Spatial Ability and Handedness as Potential Predictors of Space Teleoperation Performance

by

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B.S. in Aerospace Engineering
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Submitted to the Department of Aeronautics and Astronautics in partial fulfillment of the requirements for the degree of

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Abstract

NASA is concerned with finding performance predictors for space teleoperation tasks in order to improve training efficiency. Experiment 1 determined whether scores on tests of spatial skills could predict performance when selecting camera views for a simulated teleoperation task. The hypothesis was that subjects with high spatial ability would perform camera selection tasks more quickly and accurately than those with lower spatial ability, as measured by the Mental Rotation Test (MRT), Purdue Spatial Visualization Test (PSVT), and the Perspective Taking Ability (PTA) test. Performance was defined by task time, number of correct camera selections, preparation time, number of camera changes, and correct identification of clearance issues. Mixed regression and non-parametric tests showed that high-scoring subjects on the MRT and PTA spatial ability tests had significantly lower task times, higher camera selection scores, and fewer camera changes than subjects with lower scores, while High PSVT scorers had significantly lower preparation times.

Experiment 2 determined whether spatial ability, joystick configuration, and handedness influenced performance of telerobotic fly-to tasks in a virtual ISS environment. 11 right-handed and 9 left-handed subjects completed 48 total trials, split between two hand controller configurations. Performance was defined by task time, percentage of translational and rotational multi-axis movement, percentage of bimanual movement, and number of discrete movements. High scorers for the MRT, PSVT, and PTA tests had lower Task Times, and High PSVT and PTA scorers made fewer Discrete Movements than Low scorers. High MRT and PTA scorers had a higher percentage of translational and rotational multi-axis movement, and High MRT scorers had a higher percentage of bimanual movement. The overall learning effect appears to be greater than the effect of switching between hand controller configurations. No significant effect of handedness was found. These results indicate that these spatial ability tests could predict performance on space teleoperation tasks, at least in the early phases of training. This research was supported by the National Space Biomedical Research Institute through NASA NCC 9-58.

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1 Introduction

The experiments in this thesis were designed to improve our understanding of how spatial ability and handedness could potentially affect performance in space teleoperation. The robotic arms on the Shuttle and Space Station have been crucial for space operations, so the identification of critical skills and abilities that may affect operator performance is one that warrants further investigation. Robotics training is a long process, and finding predictors of performance is important and could be used to customize individual training.

The Space Shuttle Payload Deployment and Retrieval System (PDRS)[1] and Space Station Remote Manipulator System (SSRMS)[2] are valuable systems that have been used to complete diverse space exploration tasks which include satellite deployment, payload maintenance, repair and inspection of the Space Shuttle, and construction of the International Space Station (ISS). Two windows and six cameras provide Shuttle astronauts with views of their task environment. On the ISS, arm operators must depend on three visual displays to provide camera views of the workspace. Translational motions of the arm are controlled with the left hand joystick, and rotational motions with a right hand joystick (Figure 1.1, right).

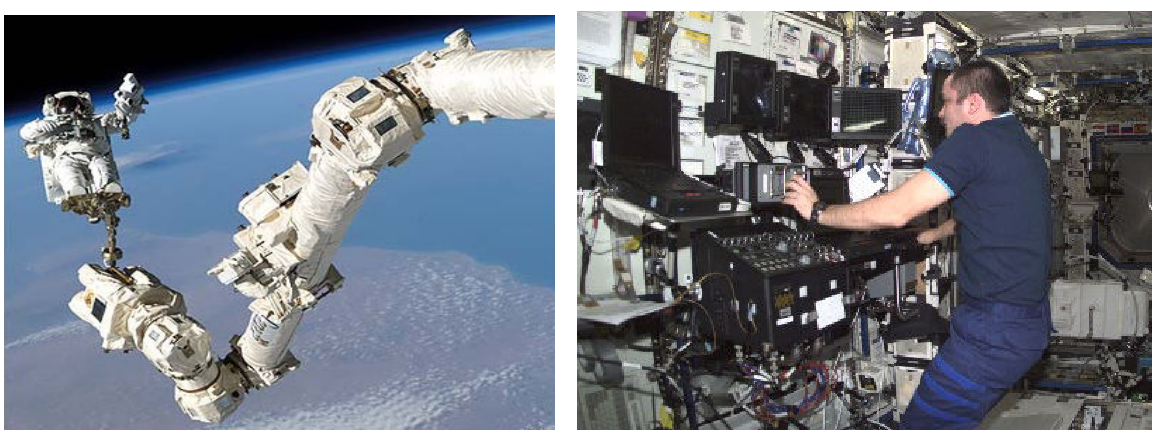

Figure 1.1: The SSRMS (left) is controlled via a robotic workstation (right)

[1] The PDRS is also known as the Canadarm or Shuttle Remote Manipulator System (SRMS)
[2] The SSRMS is also known as the Canadarm 2

Many hours of training are required to learn to manipulate either the PDRS or SSRMS. Operators of the robotic arm on the Shuttle or ISS must constantly maintain awareness of the spatial location and relative motion of all the elements in the workspace, which include the arm, payloads, and surrounding structures. This is a demanding task that requires many hours of intensive training, and operators most often work in pairs to monitor spatial situational awareness and to be alert for potential collisions. If the camera views are aligned with the arm's motion (i.e. when the operator moves the arm to the right and the arm on the screen moves right), manipulating the arm is relatively intuitive. However, the task becomes much more mentally demanding and complicated when the camera views are not aligned with the control axes.

The first experiment described in this thesis focused on the degree to which individual differences in spatial intelligence affect performance on camera selection tasks. Camera selection is a key skill addressed in NASA Generic Robotics Training (GRT) and astronauts are taught how to select the best camera views for teleoperation tasks. The second experiment investigated the extent to which handedness, in addition to individual spatial intelligence, influenced performance in teleoperation fly-to tasks. This information could be used to optimize robotics training by customizing training programs to each students skill set and ability.

2 Background

2.1 Space Telerobotics Operations and Training[3]

The Remote Manipulator Systems (RMS) on the Space Shuttle and ISS consist of a robot arm and a Robotic Workstation (RWS), which are used by astronauts to perform orbital deployment, satellite maintenance, build large structures (like the ISS itself), and to monitor the state of the Shuttle's thermal shield prior to re-entry. Both arms are controlled using the RWS (Figure 2.1, [1]), which consists of three video displays, two hand controllers (for translation and rotation), and numeric displays of arm state (including end-effector position and orientation). The crew can add additional smaller monitors to the workstation, and also use a laptop with situation awareness software known as DOUG.

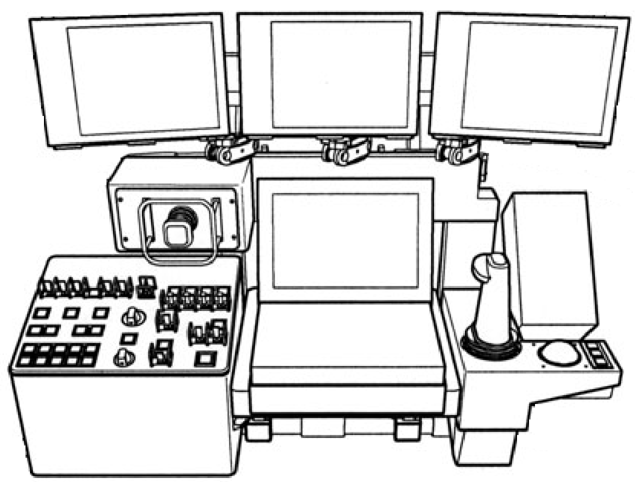

Figure 2.1: Robotic Workstation (RWS)

The Space Shuttle uses translational (THC) and rotational hand controllers (RHC) as part of its Guidance, Navigation, and Control System. The Shuttle has three RHCs on the orbiter crew compartment flight deck – one at the commander's station, one at the pilot's station, and one at the aft flight deck station – and each RHC can control vehicle rotation about three axes (roll, pitch, yaw). There are two THCs (one at the commander's station

[3] This section was adapted from the 2007 Research Proposal "Advanced Displays for Efficient Training and Operation of Robotic Systems", C.M. Oman, et al, NSBRI RFA-07001-S2, with the permission of the author.

and one at the aft flight deck station) that are used for manual control of translation along the longitudinal (X), lateral (Y), and vertical (Z) axes [2]. This RHC/THC scheme dates back to the Mercury program [3]. The RHC has always been designed for use by the right hand and the THC by the left hand. Given this setup for control of the Shuttle, it is not surprising that similar hand controllers that assign rotational and translational capabilities separately to the right and left hands respectively were used to control the PDRS.

The Space Shuttle has aft flight deck windows that permit direct visual monitoring of robotic operations, but selection of proper camera views remains very important for space robotics.[4] Each video monitor can display an image from cameras located around the payload bay of the Shuttle or on the surrounding structure of the Station, as well as on the end-effector itself. Astronauts can select and pan/tilt/zoom appropriate cameras to obtain the best possible view. However the cameras cannot be rolled, so the orientation of the camera mount can cause the view to appear tilted or even upside down. The only dependable source of information about the arm's motion and clearance is visual feedback provided by the cameras, although somewhat less accurate information on the position and orientation of the end-effector is provided by a numeric display. The operator can align the translation and rotation of the arm with a control frame fixed to the environment (known as external control mode) or centered on the tip of the end-effector or its payload (internal control mode). The orientation of external and internal control frames is typically chosen for convenience, and is frequently changed by the operator.

During the first year of their agency training to become an astronaut, candidates begin their teleoperation training with Generic Robotics Training (GRT), which consists of 15 lesson modules that teach basic manipulation tasks and strategies (e.g. flying the arm, grappling objects, choosing appropriate camera views). The main training system used during GRT is the Basic Operational Robotics Instructional System (BORIS) – a desktop virtual 6 DOF system somewhat resembling the Shuttle PDRS. Once GRT is completed,

[4] STS-130 recently installed the Cupola, which houses another RWS and permits direct views for some robotic operations.

candidates move on to either PDRS or SSRMS training flows. This is followed by flight specific training, with mission roles determined by performance during training.

During robotics training, astronauts are evaluated after specific lessons by a group of Robotics Instructors and Instructor Astronauts. Performance scores are given based on a sum of nine standardized criteria, weighted by their estimated impact on mission success[5]. Higher weighting is given to criteria relating to situational awareness, spatial and visual perception, collision and singularity avoidance, correct visualization of end position, camera selection and real time tracking, motion smoothness, and the ability to maneuver along more than one axis at a time. Remedial training is given to those astronauts that do not meet the minimal required grades, and this usually involves methods to help trainees visualize the orientation of the control reference frame. These methods strongly suggest the importance of spatial ability in space teleoperation performance. The training process could be customized and made more efficient if individual spatial strengths and weaknesses could be predicted beforehand.

Two astronauts normally work together to operate the robotic arms. The primary operator (known as M1 on ISS, R1 on Shuttle) manipulates the arm hand controllers, while the secondary operator (M2, R2 respectively) aids the M1/R1 by switching the camera views, monitoring situational awareness and obstacle clearance, and tracking moving objects with the cameras. The astronauts who demonstrate the best training performance are classified as primary operators, while those with lower but acceptable skills are classified as secondary operators. This post-training classification usually determines how operators are assigned to a mission's robotic tasks. However, for some routine tasks, an astronaut designated as an M2 can be assigned to the M1 flight position.

[5] The Instructor Astronauts are not involved in all the evaluations, but mostly on the final stage.

2.2 *Spatial Ability*

2.2.1 Spatial Orientation

During robotics training, individual differences in an astronaut candidate's ability to select correct camera views, maneuver the robot arm, and maintain adequate clearances between objects have been identified, which suggests that a particular set of factors within the operator's general intelligence could be influencing teleoperation performance. We believe spatial ability is one of those factors, and that it could help predict the strengths and weaknesses of astronaut candidates in specific aspects of teleoperation before they are trained as operators. Spatial ability can be described as our ability to imagine, transform, and remember visual information. It is believed that age, gender, and personal experience are some factors that can affect individual spatial abilities. The classification of the subcomponents of spatial ability differs slightly among authors, but one main class relevant to telerobotics is known as spatial orientation (SO).

SO is a person's ability to imagine different views of an object or environment and is subdivided into mental rotation (MR) and perspective taking (PT). The main difference between these processes is the frame of reference that is manipulated to get the new viewpoint. With MR, the observer is fixed while the object is imagined to be rotated; with PT, the object is fixed while the observer is imagined to be moving around the object. The tests described below were selected because they had been used in previous teleoperation experiments and were found to correlate with performance.

Figure 2.2 illustrates an example from the Vandenberg Mental Rotation Test (MRT, [4]), which is a classic test of MR ability. The subject is shown a picture of a 3-dimensional object made of multiple cubes and must identify two of four options that are pictures of the same object rotated into different orientations. There are two sets of ten trials, and subjects must complete as much of the set as possible in 3 minutes before moving on to the next set.

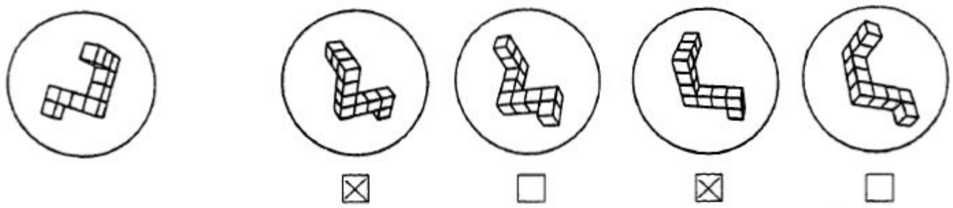

Figure 2.2: Example from the Mental Rotation Test (MRT)

In the computerized Kozhevnikov 2D Perspective Taking Ability (PTA) Test (Figure 2.3, [5]), the subject is shown a top-down view of a person surrounded by several locations. The subject is instructed to imagine being oriented like the person in the center of the picture. A flashing red dot appears beside one of the locations after five seconds is allowed for the study of the environment. The subject then must indicate the direction of the selected location relative to the person's orientation. There are 58 trials and the score is determined from response time and angular error. In Figure 2.3, the subject must imagine that they are facing the University and indicate that the Train Station is approximately 45˚ left from forward. Kozhevnikov et al [5] found that either MR or PT strategies can be used for the PTA test - mental rotation is often used for small angles (<90˚), and perspective taking is used for larger angles, except for 180˚.

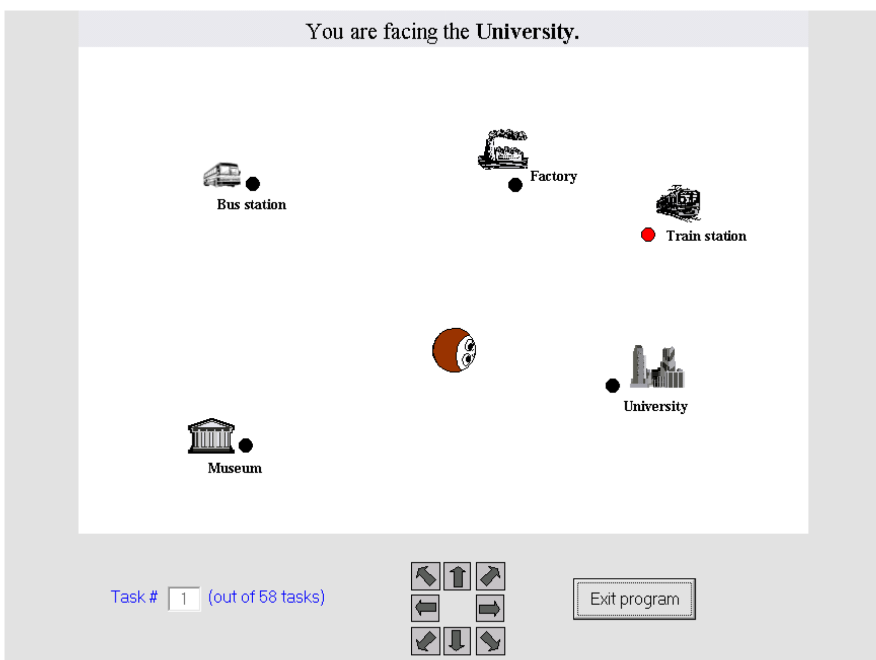

Figure 2.3: Screenshot from the Perspective Taking Ability (PTA) Test

In the Purdue Spatial Visualization Test: Visualization of Views (Figure 2.4, [6]), the subject is shown isometric views of various solid objects in the center of a see-through cube. The subject must determine the view of the object from the black dot located on one of the cube's vertices. There are 30 trials, and the subject has 6 minutes to complete as many of the trials as possible. In Figure 2.4, the answer E represents the view of the object from the indicated corner of the cube. The PSVT has not been formally validated as a PT test, however the majority of subjects in previous Man-Vehicle Laboratory (MVL) experiments self reported that they used PT more than any other strategy.

