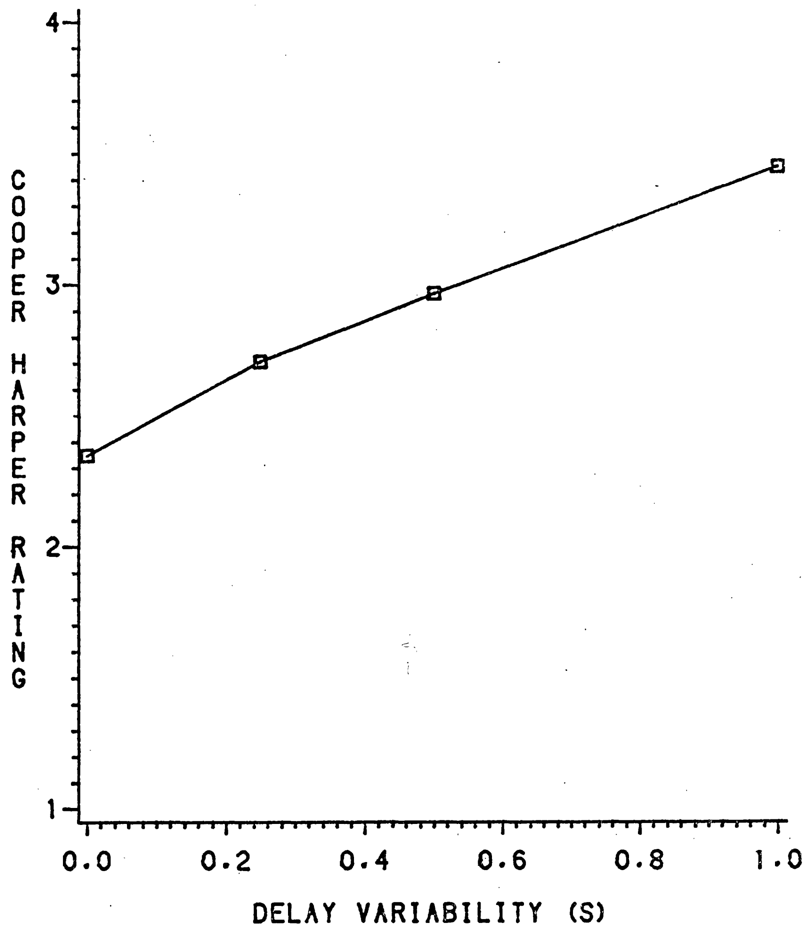


Figure 6: Mean Cooper-Harper ratings vs. delay variability.

TABLE 7

Newman-Keuls Results for the Effect of Delay Variability On Fuel Usage.

	Delay Variability (s)			
	0.00	0.25	0.50	1.00
Means*	8.37	9.41	9.70	11.37

* Treatment means with a common underline do not differ significantly from each other at $p < 0.05$

TABLE 8

Newman-Keuls Results for the Effect of Delay Variability On Cooper-Harper Rating.

	Delay Variability (s)			
	0.00	0.25	0.50	1.00
Means*	2.36	2.71	2.97	3.46
	————	————		
		————	————	
				————

* Treatment means with a common underline do not differ significantly from each other at $p < 0.05$

Effect of Repeated Measures. Newman-Keuls analyses of the treatment means were performed to determine how the repeated measures affected the error score and the task completion time. These analyses are presented in Tables 9 and 10.

The error scores decreased approximately 10 points for each successive repeated measure. This result was due to the subjects maneuvering the vehicle to the flight path and stabilizing it there sooner as they repeated each treatment combination.

The task completion time analysis indicated that each repeated measure had a significantly different mean. This result is misleading since all the subjects did not alter the forward velocity imparted to the vehicle at the beginning of each trial. The reader should note that the mean task completion time is 141.30 s and the maximum difference between any two repeated measures is 0.18 s. The variability in the task completion time was due to the variability of the experimenter manually ending each trial.