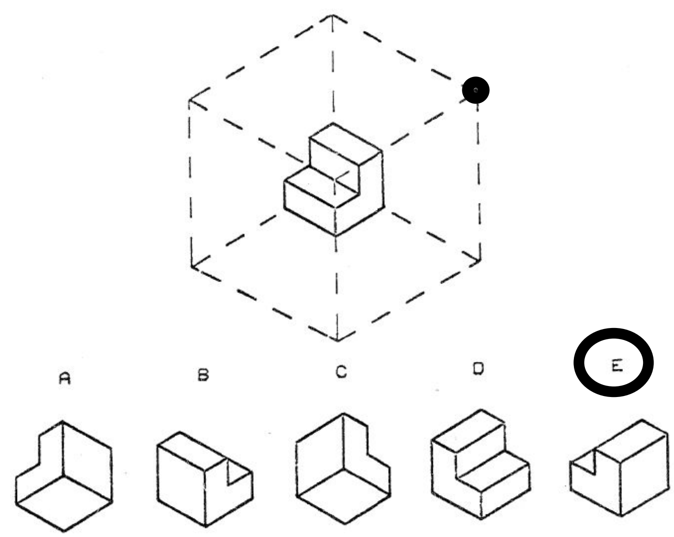

Figure 2.4: Example from the Purdue Spatial Visualization Test (PSVT)

2.2.2 Previous Research

2.2.2.1 External Studies

Indirect evidence that spatial abilities may be correlated with telerobotic performance can be seen in studies of adaptation to changes in reference frames or the use of displays. Lamb and Owen [7] found that the use of egocentric reference frames for space teleoperation tasks resulted in better performance (as measured by the rate of task completion) than the use of an exocentric (world) reference frame. Subjects used two controllers and a head-mounted display to fly a robotic arm toward a payload, grapple it, and then maneuver it into the cargo bay of the Space Shuttle. Spain and Holzhausen [8] found that increasing the number of available viewpoints in a telerobotic task does not necessarily improve performance. Although the additional views provided useful depth information that could have potentially contributed to task performance, the subjects did not use them because of the increased mental workload. Dejong et al [9] investigated how performance can be affected by disparities between hand controllers, camera, and display frames with the simultaneous use of two video monitors. They found that performance improved as the number of rotations between the reference frames decreased.

Other studies have found direct correlations between spatial abilities and performance in other types of teleoperation. However, none of these studies included the use of multiple displays. Lathan and Tracey [10] found that the spatial ability of an operator was significantly correlated with the ability to teleoperate a robot through a maze. Tracey and Lathan [11] found that subjects with high spatial ability had lower completion times on a teleoperator pick-and-place task. Eyal and Tendick [12] found a significant correlation between scores on MR, PT, and Spatial Visualization (the ability to visualize transformations of objects into other configurations) tests and a subject's ability to learn proper positioning of the laparoscope. Laparoscopic surgery is an important application of teleoperation in the medical field.

2.2.2.2 MVL Telerobotics Research

The MIT Man Vehicle Laboratory began investigating the effects of spatial ability on space teleoperation performance in 2007. The first set of experiments [13] tested whether perspective taking and spatial visualization abilities correlated with telerobotic performance. Subjects used two 3 DOF hand controllers (translational left hand controller and rotational right hand controller) to control a 2 boom, 6 DOF virtual arm and perform pickup and docking subtasks (Figure 2.5). Camera view separation and misalignments between translation control and display reference frames were introduced within the tasks. The spatial ability tests used included the PSVT and PTA to measure PT, and also the Cube Comparison (CC, [14]) Test to assess spatial visualization. The study concluded that PTA predicted performance on the pickup and docking subtasks, while CC scores were correlated with measures such as docking accuracy that did not necessarily require PT. High scoring PT subjects performed the pickup task more efficiently than low scorers, but not faster. They were, however, faster and more accurate in docking.

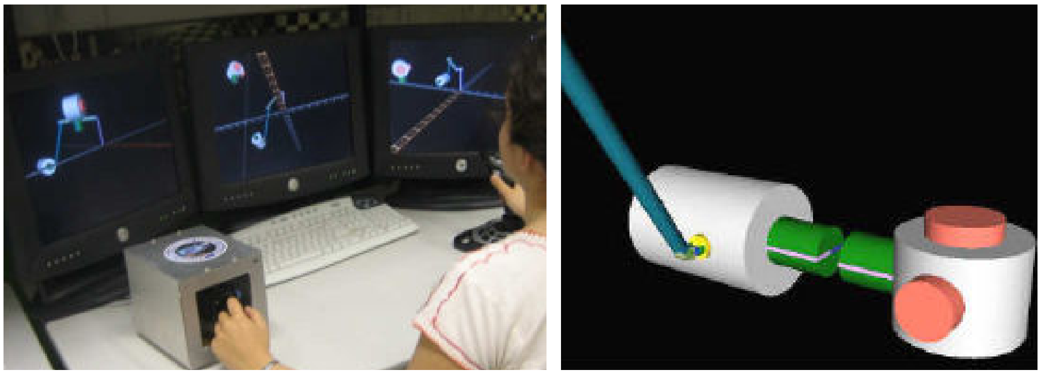

Figure 2.5: Experiment Setup (left), Docking Task Example (Right)

In 2008 a second study conducted collaboratively with NASA Johnson Space Center (JSC) investigated whether NASA robotic aptitude tests and spatial intelligence could retrospectively predict performance on a qualification test after robotics training [15]. A set of tests including the MRT, PSVT, and PTA were given to forty astronauts who had completed at least one training course (GRT, PDRS Training, or SSRMS training). Performance in Situation Awareness and Clearance tasks during GRT could be predicted with spatial ability scores, but the results were only reliable enough for use in customizing training because of the risk of misclassification. The study suggested that prediction reliability could be enhanced if the current scoring techniques used in the evaluation test were improved.

The most recent study in the MVL conducted two experiments (one on primary operator performance, and one on secondary operator performance) [16]. The MRT, PSVT, PTA, and CC tests were used to assess spatial ability. In the primary operator portion of the study (Figure 2.6), subjects manipulated a 6 DOF arm using 2 hand controllers (left hand translational and right hand rotational) to fly to a target in a virtual workspace modeled after BORIS used during GRT. For each trial, subjects were asked to move the arm from a constant starting point to a position 1.5m above a target box and aligned so that it was perpendicular to that surface. The disparity between the arm's control frame and the cameras were varied between low and high conditions. The experiment found that high PSVT and PTA scorers were better at maintaining required clearances between the arm and obstacles, and moved the arm more directly to the target. Subject performance degraded in high disparity conditions. In the secondary operator portion subjects observed the movement of a simulated robotic arm in a virtual ISS environment. High PSVT scorers had better overall secondary operator performance, while high PTA scorers were better at detecting problems before they occurred.

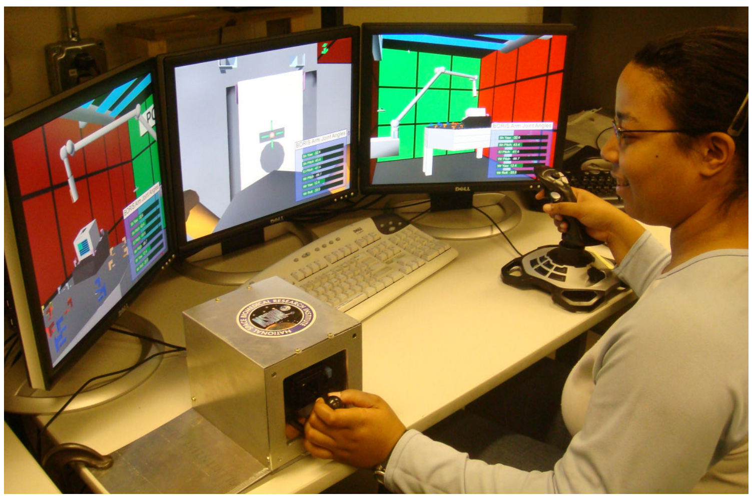

Figure 2.6: Primary Operator Experiment Setup

2.3 Joystick Configuration

Previous studies have also looked at different hand controller configurations that could be used in space robotics. Stuart et al [17] examined performance with Space Station *Freedom* candidate hand controllers and looked at both astronaut and non-astronaut controller evaluations of tasks which included docking and module transfers, and measures which included subtask completion times, number of hand controller inputs, and error counts. He found consistent trends that rate control mode was superior to position control mode; joystick controllers were superior to mini-master controllers; and the 2x3 DOF (rotational and translational) hand controllers were consistently one of the top hand controller configurations. As a result, the 2x3 DOF configuration became the baseline configuration for the Space Station. However, there have not been previous studies which examine the effects of switching the translational and rotational hand controllers for space robotics applications, thus the question of whether handedness affects performance warrants further investigation.

2.4 Handedness

As noted earlier, robotic operations on the Shuttle and ISS have always been done with a fixed hand controller configuration (THC on the left, RHC on the right). The translations tend to be long, coarse movements in comparison to the rotation movements which require a finer level of control. This suggests that right handed people could have an advantage in space telerobotic operations, since their dominant hand is being used for fine control.

Guiard and Ferrand [18] refer to *hand preference* as the fact that an individual usually chooses one hand with little hesitation to execute a unimanual task such as throwing a ball. *Hand superiority*, on the other hand, is assessed experimentally by submitting subjects to unimanual performance tasks and comparing scores obtained with the left and right hands. The ideas of hand preference and hand superiority must be reassessed once bimanual activities are analyzed – there are two possible ways to assign a pair of different roles to a pair of hands. Guiard designated *lateral preference* as the bimanual counterpart to hand preference and *lateral superiority* as the bimanual counterpart to hand superiority.

Guiard documented certain principles of bimanual cooperation as suggested by observation. For simplicity, the definitions assume right-hand dominance and include:

- Right-to-Left Reference: The preferred hand typically inserts itself into the reference frame provided by the non-preferred hand.
- Left-Right Scale Differentiation: The movements of the preferred hand are usually finer than those of the non-preferred hand.
- Left-Hand Precedence: The contribution of the non-preferred hand tends to precede that of the preferred hand (e.g. one positions the nail before hitting it with the hammer).

- Right-Hand Dominance: The fact that most human individuals express a subjective preference for one of their hands.

Over the years multiple methods of handedness assessment have been proposed. The Edinburgh Handedness Inventory Questionnaire was created by Oldfield in 1970 [19], and has been used to assess handedness in numerous studies. Studies of handedness (including a NASA study) described in the next section also used the Edinburgh Inventory as their questionnaire of choice. The original version that is most commonly used asks subjects to indicate hand preference for common activities (which include writing, drawing, striking a match, opening a box, etc), and then computes a Laterality Quotient (LQ) based upon the responses to determine the degree of right or left-handedness. Dragovic [20] proposed a revised version of the Edinburgh Handedness Inventory after numerous factor-analysis studies that found some activities to be highly correlated or outliers.

2.4.1 External Studies

Various studies have looked at how handedness affects performance in related environments. Pipraiya and Chowdhary [21] assessed the effect of handedness in flying performance in conditions that would simulate cockpit controls and looked for differences in hand dexterity between left and right-handed individuals. Subjects included left and right-handed pilots and non-pilots, and tests included a Two Hand Coordination test (THCT), Minnesota Rate of Manipulation test (MRMT) and Finger Dexterity Test (FDT). The THCT was performed with both hands simultaneously, and they found no difference in performance between left and right-handed subjects. The MRMT and FDT were performed with the dominant hand first, and then the non-dominant hand, and they found no difference between dominant and non-dominant hands for any of the subject groups. Ellis et al [22] investigated the use of the non-dominant hand as a reference frame aid and found this technique reduced control disturbances for some display coordinate misalignments by up to 64%. Right handed subjects were asked to move a cursor on a screen to a target using a stylus without watching their hand move the stylus. The control frame of reference was rotated with respect to the visual frame of reference in a random sequence. Normalized path length from start position to target was found to be shorter during trials where the non-dominant hand could be used as a reference frame aid.

2.4.2 Bimanual Control Ability

In addition to spatial ability, motor control is also considered to be important for teleoperation performance. Most research on Human-Computer Interaction (HCI) looks at the cooperative behavior of the two hands, which differs from our problem where the operator must parse desired control actions into angular and linear inputs and drive the two hands separately but nonetheless in a coordinated fashion. This is inherently difficult and different from the usual bimanual task, which is analogous to the "pat your head while rubbing your tummy" problem. Modern cockpits do have different functions allocated to each hand, where the right hand controls attitude and the left hand controls thrust. However this is a 4 DOF, not a 6 DOF, problem and the amount of coordination required between the two hands is different. Flying the Space Shuttle is a task that requires bimanual coordination, but this is rarely done in all 6 DOF simultaneously. Maneuvering the robotic arm on the Shuttle or ISS is a very demanding task because of the level of intermanual coordination and multi-axis movement on both controllers that is often required.

In order to increase efficiency, astronaut candidates are taught during GRT training to perform translational movements along or rotational movements about multiple axes simultaneously. Bock et al [23] found that their subjects were slower and less accurate when they had to coordinate the movements of two single-axis joysticks instead of only one dual-axis joystick to drive translational movements. Practice decreased the mental demands imposed by these bimanual movements.

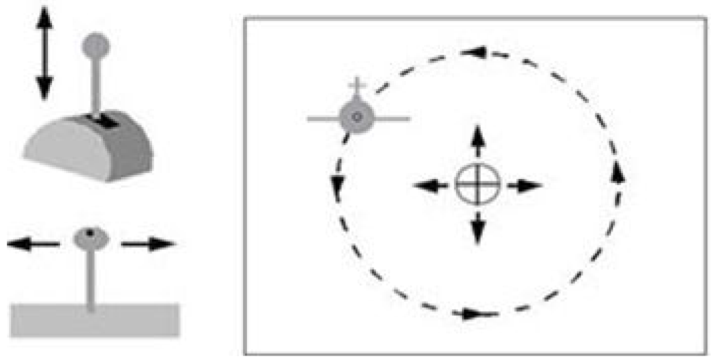

Figure 2.7: Air Force Two-Handed Coordination Test

A Two-Handed Coordination Test (THCT, Figure 2.7, [24]) has been used by the US Air Force for pilot selection for many years. The test requires participants to use two single-axis joysticks to keep crosshairs centered over an airplane moving at a varying rate around an ellipse. The score is determined from the error in the horizontal and vertical directions.

Figure 2.8: Screenshots from MVL Bimanual Control (BMC) Exercise

There are no widely accepted tests of 6 DOF bimanual control skill. NASA has an Aptitude for Robotics Test (ART) that is given to astronaut candidates prior to beginning robotics training that does include a task requiring different combinations of movements on multiple controllers simultaneously, but the details of the test are not available to the public. A previous MVL Robotics experiment (last experiment described in Section 2.2.2.2) developed a "MVL Bimanual Control" (BMC) exercise, which was modeled after NASA GRT tracing tasks. Subjects traced a path around an image of the Shuttle's nosecone (white oval shown in Figure 2.8) using both translational and rotational movements to keep one line of the end effector camera crosshairs tangent to the edge.

Completion time, angular error, and percentage of time spent moving both controllers were taken from the last 3 of 4 repetitions to compute scores.

The first experiment in this thesis focused on the degree to which individual differences in spatial intelligence affect performance on camera selection tasks, and the second experiment investigated the extent to which handedness and joystick configuration, in addition to individual spatial intelligence, influenced performance in teleoperation fly-to tasks. The analysis of both spatial ability and handedness as potential predictors of teleoperation performance could help customize robotics training to individual skills and abilities.

3 Experiment 1: Spatial Skills and Camera Selection

3.1 Objective

This experiment investigated the effect of subject spatial abilities on performance in the initial phases of training in setting up cameras to view a telerobotic task.

3.2 Hypotheses

Given the objectives outlined above, we hypothesized that:

1. Subjects with better spatial orientation skills as measured by MRT, PSVT, and PTA would select the correct camera set more quickly and more often.
2. Subjects with better spatial orientation skills would need less preparation time prior to beginning camera selection and would make fewer camera changes prior to selecting final camera views.
3. Subjects with better spatial orientation skills would be better at correctly identifying potential clearance issues.

3.3 Methods

3.3.1 MVL DST Environment

The virtual simulation used in the experiment was the Man Vehicle Laboratory Dynamic Skills Trainer (MVL DST, shown in Figure 3.1). It was modeled after the Basic Operational Robotics Instructional System (BORIS) used by NASA in the astronaut Generic Robotics Training (GRT). The dimensions of the workspace were obtained from the NASA JSC Robotics Training Handbook [25]. The environment included a 6 DOF arm and a 15 m deep x 30 m wide x 15 m high room with a workbench, free-floating grapple target, and overhead solar array. The simulation was constructed using AC3D v6.2, a 3-D modeling program (Inivis Limited, Ely, UK) and Vizard v3 VR Toolkit (WorldViz, Santa Barbara, CA).

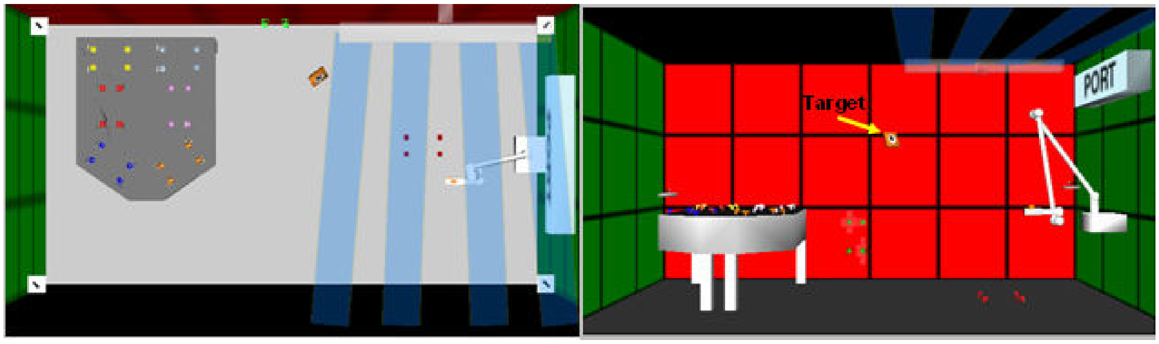

Figure 3.1: Example of Paper Plan and Elevation Views of MVL DST Environment

The location of the cameras in the room is illustrated in Figure 3.2. A window view from the forward wall was the fifth viewing option. All of the cameras except for the window view were able to pan through a 90° range in increments of 22.5°. Since Camera 3 was rolled 90°, it appeared to tilt instead of pan. The window view was completely stationary. The NASA BORIS environment has two additional cameras located on the elbow and end effector of the robotic arm that were not used in this investigation [1].

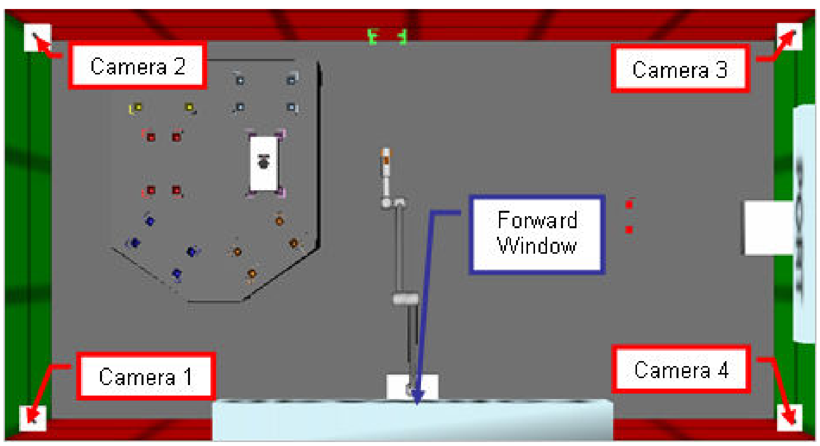

Figure 3.2: Camera Locations

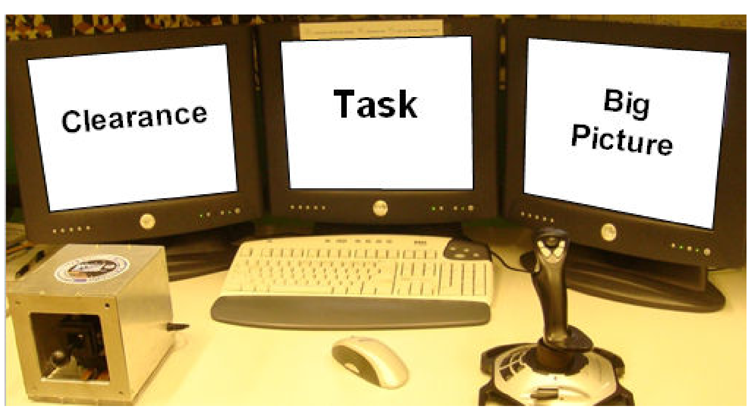

Figure 3.3: Monitor Setup

3.3.2 MVL DST Arm

The MVL DST robotic arm simulated the BORIS arm with the same kinematics, length (14m), and joints (Shoulder Yaw, Shoulder Pitch, Elbow Pitch, Wrist Pitch, Wrist Yaw, and Wrist Roll). The RRG Kinematix v.4 plug-in (Robotics Research Group, University of Texas) was used to calculate the inverse kinematics. During this experiment the arm was set in a fixed position for each trial and was not maneuvered. However, the subjects were given a brief opportunity to move the arm during the training portion of the experiment.

The arm was controlled using two 3-axis joysticks – a translational hand controller (THC) operated by the left hand and a rotational hand controller (RHC) operated by the right hand, as shown in Figure 3.4. The THC was custom-built using a 2-axis joystick, a linear potentiometer, and a USB controller card; it could be moved up/down, right/left, and forward/backward. The use of the linear potentiometer made the forward/backward motion slightly different from that of NASA's THC. The RHC was a Logitech Extreme3DPro USB game controller with 3 axes (right/left, forward/backward, and twist). Unlike NASA's RHC, the point of forward/backward rotation was at the base of the controller instead of in the hand-grip. The controllers had a central dead zone (created by the software) in all degrees of freedom (0.25 of the range in each direction). The data from the joysticks was captured at 100 Hz.

Figure 3.4: MVL Translational (left) and Rotational (right) Hand Controllers

3.3.3 Performance Metrics

At the end of each trial, several variables were recorded to a Summary Data File, characterizing the subject's performance. A summary of the recorded metrics is presented in Table 3.1. One Summary Data File was created for every 4 trials.

Table 3.1: Experiment 1 Performance Metrics

Measures of Performance	Description
Trial Time	The time that it took the subjects to select the camera views
Initial Left, Middle, and Right Monitor Views	The initial selections made for the views
Preparation Time	The time it took the subject to study the maps prior to selecting initial camera views
Left, Middle, and Right Monitor Views	The final selections (camera and pan angle) for the views
Left, Middle, and Right Monitor Changes	The number of changes made (camera and pan angle) on each of the monitors
Clearance Issue	What the subjects perceived to be the clearance issue that they had to worry about
Camera Selection Score	The number of correct camera views at the end of each trial

3.3.4 Subjects

The experiment protocol was reviewed and approved by MIT's institutional experimental review board. A total of 21 subjects (11 men, 10 women) participated in the experiment, ranging in age from 20 to 50 years (mean = 25.4 years, SD = 6.3 years). The demographics are listed in Appendix A. All but 6 had an engineering, math, or science background, with a majority being MIT undergraduate or graduate students. No subjects had previous telerobotics training, and all were right-handed. All but 7 had previous experience with video or computer game controllers, and all but 2 used a computer for at least 3 hours a day. Subjects received $20 for their participation in the study.

3.3.5 Procedure

The experiment was conducted during one 2-hour session. Subjects were first given a Pre-Test Questionnaire (demographic, virtual experience) and 3 spatial ability tests (MRT, PSVT, and PTA). They then viewed a PowerPoint presentation (Appendix D) that introduced them to the objectives of the experiment, the BORIS environment and the arm. Practice trials were included in the tutorial, and subjects were given the brief opportunity to become familiar with the dynamics of the arm and practice camera selection. These trials were reviewed with the subject by the investigator to ensure that the subject clearly understood the task. Once the practice tutorial was complete, the subject began the experiment task of selecting camera views for 12 trials.

Subjects were told that in each trial they would be given a specific scenario (defined by the starting location of the arm and location of the grapple target) and should select the camera views that would be most useful for accomplishing the trial. They did not actually move the virtual arm to the virtual grapple target, but only visualized the direct motion of the arm to the target and selected the most appropriate camera views for that scenario. A summary of the instructions given to subjects during training on how to select the best camera views is given below:

- **Left Monitor: Clearance View**: Determine what could cause a clearance violation (i.e. moving the arm too close to another object) and select an orthogonal view to monitor the distance between that object and the arm.
- **Middle Monitor: Task View**: Select a camera that will allow determination of the arm's distance from the target while grappling. This view should be orthogonal to the target.
- **Right Monitor: "Big Picture" View**: Select a camera that will show as much of the environment as possible, making the arm and target visible throughout the trial.

Prior to each trial, subjects were given a paper plan and elevation view (example in Figure 3.1) of the scenario, showing the arm’s initial position and location of the grapple target. The subjects were asked to study the plan and elevation views, to visualize the environment, and then to appropriately select cameras. Once their selected views appeared on screen, they could evaluate the selection and make changes if necessary using keyboard controls[6] to modify the views before indicating their final selection.

At the end of each trial, subjects were asked "Which clearance issue were you concerned with?" and given the option to choose from multiple answers (ex. "end-effector vs. aft wall"). The answers to these questions were later used to calculate a Clearance Question score. After completing all the trials, the subjects each completed a Post-Test Questionnaire (task difficulty, strategy). Figure 3.5 shows the timeline for the experiment.

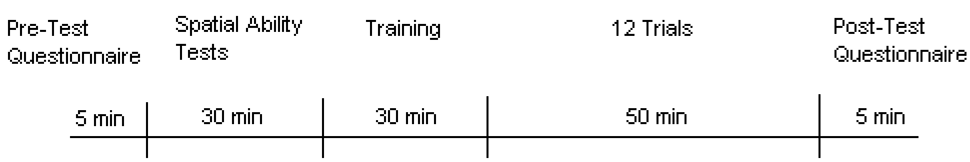

Figure 3.5: Breakdown of Experiment Times

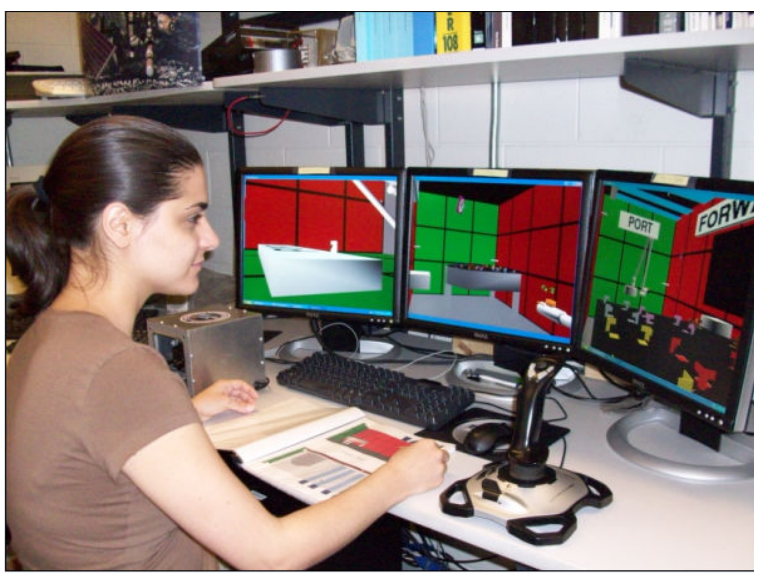

Figure 3.6: Experimental setup showing paper maps and typical camera views

[6] The F5, F6, and F7 keys allowed the subject to select a monitor (left, middle, right, respectively). The 1, 2, 3, 4, and 5 keys allowed them to select a camera for that monitor (Cameras 1-4 + the window, respectively). The left and right arrow keys allowed them to pan the camera to the sides.

3.3.6 Experiment Design

The main independent variable investigated was Spatial Ability Category (Low, High) for each of the spatial ability tests (MRT, PSVT, PTA). A subject was a (Low, High) scorer on a spatial ability test if his/her score was (below, above) the group median score for that test. Of the 12 scenarios that each subject analyzed, 6 were End Effector scenarios (in which the main clearance concern involved the robotic arm end effector) and the other 6 were considered Elbow scenarios (since the main clearance concern was with the elbow in the middle of the robotic arm). Two different starting positions were used for the arm (based on the Port or Forward wall), and the target position was different for each trial.

The main measured dependent variables were Task Time and Camera Selection Score. Task Time was the time subjects required selecting the final camera views, and Camera Selection Score was the number (0 to 3) of views that the subject selected correctly. A score of 3 meant that the subject had chosen all three camera views (Clearance, Task, and Big Picture) correctly. All but one trial had multiple correct camera combinations.

The number of total Changes made before selecting the final cameras for Clearance, Task, and Big Picture was recorded. The Clearance Question score was (0,1) if the subject's identification of the most relevant clearance situation for each trial was (incorrect, correct). The Prep Time is the time a subject spent analyzing the paper plan and elevation views before beginning camera selection.

3.4 Results

3.4.1 Spatial Ability Scores: Descriptive Statistics

SYSTAT 12 was used for statistical analysis of results. The descriptive statistics of the spatial ability test scores are shown in Table 3.2, along with statistics for the astronauts (n = 40) that were tested by Liu et al in a separate study of astronaut spatial skills and performance [15], reviewed in Section 2.2.2.2. Mann Whitney U tests showed no statistical differences in MRT, PSVT, or PTA scores between those astronauts and subjects participating in this study.

Table 3.2: Spatial Ability Score Descriptive Statistics

Test	Mean (Median)	SD	Max	Min	Astronaut Mean	Astronaut SD
MRT	18.43 (17.0)	8.50	37	0	17.28	8.74
PTA	19.82 (19.49)	5.03	28.09	11.38	19.61	3.40
PSVT	15.76 (15.0)	6.88	29	5	17.32	7.03

The subjects' MRT and PSVT scores were roughly normally distributed, while their PTA scores were roughly uniformly distributed. Significant correlations were found between scores for MRT and PSVT (R = 0.529), MRT and PTA (R = 0.582), and PSVT and PTA (R = 0.569).

3.4.2 Task Time

Figure 3.7 displays the average Task Time for Low and High Scorers for each of the spatial ability tests. High scorers on each test generally had shorter task times than Low scorers.

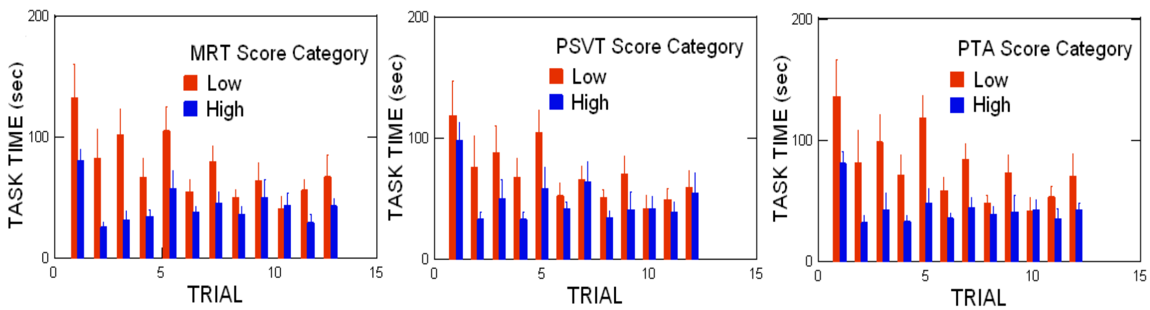

Figure 3.7: Task Time for Low and High Spatial Ability Subjects

Three mixed regressions were performed on the natural logarithm of Task Time (with subject as a random effect) against spatial ability represented by a different test score in each regression model (since the test scores were highly correlated). Both the MRT Score Category (z = 2.50, p = 0.01) and the PTA Score Category (z = 2.96, p = 0.003) were found to be significant predictors for Task Time. Lower scoring subjects on those measures took longer to complete the camera selection task. The PSVT Score Category was not found to be a significant predictor. Trial number, Scenario Type, and Gender were also included in each regression model. Trial (z = -3.79, p = 0.005) and Scenario Type (z = 2.17, p = 0.03) were significant predictors, Gender was not. Subjects took longer to select camera views for Elbow scenarios than for End Effector scenarios, and Task Time decreased significantly with increasing Trial number, a learning effect.