Post-Hoc Analyses

An additional analysis was performed to further examine the results of this experiment so as not to mislead the reader. This analysis was conducted as a result of an

TABLE 9

Newman-Keuls Results for the Effect of Repeated Measures On Error Score.

	Repeated Measures		
	1	2	3
Means*	176.94	167.06	157.88

* Treatment means with a common underline do not differ significantly from each other at $p < 0.05$

TABLE 10

Newman-Keuls Results for the Effect of Repeated Measures On Task Completion Time.

	Repeated Measures 1	2	3
Means*	141.29	141.21	141.39

* Treatment means with a common underline do not differ significantly from each other at $p < 0.05$

observation made by the experimenter during data collection. Each subject performed at least one trial in which he or she used a substantially larger quantity of fuel when compared to similar trials. It was thought that these "outlier" data points may be masking some other important result. To determine which data to remove, the fuel usage means and standard deviations were calculated for each of the eight treatment combinations. Any fuel usage value that fell outside of one standard deviation from the mean was deleted from the data set. Using this criterion, 25 data points were deleted from the data set.

A two-way MANOVA was conducted using the modified data set. As stated before, the SAS software takes into account these missing data points when performing the requested analyses. As can be seen from Table 12, this analysis demonstrated that these higher fuel usages did not cause any major change in the outcome when compared with the MANOVA of Table 2. A single one-way ANOVA for fuel usage was also performed using the modified data set. The summary table from this analysis is presented in Table 13.

Finally, a Newman-Keuls analysis was performed (Table 14). The results indicated that once again the fuel usage for the greatest delay variability was significantly larger than for the other variabilities. Additionally, however,

TABLE 12

Two-Way MANOVA Summary for Effects of the Independent Variables on the Dependent Variables Using a Modified Data Set.

Source	df	U*	F	p
Between-Subject				
Gender (G)	1	0.5331	1.53	0.2914
Subject (S)/G	11	(Error Term for G)		
Within-Subject				
Prediction (P)	1	0.6525	0.93	0.4974
P x G	1	0.7067	0.73	0.6013
P x S/G	11	(Error Term for P, P x G)		
Delay Variability (D)	3	0.1939	5.13	0.0001
D x G	3	0.6037	1.26	0.2641
D x S/G	33	(Error Term for D, D x G)		
Repeated Measures (R)	2	0.1591	6.40	0.0001
R x G	2	0.6617	0.97	0.4722
R x S/G	22	(Error Term for R, R x G)		
P x D	3	0.6069	1.24	0.2730
P x D x G	3	0.3568	1.37	0.1459

Table 12

Two-Way MANOVA Summary for Effects of the Independent Variables on the Dependent Variables Using a Modified Data Set (con't).

Source	df	U*	F	p
P x D x S/G	33	(Error Term for P x D, P x D x G)		
D x R	8	0.6117	1.22	0.2310
D x R x G	8	0.6398	1.10	0.3486
D x R x S/G	88	(Error Term for D x R, D x R x G)		
P x R	2	0.4940	1.80	0.1122
P x R x G	2	0.4760	1.91	0.0908
P x R x S/G	22	(Error Term for P x R, P x R x G)		

* where U = Wilks' criterion

TABLE 13

ANOVA Summary for Effects of Delay Variability and Repeated Measures on Fuel Usage Using a Modified Data Set.

Source	df	MS	F	p
Between-Subject				
Subject (S)	11	35.45		
Within-Subject				
Delay Variability (D)	3	66.04	8.90	0.0002
D x S	33	7.42		
Repeated Measures (R)	2	1.72	0.30	0.7463
R x S	22	5.82		

the fuel usage for the second and third delay variabilities (2.50 ±0.25 and 2.50 ±0.50 s) differed significantly from the first variability (2.50 ±0.00 s). The means for the modified fuel usage were calculated and plotted against delay variability and are presented in Figure 7.