3.4.3 Camera Selection Score

Figure 3.8 shows the average Camera Selection Score for Low and High Scorers for each of the spatial ability tests. High scorers on each spatial ability test generally also had higher Camera Selection Scores.

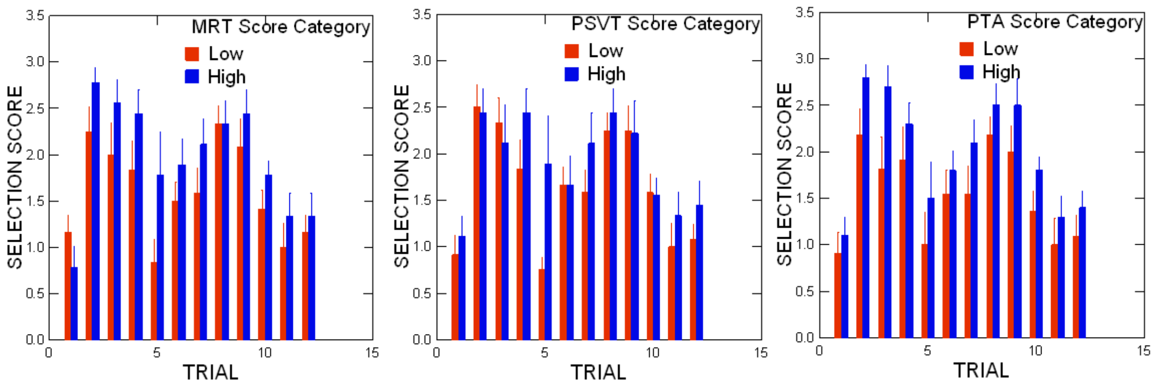

Figure 3.8: Camera Selection Score for Low and High Spatial Ability Subjects

A non parametric Mann Whitney Test was used to analyze the average Camera Selection Score over the 12 trials for each subject. High scoring subjects had significantly higher Camera Selection Scores than low scorers when classified by MRT ($U = 25.0$, $p = 0.04$) and PTA ($U = 18.0$, $p = 0.009$), but not by PSVT. The average score for each Scenario Type was found for each subject and a Friedman Test was used to assess whether the subjects had significantly different Camera Selection Scores for each of the two types. No significant difference was found.

3.4.4 Number of Camera Changes

Figure 3.9 shows the average Number of Changes for Low and High Scorers for each spatial ability test. High scorers on each test generally made fewer changes than Low scorers.

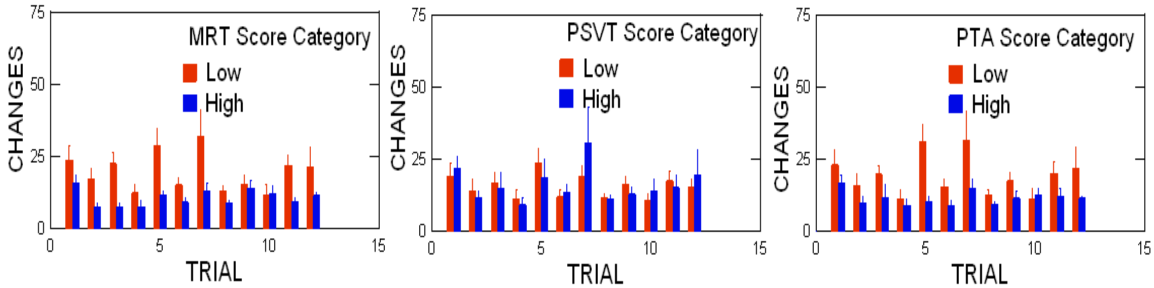

Figure 3.9: Number of Changes for Low and High Spatial Ability Subjects

A mixed regression model was performed on the logarithm of total Changes. Both the MRT Score Category (z = 3.61, p = 0.0005) and the PTA Score Category (z = 2.71, p = 0.007) were found to be significant predictors of Changes. The lower scoring subjects generally made more changes to the camera views prior to making a final decision. The PSVT Score Category was not significant. The Trial number, Scenario Type, and Gender were included in each model and were not found to be significant predictors of performance.

The average number of Changes for each monitor (Clearance, Task, Big Picture) was determined for each subject and a Friedman test was used to assess whether the subjects had significantly different numbers of Changes for each of the monitors. No significant difference was found.

It appeared that Low spatial ability scorers not only had more total changes, but also looked at more different cameras. A Mann Whitney test found that Low scoring MRT subjects looked at significantly more cameras than High scoring subjects (U = 83.0, p = 0.04). There was no significant difference between High and Low scorers when separated by PSVT and PTA.

3.4.5 Clearance Question Score

Clearance Question Scores for the 12 trials were averaged for each subject and a Mann Whitney U test was applied. No significant predictive effect was found for any of the aptitude tests.

3.4.6 Preparation Time

A mixed regression model was applied to the square root of Preparation Time in order to meet the results of the regression model. The PSVT Score was significant (z = 2.07, p = 0.04), and suggested that low-scoring subjects have longer Prep Times before beginning camera selection. MRT and PTA Scores were not significant. Subjects had significantly lower Prep Times as the Trial number increased (z = -9.0, p = 0.005), but Scenario Type had no significant effect on Prep Time.

3.4.7 Post-Test Questionnaire

The post-test questionnaire asked subjects to indicate which viewpoint type (Clearance, Task, or Big Picture), if any, was the most difficult to select. More subjects (42.9%) identified the Clearance view as the hardest. A Friedman Test (Q = 16.4, p = 0.0005) found a significant difference between scores for the three viewpoints. Subjects selected the correct camera for the Clearance view less often than for the Task view (p = 0.03) and the Big Picture view (p = 0.0005), as measured by the Sign Test. There was no significant difference between scores for Task and Big Picture views.

Subjects were additionally asked whether their strategy was to spend more time looking at the maps or trying to figure out things as they went along, with the majority (71.4%) of subjects reporting that they spent more time studying the map. A Mann Whitney test found no significant difference in average Camera Selection Scores between the two strategies. A Chi-Square test showed no significant relationship between High/Low scorers (for MRT, PSVT, and PTA) and choice of strategy.

3.5 Discussion

The results showed that the MRT and PTA tests consistently supported the hypothesis that high spatial ability subjects perform camera selection tasks more quickly and accurately than lower spatial ability subjects. The High scorers for the MRT and PTA tests had significantly lower Task Times and higher Camera Selection scores than the

Low scorers. There was no significant difference in performance between the Low and High PSVT subjects. Subjects also took longer to select camera views for Elbow scenarios compared to End Effector scenarios. This suggests that the difference conceivably might have been reduced if subjects had more training in moving the arm.

MRT and PTA scores were predictive of Camera Changes. PSVT predicted time spent in preparation. We interpret this to mean that lower (MRT and PTA) scorers were less confident in their selections and lower PSVT scorers chose to spend more time looking at the map beforehand. There is no immediate explanation for why PSVT scores were only predictive for Prep Time. High scorers on each of the three spatial ability tests did have marginally higher average Clearance Question Scores, but no significant predictive effect was found for any of the aptitude tests.

Each subject had to fill out questionnaires, take three spatial ability tests, go through the tutorial and then perform the task. This took two hours and left little time for additional training. Additional training time would have been useful for more camera selection practice trials, as well as for more practice moving the arm which may have helped subjects better understand the kinematics of the arm when visualizing its movement during the experiment.

4 Experiment 2: Spatial Skills, Joystick Configuration and Handedness

4.1 Objectives

This experiment investigated the effect of spatial abilities, joystick configuration, and handedness on performance in the early phases of simulated space telerobotic training to perform a fly-to task

4.2 Hypotheses

We hypothesized that:

1. Subjects with higher spatial ability, as measured by MRT, PSVT, and PTA tests, would perform simulated robotic fly-to tasks better[7] than low scoring spatial ability subjects.
2. Subjects would perform better when manipulating the arm with their dominant hand on the rotational hand controller ("dominant configuration") than when performing with a non-dominant configuration.

4.3 Methods

4.3.1 ISS Environment

In order to make the tasks more realistic and challenging, a virtual mockup of the ISS was used in the second experiment. As shown in Figure 4.1, the simulation included a 6 DOF arm[8] and the station's core modules and truss (as configured in 2007). The arm used in this environment was 3m longer than the arm in previous MVL DST simulations in order to better simulate the SSRMS. The rotational and translational hand controllers

[7] Better performance was defined by several metrics including shorter task time, higher percentage of translational and rotational multi-axis movement, higher percentage of bimanual movement, and fewer number of discrete movements.

[8] The ISS arm (SSRMS) is actually a 7 DOF system, but the extra DOF makes predicting movements more complex. Since the subjects had a relatively low amount of training, the 6 DOF arm introduced in Experiment 1 was used instead. The arm used in the simulation also differed from the actual SSRMS since it did not incorporate arm dynamics and employed a higher rate of arm movement that was used for experimental convenience.

were the same ones used in Experiment 1, as described in Section 3.3.2, and were mounted approximately 18.5 inches apart.

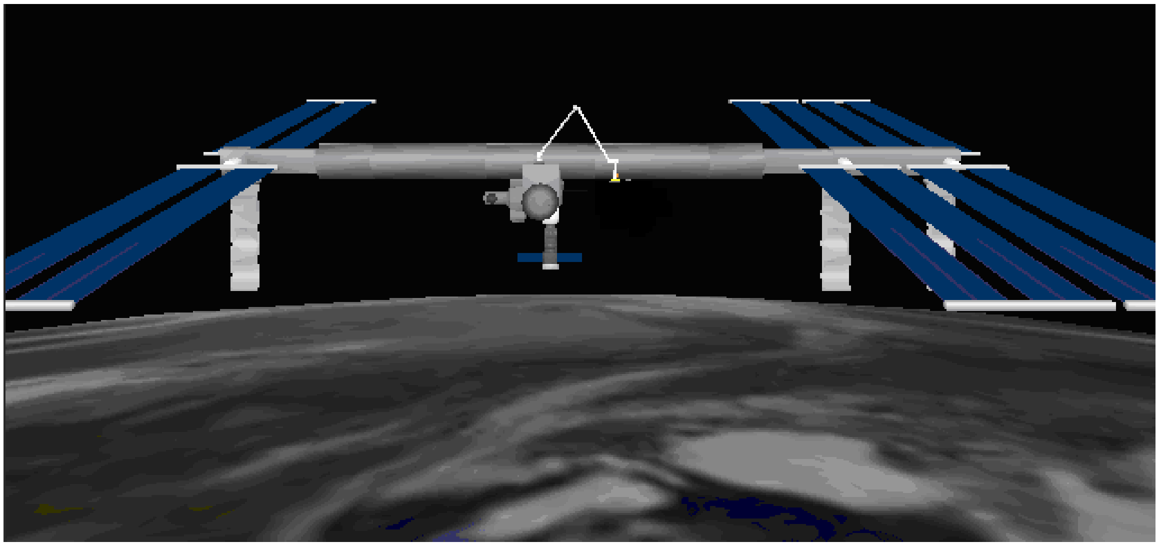

Figure 4.1: ISS Virtual Environment

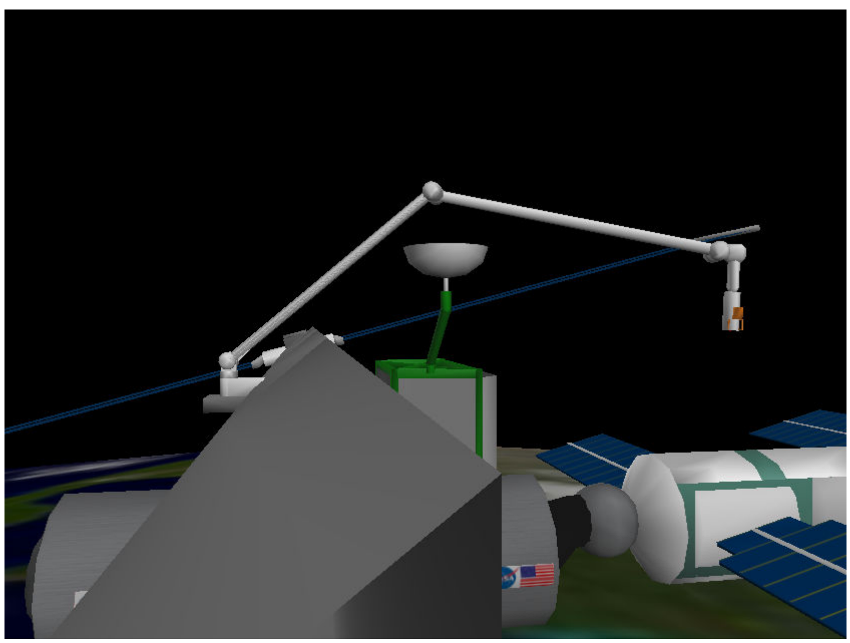

Figure 4.2: Virtual Simulation of SSRMS

4.3.2 Performance Metrics

At the end of each trial, several variables were recorded to a Summary Data File, characterizing the subject's performance. A summary of the metrics recorded and those subsequently calculated is presented in Table 4.1. One Summary Data File was created for every 12 trials. These metrics were of interest because they are normally emphasized during NASA GRT, and previous experiments in our laboratory [13,16] also used similar performance metrics.

Table 4.1: Experiment 2 Performance Metrics

Measures	Description	Recorded	Calculated
Trial Time	Total time (sec) that the subject took for the trial	X	
Movement Time	Total amount of time (sec) the arm was moving	X	
ContMoves	Number of discrete movements made	X	
TransMA Time	Amount of time the arm was translating along 2+ axes	X	
RotMA Time	Amount of time the arm was rotating along 2+ axes	X	
BiMan Time	Amount of time the arm was both translating/rotating	X	
TransMA %	Percentage of moving time that the arm was translating along 2+ axes = TransMA Time / Movement Time		X
RotMA %	Percentage of moving time that the arm was rotating along 2+ axes = RotMA Time / Movement Time		X
Bimanual %	Percentage of moving time that the arm was translating and rotating = BiMan Time / Movement Time		X

4.3.3 Subjects

The experiment protocol was reviewed and approved by MIT's institutional experimental review board. A total of 20 subjects (16 men, 4 women) participated in the experiment, ranging in age from 18 to 34 years (mean = 24.7 years, SD = 3.5 years). The demographics are listed in Appendix H. All but 4 had an engineering, math, or science background, with a majority being MIT undergraduate or graduate students. Eleven subjects were right-handed and nine were left-handed (as determined by the Edinburgh Handedness questionnaire), and five were subjects that had participated in Experiment 1. All but 2 had previous experience with video or computer game controllers, and all but 2 used a computer for at least 3 hours a day. Subjects received $10/hr for their participation in the study.

4.3.4 Procedure

The experiment took place over 2 consecutive days, for approximately 2 hours each day. Table 4.2 outlines the content for each day. Each day involved two successive sessions of 2 practice trials and 12 experimental trials.

Table 4.2: Experiment 2 Session Descriptions

Day 1	Day 2
• Pre-Test Questionnaire (Appendix B with results in Appendix I) • Handedness Questionnaire (Appendix O) • Spatial Ability Tests (MRT, PSVT) • Powerpoint Orientation (Appendix J) • Practice Session 0 (2 Trials) • Session 0 (12 Trials) • Practice Session 1 (2 Trials) • Session 1 (12 Trials)	• Spatial Ability Test (PTA) • Refresher Powerpoint Training (Appendix K) • Practice Session 2 (2 Trials) • Session 2 (12 Trials) • Practice Session 3 (2 Trials) • Session 3 (12 Trials) • Post-Test Questionnaire (Appendix L with results in Appendix M)

Across both days each subjects completed 4 sessions and a total of 48 telerobotic fly-to trials (4 repetitions of 12 trials) in the simulated ISS environment. Appendix N details the design of the 12 trials. Sessions 0 and 2 were performed with the subject's dominant hand on the rotational controller and Sessions 1 and 3 were performed with the subject's dominant hand on the translational controller. The subject's dominant hand was determined using the revised version of the Edinburgh Handedness Questionnaire (included in Appendix O).