TABLE 14

Newman-Keuls Results for the Effect of Delay Variability On Fuel Usage.

	Delay Variability (s)			
	0.00	0.25	0.50	1.00
Means*	7.63	8.16	8.84	10.00

* Treatment means with a common underline do not differ significantly from each other at $p < 0.05$

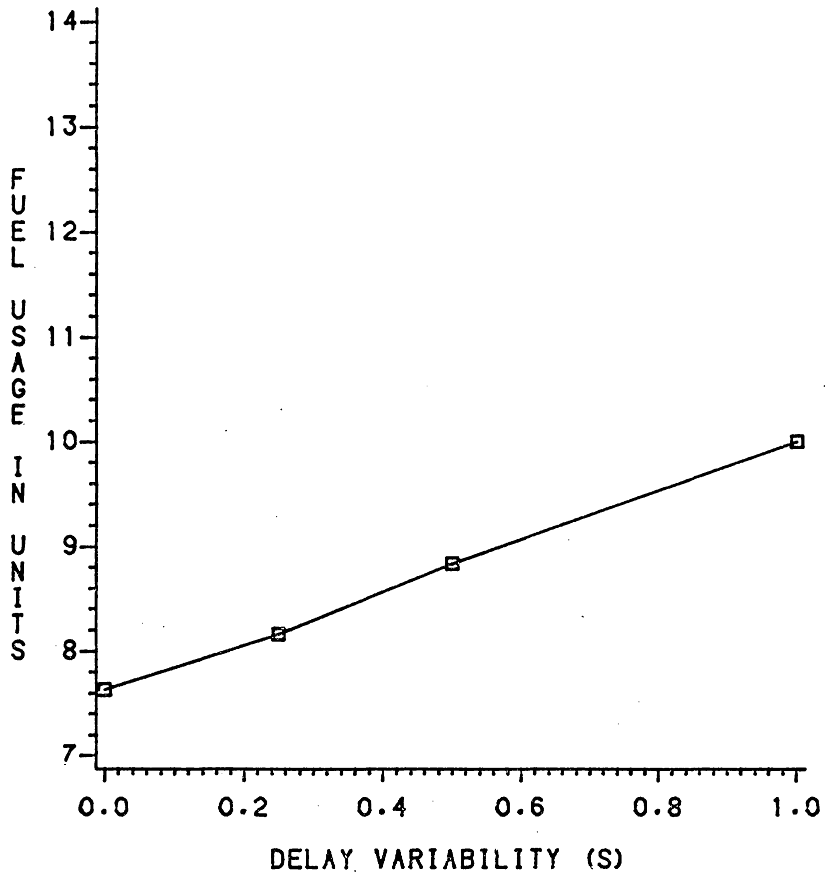


Figure 7: Mean fuel usage vs. delay variability using the modified data set.

DISCUSSION

Delay Variability Effect

The analyses for fuel usage demonstrated that as the delay variability increased, so did the fuel usage. It was observed, though, that all subjects on every run were able to stabilize the vehicle on the flight path prior to entering the task completion box. These findings point to a greater difficulty in maneuvering the vehicle as delay variability increased although the subjects were able to compensate accordingly and successfully complete each task.

The Cooper-Harper rating results demonstrated that as the delay variability increased, so did the subject's perception of the task difficulty. This result agrees with the previous discussion. Also, the grouping of the delay variabilities in the Cooper-Harper Newman-Keuls analysis was very similar to the delay variability grouping in the Newman-Keuls analysis for fuel usage using the modified data set. This result again points to the similarities in the subject's perceived difficulty of the tasks and their actual performance.

As stated earlier, the subjects were informed of the level of delay variability prior to the beginning of each task. This procedure was used to duplicate accurately the best estimate of actual flight operations. A pilot controlling an operational space vehicle would know the amount of delay variability and would be trained to compensate for it. In this experiment, each subject was trained to control the vehicle for each level of delay variability before data were collected.