For each trial subjects were asked to fly the robotic arm over to a grapple target, and to position the end-effector 2 meters from the target and aligned perpendicular to the target's surface, with the crosshairs in the end effector camera aligned over the target pin. When subjects were satisfied with their final position they pressed the spacebar on the keyboard to move onto the next trial. Before each Session, subjects were given two practice trials in which to become familiar with the joystick configuration. After each set of 12 trials, the translational and rotational hand controllers were switched and the subjects repeated the task. All of the subjects underwent the same treatments in the same order.

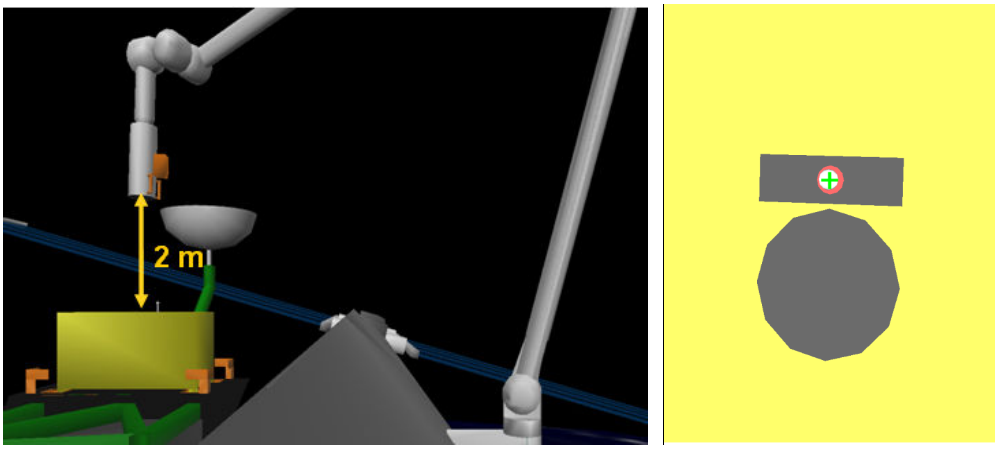

Figure 4.3: Experiment 2 Task (a) subjects asked to position EEF 2 m from target surface (b) view from EEF camera with crosshairs over the target grapple pin

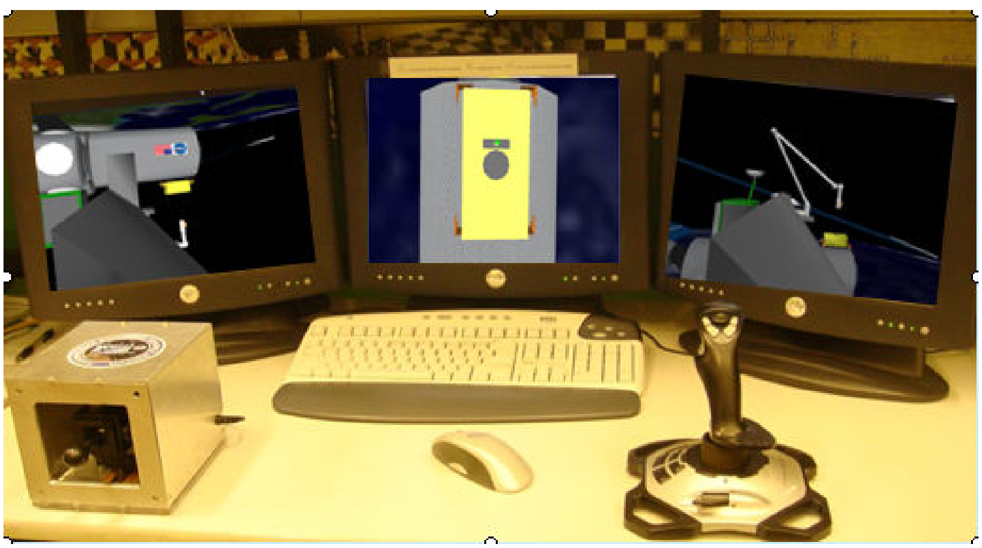

Figure 4.4: Experiment 2 Setup

The monitor setup was the same as in Experiment 1. The center monitor always showed a view from the end-effector camera, and the two side monitors provided additional information on distance and orientation of the robotic arm. The camera views were appropriately pre-selected for the subjects before each trial; the subjects were not responsible for selecting camera views.

4.3.5 Experimental Design

The main independent variables investigated were Spatial Ability Category (Low, High) for each of the spatial ability tests (MRT, PSVT, PTA), Configuration (Dominant, Non-Dominant), and Handedness (Left, Right). A subject was a (Low, High) scorer on a spatial ability test if his/her score was (below, above) the median score of all 20 subjects for that test. The dependent variables included Trial Time, Translational Multi-Axis Movement %, Rotational Multi-Axis Movement %, Bimanual Movement %, and number of Discrete Movements. Better performance is defined by shorter trial time, higher percentage of translational and rotational multi-axis movement, higher percentage of bimanual movement, and fewer total movements. We expect performance to improve with increased experience, with subjects making fewer and smoother, more fluid movements to get to the target.

4.4 Results

4.4.1 Spatial Ability Scores: Descriptive Statistics

SYSTAT 13 was used for statistical analysis of results. The descriptive statistics of the spatial ability test scores for the entire test population are shown in Table 4.3, along with statistics for the NASA astronauts (n = 40) that were tested by Liu et al in a separate study of astronaut spatial skills and performance [15]. Mann Whitney U tests showed no statistical difference in PSVT or PTA scores between those astronauts and subjects participating in this study. There was a significant difference in MRT scores, with the experimental subjects having slightly but significantly higher MRT scores than the astronauts ($p = 0.003$).

Table 4.3: Spatial Ability Score Descriptive Statistics

Test	Mean (Median)	SD	Max	Min	Astronaut Mean	Astronaut SD
MRT	25.70 (26.0)	8.86	38.0	12.0	17.28	8.74
PTA	21.28 (21.625)	3.45	26.2	15.44	19.61	3.40
PSVT	18.60 (18.0)	6.14	28.0	7.0	17.32	7.03

Significant correlations were found between scores for MRT and PSVT (R = 0.45), MRT and PTA (R = 0.642), and PSVT and PTA (R = 0.635).

Table 4.4: Spatial Ability Results for LH and RH subjects

Test	LH Mean (Median)	LH SD	RH Mean (Median)	RH SD
MRT	26.33 (26.0)	10.43	25.18 (26.0)	7.85
PSVT	17.11 (18.0)	7.32	19.82 (18.0)	5.02
PTA	21.14 (21.64)	3.34	21.40 (21.54)	3.66

The spatial ability of the LH and RH subject groups were compared using the Mann Whitney U test and no significant difference was found between the groups on any of the three tests.

4.4.2 Learning Effects

The subjects' performance in several metrics improved over the course of the experiment. A Sign test performed on subject-by-subject performance differences between successive sessions showed that, as expected, the subject trial times decreased between Sessions 0 and 1 ($p<0.001$), and between Sessions 1 and 2 ($p<0.001$), but there was no difference in task times between Sessions 2 and 3. There was also a significant decrease in the number of discrete movements between Sessions 0 and 1 ($p = 0.01$) and between Sessions 1 and 2 ($p<0.001$), but no difference between Sessions 2 and 3. A Sign test also showed a significant increase in the percentage of translational multi-axis movement between Sessions 1 and 2.

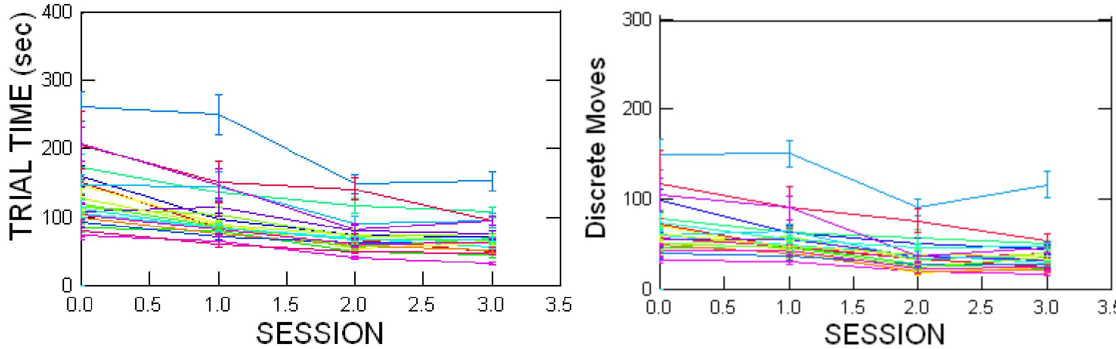

Figure 4.5: Learning for each subject for (a) Trial Time (b) Discrete Moves

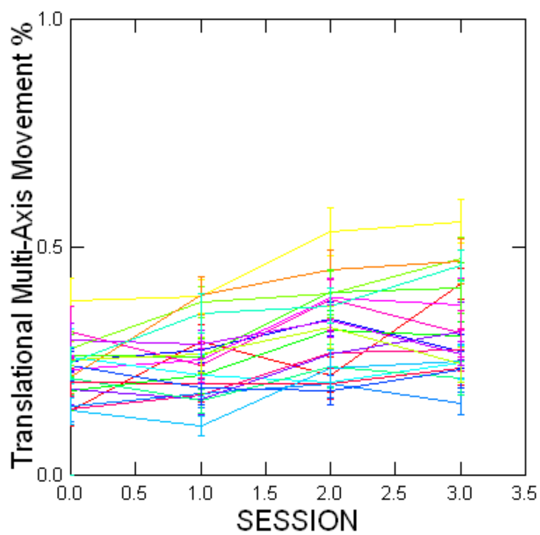

Figure 4.6: Translational Multi-Axis Movement % vs. Session

4.4.3 Spatial Ability Effects

4.4.3.1 Trial Time

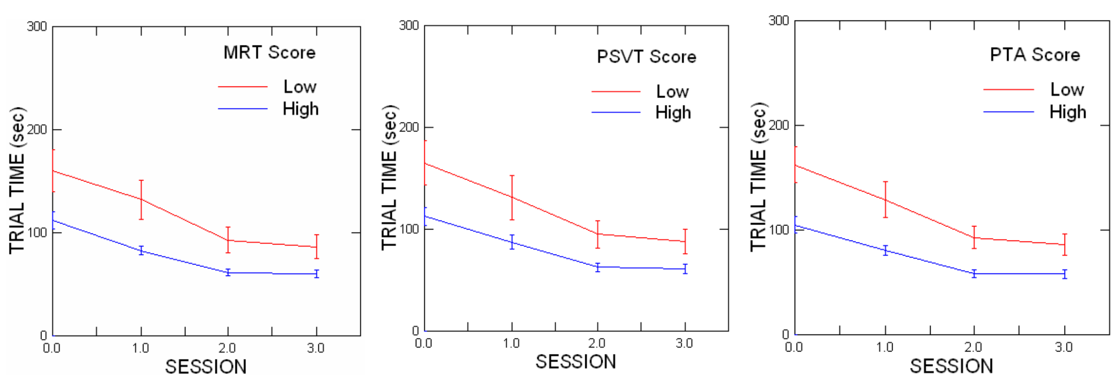

Figure 4.7: Effect of Spatial Ability on Trial Time

Since simple transformations did not succeed in creating a distribution that would yield normally distributed, homoscedactic residuals needed for an ANOVA, non-parametric tests were used to analyze the effect of spatial ability on Task Time. We found that the differences between observed task times for high and low scorers were significant for all three tests: MRT (U = 78.0, p = 0.03), PSVT (U = 77.0, p = 0.025), and PTA (U = 87.0, p = 0.005). High scorers took significantly less time than low scorers to complete each trial.

4.4.3.2 Discrete Moves

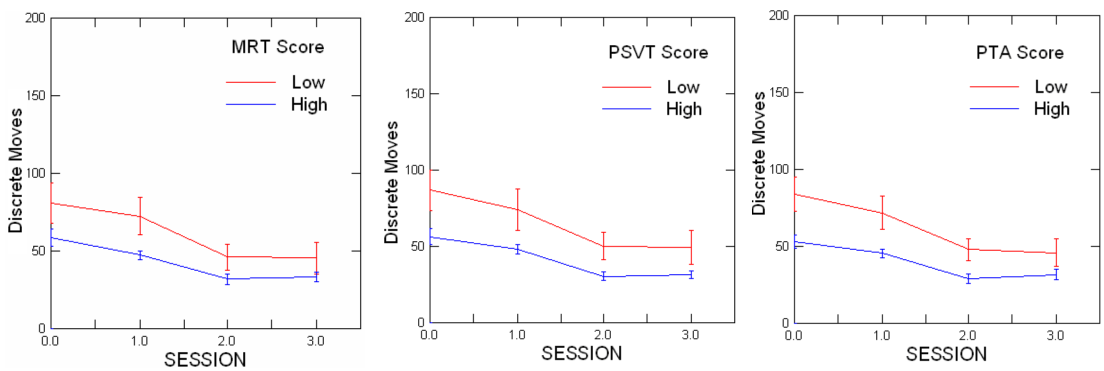

Figure 4.8: Effect of Spatial Ability on Discrete Moves

Three Analysis of Variance (ANOVA) models were performed on the logarithm of the number of Discrete Moves made, analyzed against spatial ability[9].Since the test scores were highly correlated, one analysis was done for each spatial ability test. PSVT (F (1, 16) = 6.52, p = 0.02) and PTA (F (1, 16) = 6.73, p = 0.02) were significant predictors of the number of Discrete Movements, while MRT was not. High scorers made significantly fewer movements to complete each trial, which indicates that they took smoother, more fluid paths to the targets.

[9] For each ANOVA, the spatial ability test and DomHand (whether subjects were LH or RH) were used as fixed effects. DomHand was not found to be significant for any of the three tests, and there were no significant cross effects.

4.4.3.3 Translational Multi-Axis Movement Percentage

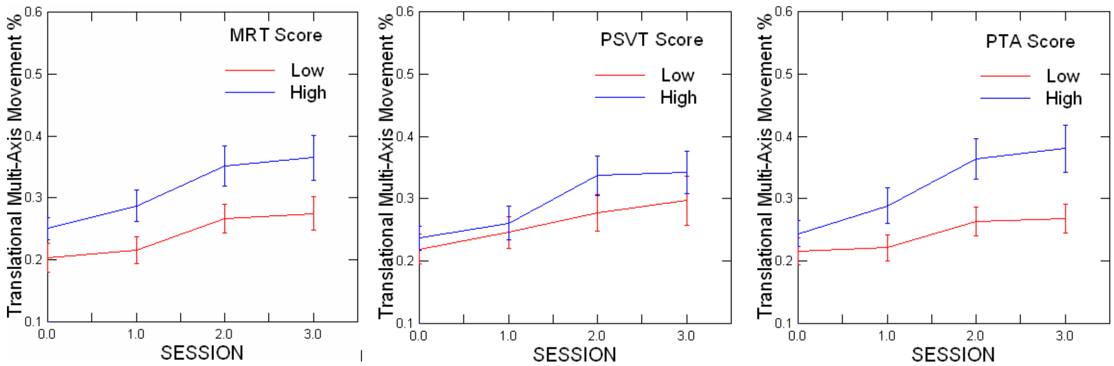

Figure 4.9: Effect of Spatial Ability on Translational Multi-Axis Movement %

Three Analysis of Variance (ANOVA) models, one for each spatial ability test, were performed on (the arcsine of the square root of) the percentage of translational multi-axis movement[10]. MRT (F (1, 16) = 5.78, p = 0.029) and PTA (F (1, 16) = 6.11, p = 0.025) were found to be significant predictors, while PSVT was not. High scorers had a higher percentage of translational multi-axis movement than low scorers.

4.4.3.4 Rotational Multi-Axis Movement Percentage

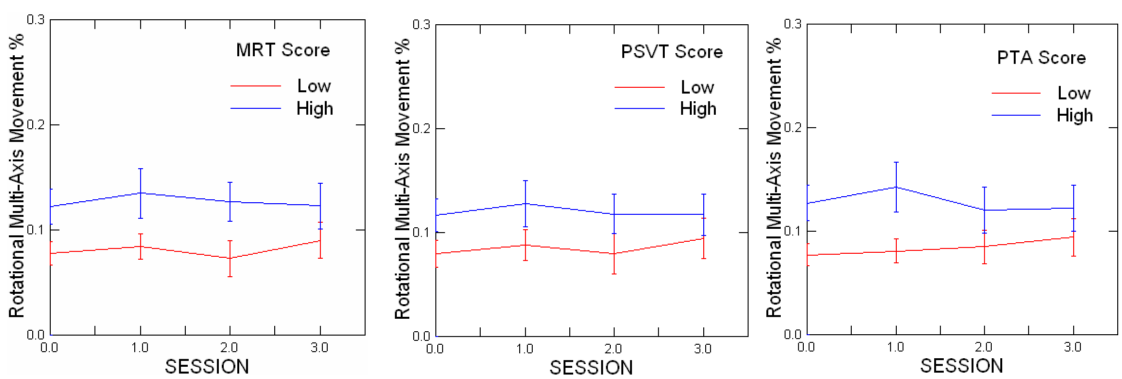

Figure 4.10: Effect of Spatial Ability on Rotational Multi-Axis Movement %

A similar pattern was found in the analysis of percentage of rotational multi-axis movement with the Mann Whitney U test. The effects of MRT (U = 21.0, p = 0.03) and PTA (U = 23.0, p = 0.04) were significant, while the effect of PSVT was not. High

[10] For each ANOVA, the spatial ability test and DomHand (whether subjects were LH or RH) were used as fixed effects. DomHand was not found to be significant for any of the three tests, and there were no significant cross effects.

scorers on the MRT and PTA had a significantly higher percentage of rotational multi-axis movement than low scorers.

4.4.3.5 Bimanual Movement Percentage

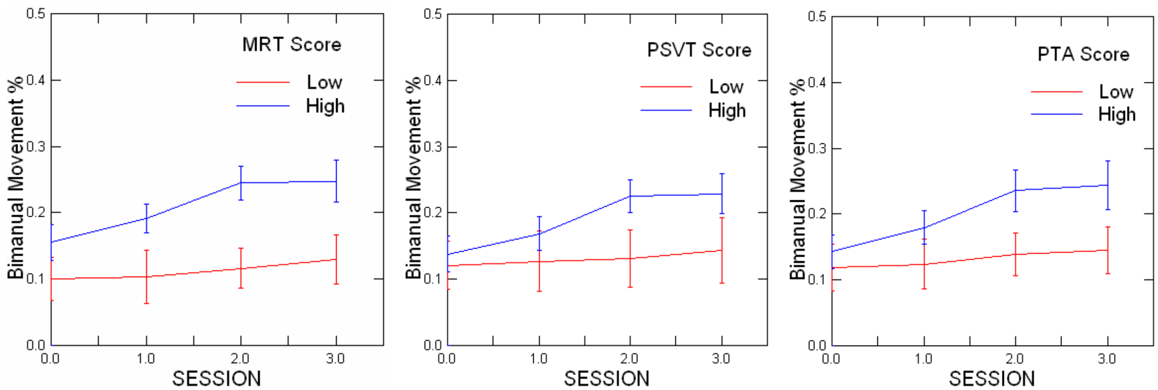

Figure 4.11: Effect of Spatial Ability on Bimanual Movement %

The Mann Whitney U test was also used to analyze the effect of spatial ability on bimanual movement. MRT (U = 21.0, $p = 0.03$) was found to be significant, while PSVT and PTA were not. High scorers on the MRT showed a significantly higher percentage of bimanual movement.

4.4.4 Joystick Configuration Effects

4.4.4.1 Trial Time

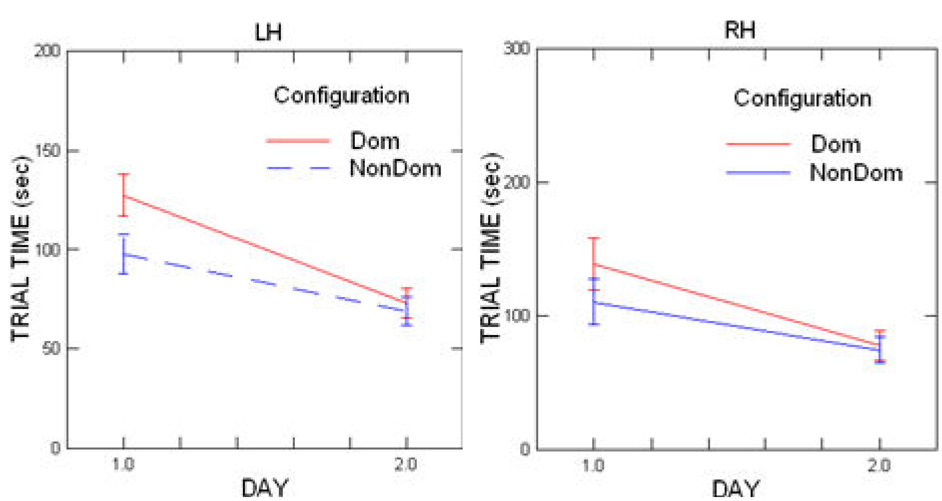

Figure 4.12: Effect of Joystick Configuration on Trial Time

The non-parametric Sign test was used to test for an effect of Dominant or Non-Dominant Joystick configuration on Task Time. Both LH (p = 0.039) and RH (p = 0.001) subjects took significantly less time to complete the task in a Non-Dominant configuration on Day 1, but there was no significant effect of configuration on Day 2. Our hypothesis was that subjects would consistently take less time in the Dominant configuration, but the result we found may be attributable to the effect of order and learning. All subjects performed the Dominant configuration before the Non-Dominant configuration on both days, so the apparent effect could be explained if the overall learning effect was stronger than the effect of configuration.

4.4.4.2 Discrete Moves

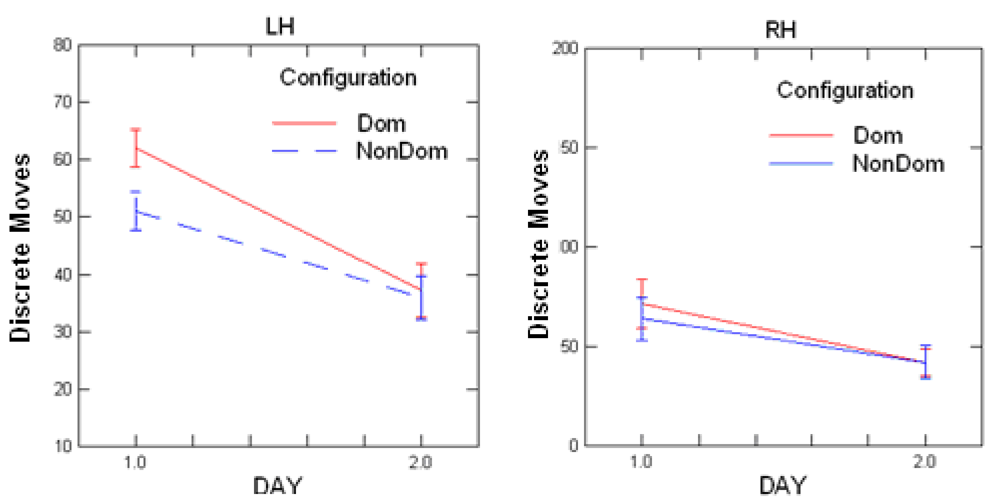

Figure 4.13: Effect of Joystick Configuration on Discrete Moves

A Sign test showed a significant effect (p = 0.039) of configuration on Day 1 for LH subjects, with subjects making fewer discrete movements in the Non-Dominant configuration. There was no significant difference between configurations on Day 2 for LH subjects, and for either day for RH subjects.

4.4.4.3 Translational Multi-Axis Movement Percentage

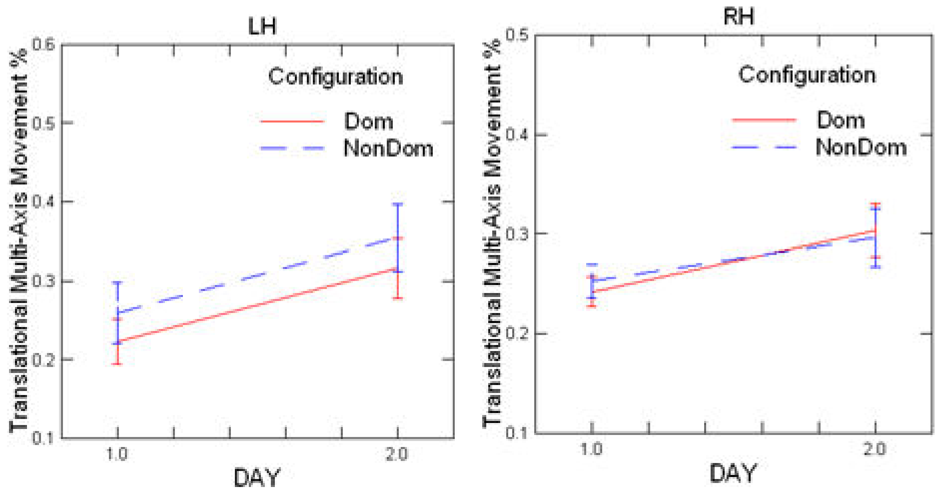

Figure 4.14: Effect of Joystick Configuration on Translational Multi-Axis %

A Sign test showed a small but statistically significant effect ($p = 0.039$) of joystick configuration on percent of translational multi-axis movement on Day 2 only for LH subjects. Subjects had a higher percentage of translational multi-axis movement in the Non-Dominant setup. There was no significant difference between configurations on Day 1 for LH subjects, and for either day for RH subjects.

4.4.4.4 Rotational Multi-Axis Movement Percentage

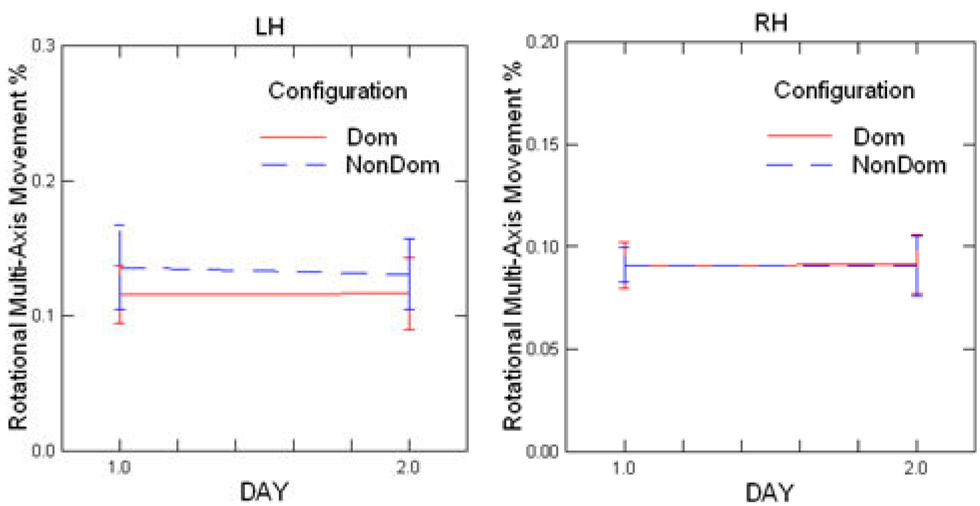

Figure 4.15: Effect of Joystick Configuration on Rotational Multi-Axis Movement %

A Sign test showed a small but statistically significant difference ($p = 0.039$) between configurations on Day 2 only for LH subjects, with subjects having a higher percentage of rotational multi-axis movement in the Non-Dominant setup. There was no significant effect of configuration on Day 1 for LH subjects or on either day for RH subjects.

4.4.4.5 Bimanual Movement Percentage

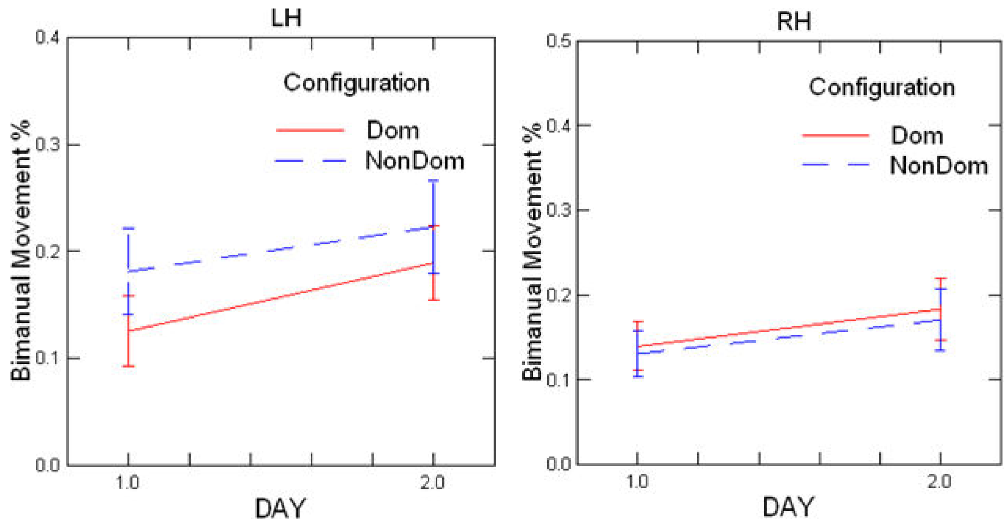

Figure 4.16: Effect of Joystick Configuration on Bimanual Movement %

A Sign test also showed a small but significant difference ($p = 0.039$) between configurations on Days 1 and 2 but again only for LH subjects, with subjects having a higher percentage of bimanual movement in the Non-Dominant setup. There was no significant difference between configurations on either day for RH subjects.

4.4.5 Handedness Effects

4.4.5.1 Trial Time

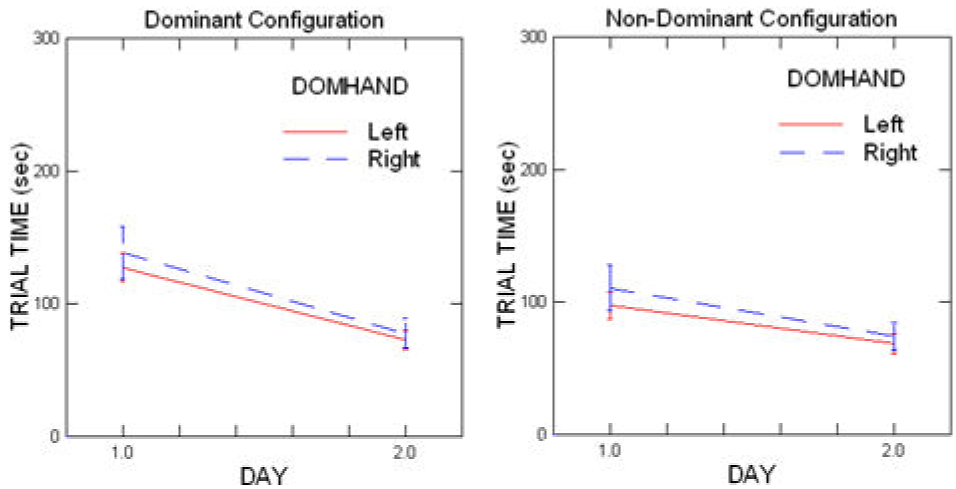

Figure 4.17: Effect of Handedness on Trial Time

A Mann Whitney U test showed no significant difference in Task Time in both the Dominant and Non-Dominant configurations between LH and RH subjects on either day.