For future studies, two methods could be used to minimize the effect of informing subjects, if it did occur, of the level of delay variability. One method would be to use a between-subject design although subject variability could increase. The other method would be to inform the subjects that they will experience only one range of delay variability, the largest the experiment was testing, and have them operate all levels of delay variability under this assumption. This small amount of deception would cause few, if any, problems for the subjects.

Error score, on the other hand, was not significantly affected by delay variability. This was probably due to the fact that the subjects were told to minimize their fuel usage as their first priority. Therefore, small inputs were made to slowly bring the vehicle down to the flight path.

The longer the vehicle was above or below the flight path, the greater the error score.

After analyzing the data, it was felt by the experimenter that if the subjects were asked to minimize error score instead of fuel usage, a greater use of fuel would have been the result for two reasons. First, the faster the vehicle accelerated to get to the flight path, to minimize the error score, the greater the quantity of fuel used. Also, the greater the vehicle's velocity, the farther it would travel if the deceleration command was not read in time to stop the vehicle's motion in a variable delay scenario. It is the opinion of the experimenter that the result would be higher fuel usage in addition to an increase in the error score. This result would defeat the strategy of getting to the flight path quickly to reduce the error score.

Secondly, based on observations of the subjects during orientation and training, the faster they flew the vehicle, the greater the difficulty they had stabilizing it on the flight path. Pilot induced oscillations resulted from these frequent inputs which in turn increased fuel usage and error score. Therefore, considering the results of this experiment, it is felt that this type of error score paradigm would not be useful in the way it was implemented in this type of spacecraft study.

Error score was significantly affected by repeated measures. It is the opinion of the experimenter that this was the result of the subjects gaining experience with each repetition of a treatment combination and inputting the commands to maneuver the vehicle earlier in the trial.

As it turned out, task completion time was not a good measure for task difficulty. The reason for this result differing from the previous studies is that all subjects used as little forward velocity as possible to reduce fuel usage. Thus, all the subjects flew the vehicle as slow as possible to the target resulting in all the subjects requiring the same amount of time to reach the target.

Speed is typically not an important factor when maneuvering a space vehicle. Since the vehicle was initially given a small amount of forward velocity in this study, it was rarely adjusted by the subjects. If the vehicle were to have been at rest at the beginning of the data collection trials, as it was in two of the training scenarios, the subjects would have used the smallest amount of forward acceleration along the x axis to get to the target. This strategy of using the smallest amount of forward velocity would have resulted in a similar outcome in which the subjects would require the same amount of time to complete the task. The critical maneuvering in this experiment was conducted in the z axis, which was measured by the dependent variable fuel usage. It is the opinion of the experimenter that later studies incorporating the third translational DOF (in the y axis) would have similar results with task completion time in that the operators would require approximately the same amount of time to complete a docking task with a stationary, cooperative target. Studies involving vehicles with rotational DOFs, which are discussed later, will probably have greater use for this dependent variable measuring task difficulty.

Predictor Effect

Two possible theories are presented to explain why the predictor did not have a significant effect upon the subjects performance. The first theory involves the task itself, while the second applies to the predictor. A combination of both is believed to have been the cause of this study's results.

The first explanation is based upon the difficulty of the task itself. If the task was too easy, the predictor would have provided only a small amount of useful information to the subjects concerning the future position of the vehicle.

The two initial conditions used in this experiment were employed for two reasons: (1) to make the trials equally difficult, and (2) to represent a docking task with a stabilized target. These initial conditions, as a result, gave the vehicle a relatively docile initial velocity. In an actual docking situation, though, a spacecraft would not intentionally be approaching its target with a high velocity, but instead would have a relatively slow approach velocity while performing these final docking maneuvers.