4.4.5.2 Discrete Moves

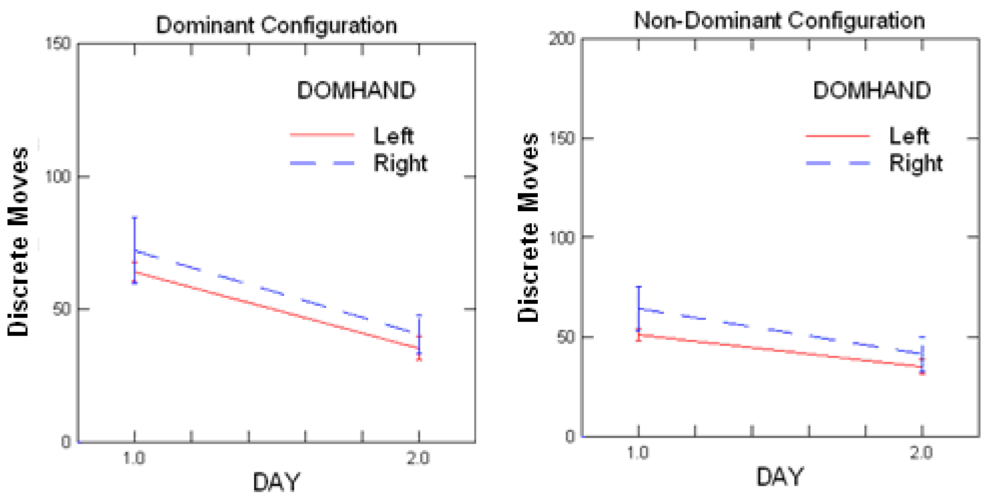

Figure 4.18: Effect of Handedness on Discrete Moves

A Mann Whitney U test found no significant difference in the number of Discrete Moves in both the Dominant and Non-Dominant configurations between LH and RH subjects on either day.

4.4.5.3 Translational Multi-Axis Movement Percentage

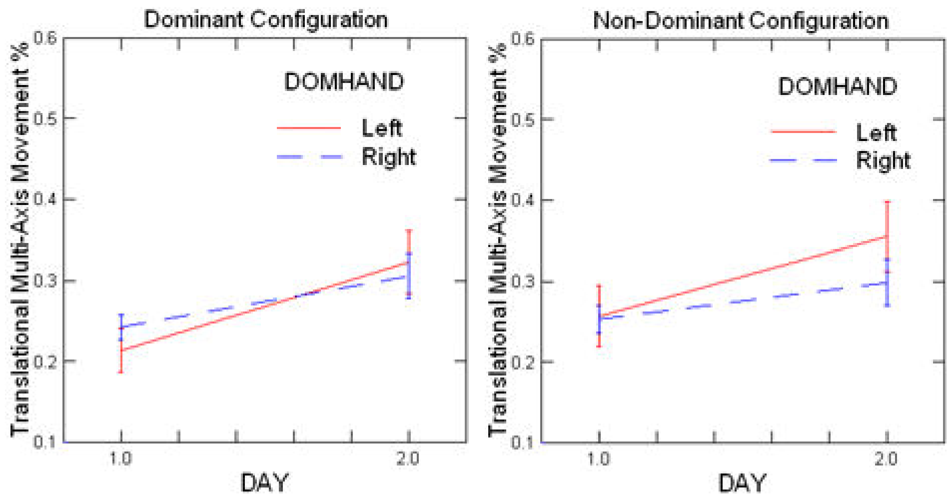

Figure 4.19: Effect of Handedness on Translational Multi-Axis Movement %

A Mann Whitney U test found no significant effect on percentage of translational multi-axis movement in both the Dominant and Non-Dominant configurations between LH and RH subjects on either day.

4.4.5.4 Rotational Multi-Axis Movement Percentage

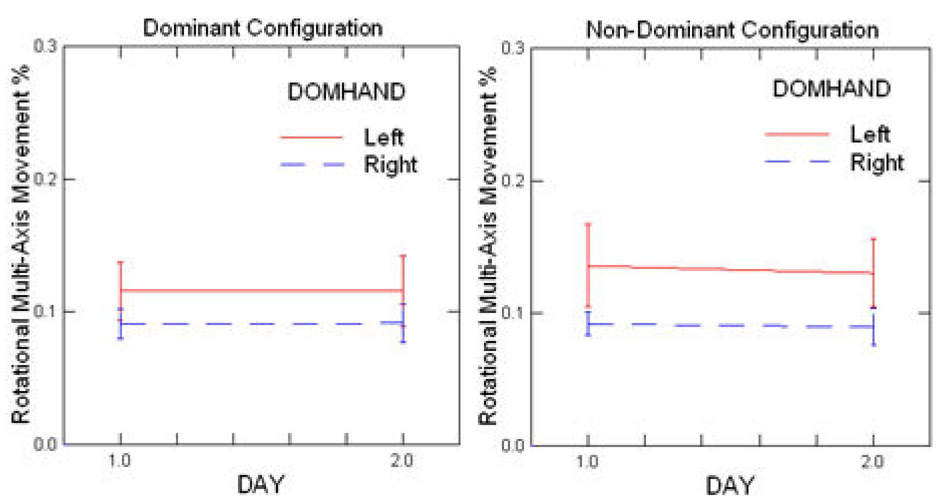

Figure 4.20: Effect of Handedness on Rotational Multi-Axis Movement %

A Mann Whitney U test found no significant effect on percentage of rotational multi-axis movement in both the Dominant and Non-Dominant configurations between LH and RH subjects on either day. LH subjects do however appear to perform marginally better on average for this metric in both configurations.

4.4.5.5 Bimanual Movement Percentage

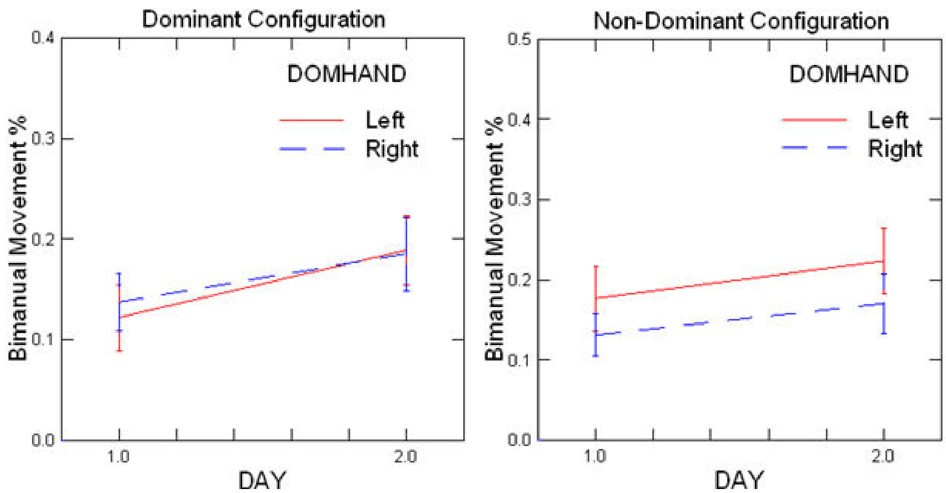

Figure 4.21: Effect of Handedness on Bimanual Movement %

A Mann Whitney U test found no significant difference in percentage of bimanual movement in both the Dominant and Non-Dominant configurations between LH and RH subjects on any Day. Again, LH subjects do however appear to perform marginally better in the Non-Dominant configuration.

4.4.6 Post Test Questionnaire

70% of subjects preferred using the joysticks in the Dominant setting (RH preferred rotational hand controller on right, and LH preferred rotational hand controller on the left). The majority of the subjects that preferred a Dominant configuration stated that they felt more comfortable controlling the finer movement of the rotational controller with their dominant hand. When subjects were asked whether integrating the camera views, understanding the movement of the arm, or understanding multi-axis/bimanual movement was the most difficult part of the experiment, the majority of subjects (55%) chose multi-axis/bimanual movement. A Chi-Square test showed no significant relationship between High/Low scorers (for MRT, PSVT, and PTA) and preferred configuration, or between spatial ability and choice for experiment difficulty.

4.5 Discussion

The results supported the hypothesis that high spatial ability subjects perform fly-to telerobotic tasks more quickly and accurately than lower spatial ability subjects during early telerobotics training. The High scorers for the MRT, PSVT, and PTA tests consistently had significantly lower Task Times and High scorers for PSVT and PTA made fewer Discrete Movements than Low scorers. High MRT and PTA scorers also had a significantly higher percentage of translational and rotational multi-axis movement, and High MRT scorers had a higher percentage of bimanual movement. This finding represents an experimental confirmation of similar findings in Experiment 1 and previous experiments in our laboratory [13, 16].

The results did not support the hypothesis that left and right handed subjects would perform better in the Dominant joystick configuration. On Day 1, both LH and RH subjects took significantly less time to complete the task in the Non-Dominant configuration, and LH subjects had significantly fewer discrete movements in the Non-Dominant configuration. This result may have been due to an order effect and task learning, since all subjects performed the task in the Dominant configuration prior to the Non-Dominant configuration on both days. It is possible the opposite results may have occurred if the order had been switched. However, neither LH nor RH subjects showed any significant difference in Trial Time or number of Discrete Moves on Day 2. The overall learning effect appears to be much stronger than the effect of joystick configuration itself.

LH subjects showed a small but statistically significant increase in percentage of translational and rotational multi-axis movement on Day 2 in the Non-Dominant configuration, versus no difference in performance for RH subjects. LH subjects showed a significant increase in percentage of bimanual movement on both days, with better performance in the Non-Dominant setting. There was no difference in bimanual movement between configurations for RH people. These results suggest that the effect of configuration is not quite as strong for LH people, since there was discrete significant improvement for some of the metrics. This makes sense since LH people often have to adapt to RH settings in the real world, where manual tasks often are optimized for RH individuals. There was no significant difference between LH and RH subjects when compared across all five dependent variables separately in the Dominant and Non-Dominant settings. However, on average the LH group appeared to slightly outperform the RH group, particularly for rotational multi-axis percentage and bimanual percentage in the Non-Dominant setting. These results suggest that in the early stages of training for this experiment that Guiard's [18] idea that the dominant hand is better equipped to perform finer resolution tasks (operation of the RHC in this case) does not apply.

5 Conclusions

In summary, the results of the camera selection experiment showed:

- Performance on camera selection for space telerobotics was affected by specific spatial skills. High scorers for the MRT and PTA tests had significantly lower Task Times and higher Camera Selection Scores, and made fewer Changes. In addition, High scorers for the PSVT test have significantly lower Prep Times than Low scorers. Previous research in our laboratory has shown that spatial skills influence primary and secondary operator performance. This experiment demonstrates that spatial skills influence performance in an important operator subtask – camera selection.

The results of the spatial ability and handedness experiment showed:

- High spatial ability scorers performed significantly better than Low scorers on a telerobotic fly-to task. They took significantly less time, made fewer discrete movements, and showed higher percentages of translational and rotational multi-axis movement and bimanual movement. There was no significant difference in spatial ability between LH and RH subjects. That spatial ability tests predict performance in the early stages of space telerobotics training confirms previous results from our laboratory.
- The overall learning effect appears to be greater than the effect of switching between Dominant and Non-Dominant hand controller configurations. When a difference was present, our subjects performed better with a Non-Dominant configuration. However, this is most likely because all subjects performed the Non-Dominant configuration after the Dominant configuration on both days.
- There was no significant difference between RH and LH subjects for any of the performance metrics in either the Dominant or Non-Dominant configuration. However, LH subjects performed slightly better than RH subjects, particularly in the Non-Dominant setting.

The data indicates that performance in multiple areas is most influenced by spatial ability, at least in the early stages of robotics training simulated here. Both experiments show MRT and PTA scores as the most reliable predictors of performance, while PSVT appears to be slightly less reliable. Table 5.1 summarizes how the different spatial ability scores appear to relate to performance, with results similar to those found in a previous MVL experiment [16].

Table 5.1: Connections between Spatial Ability and Performance

	Performance Characteristics
MRT	▪ Time required to complete a camera selection task ▪ Number of correct camera views selected ▪ Number of changes made prior to selecting final camera views ▪ Time required to complete a fly-to task ▪ Percentage of translational and rotational multi-axis movement ▪ Percentage of bimanual movement
PSVT	▪ Time spent studying a map prior to selecting camera views ▪ Time required to complete a fly-to task ▪ Number of movements made in a fly-to task
PTA	▪ Time required to complete a camera selection task ▪ Number of correct camera views ▪ Number of changes made prior to selecting final camera views ▪ Time required to complete a fly-to task ▪ Number of movements made in a fly-to task ▪ Percentage of translational and rotational multi-axis movement

The results of the second study indicate that handedness was not a consistent predictor of performance as compared to spatial ability. No significant difference was seen in any of the metrics for left or right-handed subjects. The joystick configuration does not appear to affect performance to the extent originally hypothesized. We cannot rule out the possibility of a small configuration related effect, but overall learning in the telerobotics environment is much more influential than the effect of configuration. The results do indicate however that configuration has a smaller effect on LH subjects, especially when looking at performance in a Non-Dominant configuration. This may be because LH people are more accustomed to using both hands for various tasks in having to adapt to a world mainly designed for RH people.

These studies were designed to investigate performance only during early telerobotics training. While the data cannot be used to predict final performance levels, the results could potentially be used to create individual skill profiles that could be used to create individualized lesson plans for beginner robotics trainees.

6 Suggestions for Future Work

This thesis continued the efforts begun by previous students in the laboratory to investigate the effect of spatial ability on space teleoperation. At the same time, it searched for other potential predictors of performance such as joystick configuration and handedness. However, many questions remain and future experiments should help to improve our understanding of these unresolved issues.

- The simulation of the ISS robotic environment used in Experiment 2 was unable to accurately determine when clearance violations or collisions occurred between the robotic arm and the environment. It would be useful to improve this feature for future experiments so that subjects could have more accurate, real-time feedback on their performance.
- These studies utilized only one set of camera views per task scenario. However, astronauts must constantly change camera views, zoom, and multiplex views onto a single monitor during actual robotics tasks. We kept the views consistent across all trials for scientific purposes. Allowing subjects to optimize camera views throughout the experiment could improve performance and face validity.
- Subjects were only permitted two practice trials in each configuration. All of our experiments used the same training procedure for all subjects, which mainly consisted of PowerPoint tutorials followed by the two practice trials. Subjects learn at different rates, and this training procedure does not necessarily work best for them all. If time had permitted us to more thoroughly train subjects to a criterion level of asymptotic performance in each configuration, learning effects would have been greatly reduced, and perhaps we might have been able to detect small configuration effects. It would be interesting to develop multiple instruction styles and determine if there is a correlation between spatial ability scores and the instruction style that works best.
- In both experiments subjects were given fixed numbers of training sessions, but in actual training astronauts are allowed to practice as much as required to become proficient at each lesson. It would be useful to design a longer experiment that would allow subjects to train to proficiency, and then see how much training is

required to minimize the effect of individual spatial ability differences. Task time should also be limited to reduce the effects of fatigue for subjects who take longer to finish.

- It may be useful to improve the mechanical characteristics of the hand controllers to help reduce accidental motion in more axes than are intended. For instance, incorporating stiffer springs into the hand controllers might help reduce accidental cross-coupled control by requiring greater forces to activate the controller in each axis.

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8 Appendices

Appendix A - Experiment 1 Basic Subject Data

Subject	Gender	MRT	PSVT	PTA
1	M	37	16	27.18
2	M	14	17	20.62
3	M	13	15	18.89
4	M	25	29	23.78
5	M	27	23	14.45
6	M	21	28	24.21
7	M	26	24	26.04
8	F	17	9	17.99
9	F	16	13	11.38
10	M	4	7	18.26
11	M	16	16	19.49
12	M	25	14	20.98
13	F	12	13	25.82
14	M	29	13	24.03
15	F	16	16	18.35
16	F	18	7	14.42
17	F	17	15	20.66
18	F	26	27	28.09
19	F	16	13	15.73
20	F	12	5	13.82
21	F	0	11	11.97

Appendix B - Experiment 1 and 2 Pre-Test Questionnaire

Gender: F M **Age:**

Right/Left Handed: Right Left **Major/ Course #:**

Colorblind? Y N (If yes, can you differentiate between red and green?

1. **Do you have experience with Virtual environments (e.g. 3-D games, CAD, graphic design, etc.)?**

(Yes No) (If "Yes," can you please describe this experience?)

2. **Do you have experience with joysticks/game controllers? (e.g. computer/video games, robotics)**

(Yes No) (If "Yes," can you please describe this experience?)