The second possibility concerns the predictor itself. Since the delay variability was random, there was no way to know what the delay would be at any given time. It was therefore impossible to provide a 100% accurate predictor. With this in mind, the predictor's position was based on the mean delay of 2.5 seconds. In other words, no matter what the delay actually was, the predictor indicated where the vehicle would be in 2.5 seconds. What may have caused the predictor's inability to significantly affect these subject's performance was that it was not accurate enough for this type of easy, docile task in which the subjects could eventually compensate for the delay variability and successfully complete the task.

General Comments

For all the analyses, gender was included as an independent variable since past studies in manual control tasks have occasionally indicated gender differences. The results of this experiment indicated that this variable had no effect on a subject's ability to control this vehicle.

None of the subjects had ever operated a vehicle similar to the one used in this experiment. Therefore, approximately three hours of training were used, with performance criteria employed to gauge the subjects increasing ability, to bring them to a point where they were approximately equal in their skill levels in operating the vehicle. Initially, all subjects used frequent and long control inputs to maneuver the vehicle. This resulted in induced oscillations when subjects attempted to slow down the vehicle or change its directions. Eventually all the subjects used the "move-and-wait" strategy used by subjects in previous delay experiments (Black, 1970; Ferrell, 1965; Martin Marietta, 1982; Pennington, 1983; and Sheridan, 1963). A second strategy was also used to compensate for the long delays in the system. When small changes in the vehicle's position were desired, the subjects had to anticipate the vehicle's motion after an input was made before a second input was commanded in the opposite direction to stop the vehicle's motion. This second input was made before the subject was able to view the results of the initial input. This tactic was also used by the pilots in the Martin Marietta (1982) study.

CONCLUSIONS AND SUGGESTIONS FOR FUTURE RESEARCH

This experiment found that the subjects used a significantly larger quantity of fuel maneuvering the vehicle during the condition in which they experienced the greatest delay variability, 2.50 ± 1.00 s. From the Cooper-Harper rating analyses, the subjects felt that this situation warranted improvement 44% of the time.

One of the findings of this experiment was that the predictor did not significantly affect the subjects performance. This indicates that the type of predictor used in this study may not be a useful tool in a variable time delayed teleoperated spacecraft docking task using a stabilized target. The slow velocities used and the motionless target allowed the trained subjects to eventually compensate for the variable delays. Studies involving greater uncertainty of a vehicle's future position, due to the variable delays and an increase in task complexity, may demonstrate that this type of predictor could be a useful tool for more complicated spacecraft docking situations.

Therefore, several strategies could be used to increase the difficulty of this task. Adding the third translation

DOF would increase task difficulty by requiring the subjects to control for an additional dimension. Adding the full six DOFs to the simulation would allow the subjects to compensate for center of gravity offsets (which would couple translational and rotational motions) and to match rotation rates with a spinning target, both realistic situations. These strategies are expected to give the predictor the ability to provide a greater amount of useful information to the operator, thus potentially increasing the operator's performance.

A final suggestion for future research is to use an inside-out display. The outside-in display served its purpose for the limited scope of this experiment. For follow-on studies, involving a greater number of DOFs, the inside-out would be preferable since it would allow all the DOFs to be presented to the operator on one display. This is also the type of display that is expected to be used for operational flights.

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Appendix A

INTRODUCTION TO THE EXPERIMENT

This study will investigate the effects of simulated variable transmission delays on the operation of a free-flying teleoperated space vehicle. The study will also look into the effect of a predictive cue in conjunction with the variable delay and assess its impact on the operation of the vehicle. The research is being conducted in the Department of Industrial Engineering and Operations Research (IEOR) at the Virginia Polytechnic Institute and State University located in Blacksburg, Virginia 24060. The research is being conducted by graduate student Michael Merriken (961-7962) under the direction of Dr. Walter W. Wierwille, professor in the Department of IEOR.

All of the tasks will be performed at a microcomputer using a control stick. Your task as a participant in this study is to first become familiar with the handling characteristics of the simulated vehicle. After you have acquired the desired proficiency you will then be given the same type task to perform with a variable delay and finally a prediction will be included with the variable delay. Upon the completion of these training tasks you will be asked to perform a set of similar flying tasks to the best of your ability and then assign a subjective rating value to the handling characteristics of the vehicle in each scenario.

Participation in the study is entirely voluntary and you have the right to discontinue the experiment at any time. If you choose to participate you will need to attend a training session of approximately one hour, including the introduction and breaks, where you will be trained to fly the simulated vehicle. You will be asked to fly the vehicle with no transmission time delays and with no predictor until a desired level of performance has been achieved. If within a specified time you are not able to achieve this level of performance you will be asked to leave the study and will be paid for your time. You should be aware that many people are expected not to be able to achieve the desired level of performance. Should you turn out that you are one of them, this is no cause for alarm and is not a reflection of your intelligence or general aptitude. If, however, you do become proficient in flying the vehicle you will be given another training task. This task will be similar in nature to the first task but a 2.5 second delay will be added between the time you make a command input with the control stick and when the vehicle responds to that input. After several trials with the constant delay you will be given eight more tasks to perform. These will give you practice controlling the vehicle with the four variable delays with and without the predictor cue.

You will then be asked to return a second day to perform these same tasks. After arriving you will first fly the vehicle in the no delay, no prediction scenario until the specified performance level is again achieved. You will then fly two groups of flights each with four training tasks before the data collection tasks begin. After each flight you will be asked to rate the controllability of the vehicle in that task. A break will be given between the two groups of trials.

You will receive $3.50 per hour after you have completed the second group of tasks for the time spent in the experiment, including breaks. The entire experiment, over the course of two days, should require a total of three hours of your time.

I hope this experiment will be an interesting experience for you. It is possible that at times you may feel frustrated or stressed. At times the task may seem difficult. Just remember, your level of performance on the task reflects only on the difficulty of the task. After you have completed the experiment, your data will be treated anonymously.

Your participation is greatly appreciated. If you have any questions about the experiment please do not hesitate to ask. I will answer your questions openly and honestly as possible without biasing the experiment. Please do not discuss the experiment with other persons, especially students who may participate in this study.

Since it is expected that all data will be collected by September 1, 1985, you may feel free to discuss the experiment with anyone after that time. If more detailed information is desired at that time, please contact me and a full report will be made available to you.

Appendix B

PARTICIPANT'S INFORMED CONCENT

The purpose of this document is to obtain your consent to participate in this experiment and to inform you of certain rights you have as a participant.

You have the right to stop participating in the experiment at any time. If you choose to terminate the experiment, you will receive pay only for the portion of the time that you participated.

You have the right to be informed of the overall results of the experiment. If you would like a summary of the results please include your address with your signature an the next page. If more detailed information is desired at that time, please contact the researcher and a full report will be made available to you.

If you have any problems with or questions about the research itself, you may contact Dr. Walter W. Wierwille at 961-7952. If you have questions about your rights as a participant, you may contact Mr. Charles D. Waring, Chairman of the Institutional Review Board at Virginia Tech at 961-5283.

The risks involved in this experiment are minimal; no more than you would experience in your day to day life.

Your signature below indicates that you have read your above stated rights as a participant and that you consent to participate. If you include your printed name and address below, a summary of the experimental results will be sent to you.

signature

Appendix C

INSTRUCTIONS FOR THE EXPERIMENT

In front of you is an IBM Personal Computer. On the screen the experimenter will point out: (1) the vehicle; (2) the approach envelope; (3) the flight path; (4) the target; and (5) the task completion box. The handcontroller ,also in front of you, will be used to control the vehicle. It is a pistol grip, two axis, spring centered stick. In the positive and negative directions for each axis there are two detent positions. Only the first detent will be used for this experiment. Moving to the first detent position will produce a constant acceleration on the simulated vehicle. This acceleration will cease when the stick is returned to the neutral or center position. However, the vehicle will continue to move at a constant velocity. This must be removed by a control movement in the opposite direction.

The vehicle you will be flying has the control dynamics and responses of a vehicle in free space. The vehicle will follow Newton's first law; an object in motion will stay in motion unless acted upon by an outside force. Since there is no air friction or gravity in free space there is nothing to stop the vehicle moving once it has been set in motion except for the propulsion system on the vehicle. Your handcontroller will control its propulsion system.

Before you begin a trial, I will inform you when you may begin. When you feel ready to start depress the space bar on the keyboard.

You will be asked to fly two types of scenarios. The first will be to fly the vehicle from a position within the approach envelope, with some initial velocity, to the flight path and continue to the target. The trial will end when the vehicle remains in the task completion box for three seconds. There is no time limit to complete these trials but you should try to reach the task completion box and stay within its boundaries with a minimum amount of control inputs and fuel consumed. There will be four lengths of delay variability presented to you each three times.

The second scenario will be identical to the first except that a prediction cue will be included. This cue will indicate where the vehicle will be 2.5 seconds from any given moment if the vehicle's velocity has not changed. The task completion requirements are the same as the first scenario.

After each task you will be prompted by the computer to use the Cooper- Harper scale to assign a rating to the task.

The instructions to use this scale will be given to you before the experiment begins.

If you have any questions regarding the procedures of the experiment, please ask the before the experiment begins.

If you have any questions now, please ask them.

Appendix D

COOPER-HARPER RATING SCALE INSTRUCTIONS

Overview

After each of the following trials, you will be asked to give a rating on the Cooper-Harper rating scale for vehicle controllability (Cooper and Harper, 1969). This rating scale is shown in Figure 8. Before you begin, we will review:

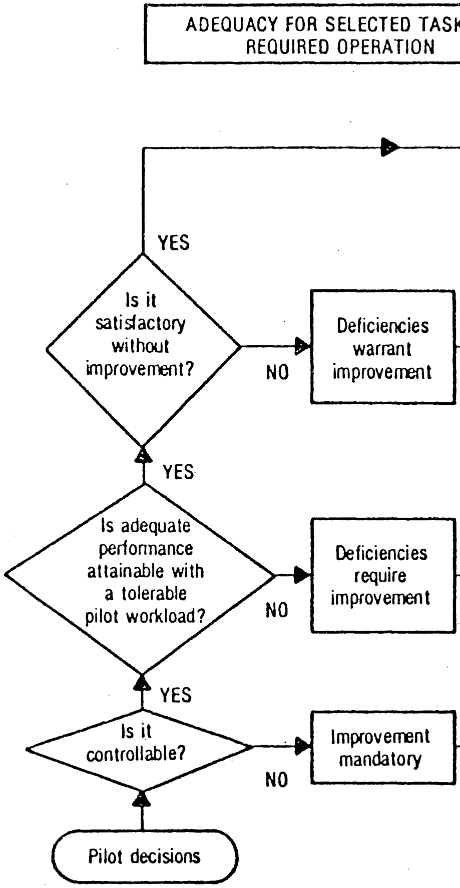
1. The definitions of the terms used in the scale
2. The steps you should follow in making you ratings on the scale, and
3. How you should think of the ratings.

If you have any questions as we review these points please ask me.

Important Definitions

To understand and use the Cooper-Harper scale properly, it is important that you understand the terms used on the scale and how they apply in the context of this experiment.

First, the pilot in this situation is you. You will be flying the vehicle and using the rating scale to quantify your experience.



SPACE CRAFT CHARACTERISTICS	DEMANDS ON THE PILOT IN SELECTED TASK OR REQUIRED OPERATION*	PILOT RATING
Excellent Highly desirable	Pilot compensation not a factor for desired performance	1
Good Negligible deficiencies	Pilot compensation not a factor for desired performance	2
Fair-Some mildly unpleasant deficiencies	Minimal pilot compensation required for desired performance	3
Minor but annoying deficiencies	Desired performance requires moderate pilot compensation	4
Moderately objectionable deficiencies	Adequate performance requires considerable pilot compensation	5
Very objectionable but tolerable deficiencies	Adequate performance requires extensive pilot compensation	6
Major deficiencies	Adequate performance not attainable with maximum tolerable pilot compensation. Controllability not in question.	7
Major deficiencies	Considerable pilot compensation is required for control	8
Major deficiencies	Intense pilot compensation is required to retain control	9
Major deficiencies	Control will be lost during some portion of required operation	10

*Definition of required operation involves designation of flight phase and/or subphases with accompanying conditions.

Figure 8: Cooper-Harper subjective rating scale

Second, the vehicle characteristics include all the elements of the system. For this experiment the vehicle dynamics, the time delays, and the prediction cue (when applicable) make up the vehicle control characteristics.

Third, deficiencies are defined as shortcomings in the system that make the vehicle difficult to control.

Finally, the workload is the amount of mental effort required to fly the vehicle in the various situations.

Rating Scale Steps

On the Cooper-Harper scale you will notice that there are a series of decisions that follow a predetermined logical sequence. This logic sequence is designed to help you make more consistent and accurate ratings. Thus, you should follow the logic sequence on the scale for each of your ratings in this experiment. The steps that you will follow areas follows:

1. First you will decide if the vehicle is controllable enough to accomplish the task reliably; if not, then your rating is a 10 and you should score a 10 when the computer prompts you.

2. Second, you will decide if adequate performance is attainable. Adequate performance means that there is at least a tolerable pilot workload and there are no major deficiencies in the vehicle's handling characteristics. If not, then you should proceed to the right. By reading the descriptions associated with numbers 7, 8, and 9 you should be able to select the one that best describes the situation you have experienced. You should then score the appropriate number when the computer prompts you.

3. If adequate performance is attainable, your next decision is to decide if the vehicle's control characteristics are satisfactory without any improvement. If you feel some improvement is necessary then select a rating of 4, 5, or 6. One of these three ratings should describe the situation you have experienced and you should score it accordingly.

4. If the vehicle was controllable with a minimum amount of pilot workload, you should move to the top three descriptions on the scale. You should read and carefully select the rating 1, 2, or 3 based on the corresponding descriptions that best describe your experience. Score the number you have selected.

How You Should Think of the Ratings

Before you begin making ratings there are several points that need to be emphasized. First, be sure to try to perform the task to the best of you ability.

Second, the rating scale is not a test of your personal skill. On all of your ratings, you will be evaluating the vehicle's control characteristics for a general population, not just yourself. You may assume you are an experienced member of that population. You should make the assumption that problems you encounter are not problems you created. They are problems created by the system and the instructed task. In other words, don't blame yourself if the vehicle's handling characteristics are deficient, blame the vehicle.

Third, try to avoid the problem of nit picking an especially good set of vehicle control characteristics, and of saying that a set of characteristics that is difficult to use is not difficult to use at all. These problems can result in similar rating for characteristics which are quite different. Also try not to overreact to small changes in the control characteristics. This can result in ratings that are extremely different when in fact they are quite similar. Thus to avoid any problems, always try to "tell it like it is" when making your ratings.

If you have any questions please ask the experimenter at this time.

Appendix E

ACRONYMS AND INITIALISMS

A-D	Analog to Digital
ANOVA	Analysis of Variance
DOF	Degree of Freedom
DOMSAT	Domestic Satellite
GLM	General Linear Model
IBM	International Business Machines, Inc.
I/O	Input/Output
IEOR	Industrial Engineering and Operations Research
MANOVA	Multivariate Analysis of Variance
NASA	National Aeronautics and Space Administration
NASCOM	NASA Communications System
OMV	Orbital Maneuvering Vehicle
PC	Personal Computer
POCC	Payload Operations Control Center
SAS	Statistical Analysis System
STS	Space Transportation System
TDRS	Tracking and Data Relay Satellite

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