3. **How many hours per day do you use the computer?**
   ☐ 0 ☐ 1 – 3 ☐ 3 – 5 ☐ 5 – 7 ☐ More than 7
4. **What do you typically use the computer for? (Please check all that apply)**
   ☐ Email/Internet/Word processing ☐ Design (Graphical/Mechanical)
   ☐ Programming ☐ Gaming ☐ Other__________________________________
5. **Have you previously or do you currently have a habit of playing video/computer games?**

(Yes No) (If "No," go to question 10)

6. **How old were you when you started playing video/computer games?**
   ☐ < 5 ☐ 5 – 12 ☐ 12 – 18 ☐ 18- 25 ☐ > 25
7. **On average, how often (hours/week) did you play video/ computer games <u>when you played the most frequently</u>?**
   ☐ 1 – 3 ☐ 3 – 7 ☐ 7 –14 ☐ 14 – 28 ☐ > 28

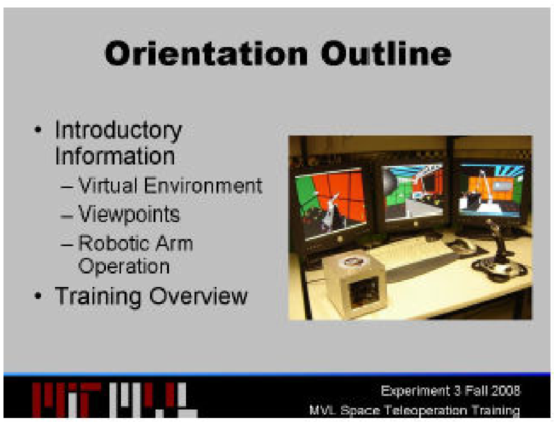
   How many years ago was that?
   ☐ 0 ☐ 3 – 5 ☐ 5 – 10 ☐ 10 – 15 ☐ > 15
8. **On average, how often (hours/week) have you played video/computer games <u>in the past 3 years</u>?**
   ☐ 0 ☐ 1 – 3 ☐ 3 – 7 ☐ 7 –14
   ☐ 14 – 28 ☐ > 28
9. **What kind of video/computer games do you play the most? (check as many as apply)**
   ☐ First person ☐ Role-playing/Strategy ☐ Arcade/Fighting
   ☐ Simulation (driving, flying) ☐ Sports ☐ Other
10. **Have you ever taken any spatial ability tests before?**
   ☐ Yes, for a previous robotics experiment with the MVL
   ☐ Yes, for some other reason (please list: ____________________)
   ☐ No

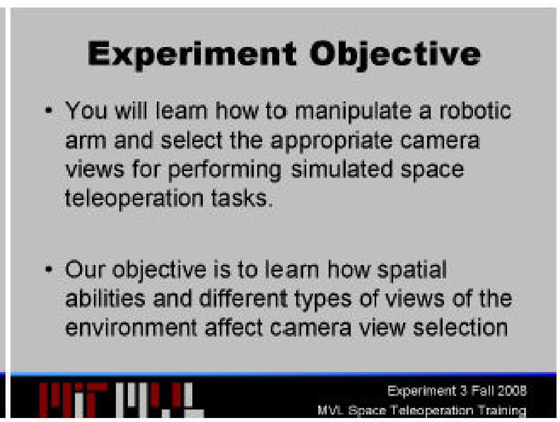
Thank you. Please give this questionnaire back to the experimenter.

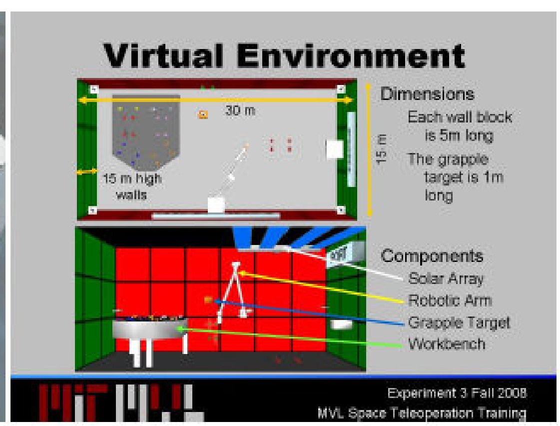
Appendix C – Experiment 1 Pre-Test Questionnaire Results

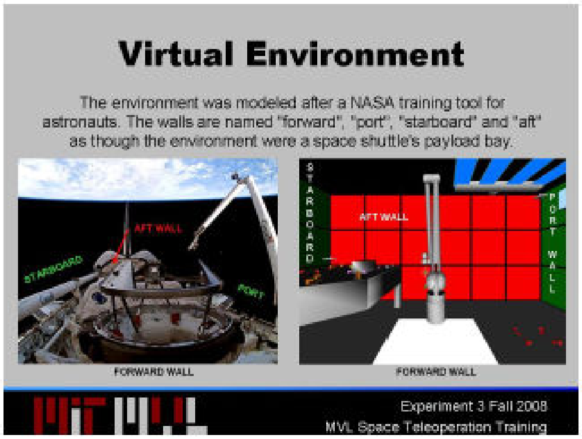
	3D?	3-D Type	Contr Exp?	Exp Type	Comp Hours	Comp Usage	Game Habit?	Game Age	Game Hours	Game Years	Game Recent	Game Type	Prev SA?
1	Y	G&CAD	Y	Video	7+	E&P	Y	5-12	7-14	0-3	7-14	Sports	N
2	Y	Games	N	N/A	7+	Email	Y	12-18	3-7	0-3	7-14	RP	N
3	N	N/A	N	N/A	7+		N	N/A	N/A	N/A	1-3	Sim	N
4	Y	Games	Y	Sim	7+	Email	Y	5-12	14-28	5-10	3-7	RP&Sim	N
5	Y	G&C&Sim	Y	Sim&Video	1-3	Email	Y	5-12	7-14	5-10	0	FP&Sim	Y
6	Y	G&CAD	Y	Comp&Video	3-5		N	5-12	3-7	10-15	0	FP	N
7	Y	CAD	Y	Video	5-7	Email	N	5-12	7-14	5-10	0	FP	N
8	Y	Games	N	N/A	7+		N	18-25	1-3	0-3	1-3	FP	N
9	Y	CAD	Y	Video	5-7	Email	N	N/A	N/A	N/A	N/A	N/A	N
10	Y	Games	Y	Video	3-5	E&P	Y	5-12	3-7	5-10	1-3	RP&Sim	N
11	Y	Games	Y	Video	3-5	E&G	Y	5-12	7-14	3-5	1-3	FP&S	N
12	Y	G&CAD	N	Video	5-7	Email	Y	5-12	14-28	5-10	1-3	FP&RP	N
13	Y	Games	Y	Video	1-3	Email	Y	5-12	14-28	3-5	1-3	RP	N
14	Y	Design	Y	Video	3-5	E&P&D	Y	5-12	3-7	5-10	1-3	Sports	N
15	N	N/A	Y	Video	5-7		N	N/A	N/A	N/A	N/A	N/A	N
16	Y	CAD	Y	Video	7+	E&P&D	N	5-12	7-14	>15	0	Sim	N
17	Y	CAD	Y	Sim	5-7	Email	Y	5-12	1-3	0-3	1-3	Sim	Y
18	Y	CAD	N	N/A	5-7	Email	N	N/A	N/A	N/A	N/A	N/A	N
19	Y	CAD	N	N/A	7+		N	N/A	N/A	N/A	N/A	N/A	N
20	Y	CAD	Y	Video	3-5		N	N/A	N/A	N/A	N/A	N/A	N
21	Y	CAD	N	N/A	5-7	E&P&D	N	N/A	N/A	N/A	N/A	N/A	N

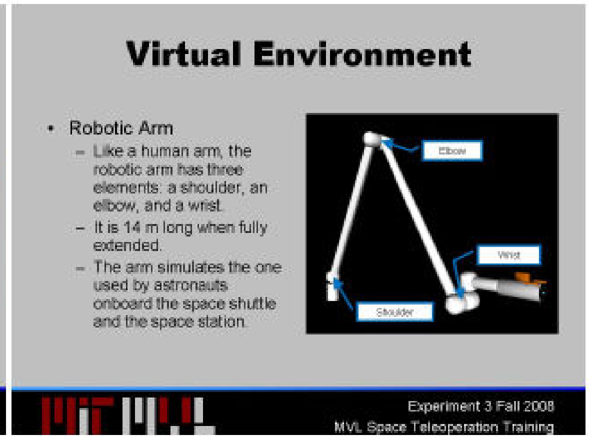
Appendix D – Experiment 1 Training

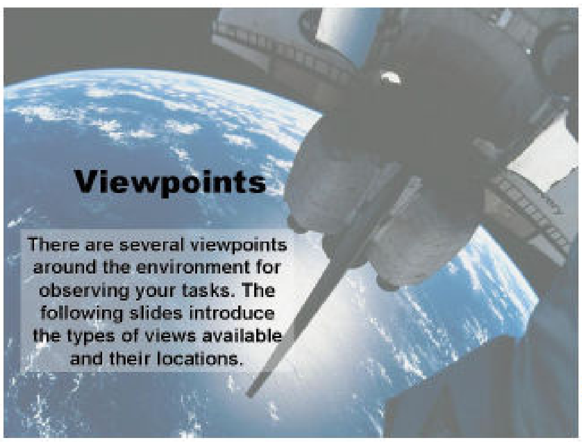


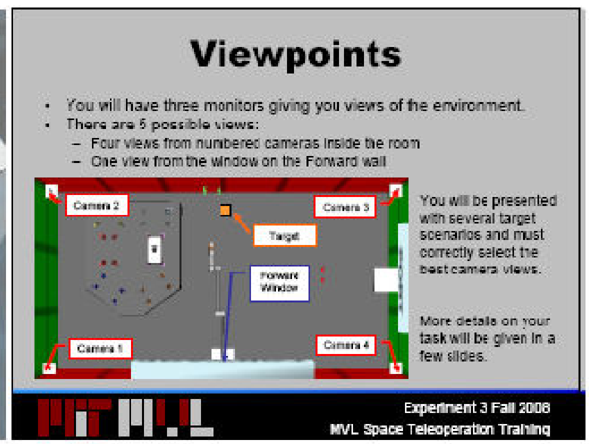





Virtual Environment
The environment was modeled after a NASA training tool for astronauts. The walls are named "forward", "port", "starboard" and "aft" as though the environment were a space shuttle's payload bay.
AFT WALL
STARBOARD
PORT
FORWARD WALL
AFT WALL
STARBOARD
PORT WALL
FORWARD WALL
Experiment 3 Fall 2008
MVL Space Teleoperation Training


Virtual Environment
• Robotic Arm
– Like a human arm, the robotic arm has three elements: a shoulder, an elbow, and a wrist.
– It is 14 m long when fully extended.
– The arm simulates the one used by astronauts onboard the space shuttle and the space station.
Elbow
Wrist
Shoulder
Experiment 3 Fall 2008
MVL Space Teleoperation Training


Viewpoints
There are several viewpoints around the environment for observing your tasks. The following slides introduce the types of views available and their locations.


Viewpoints
• You will have three monitors giving you views of the environment.
• There are 5 possible views:
– Four views from numbered cameras inside the room
– One view from the window on the Forward wall
Camera 2
Camera 3
Target
Forward Window
Camera 1
Camera 4
You will be presented with several target scenarios and must correctly select the best camera views.
More details on your task will be given in a few slides.
Experiment 3 Fall 2008
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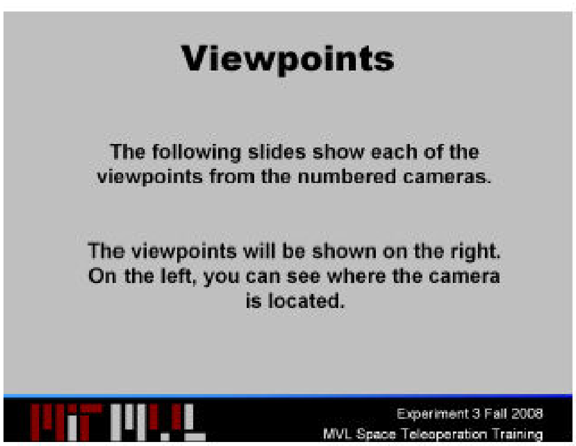
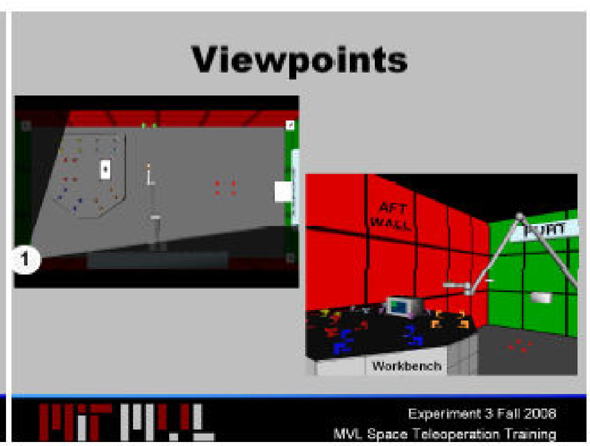
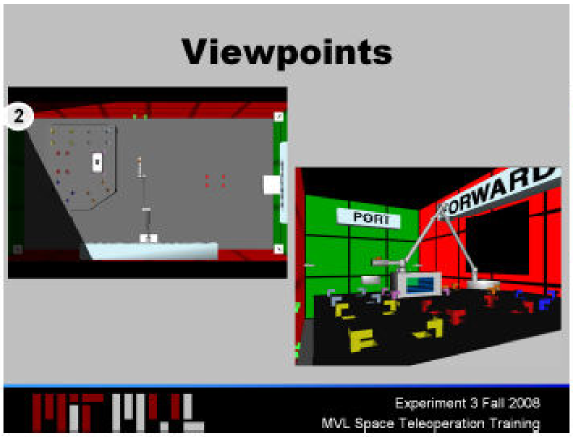
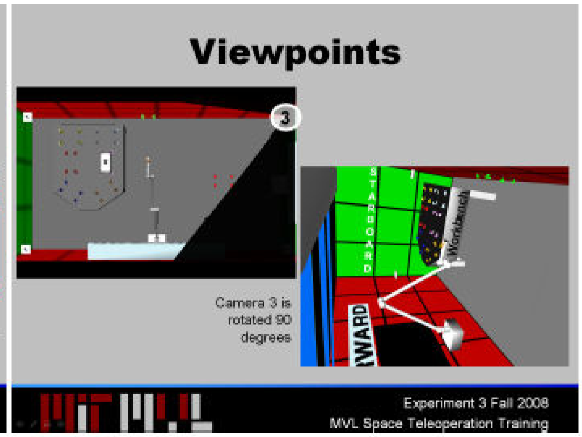
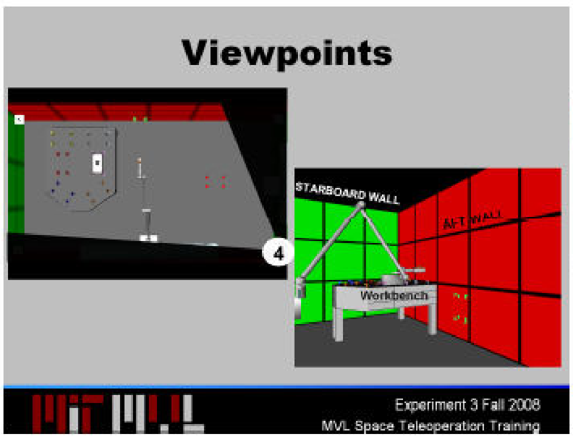
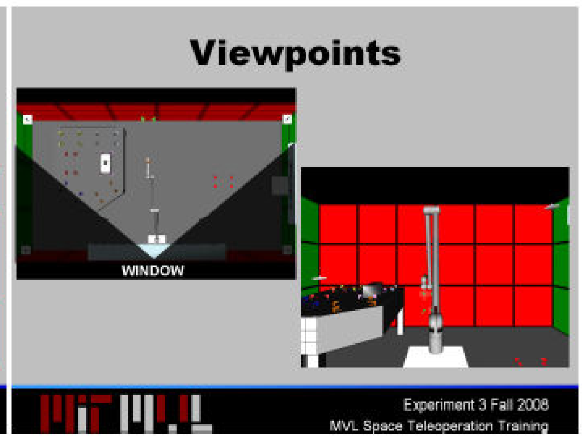

Viewpoints
The following slides show each of the viewpoints from the numbered cameras.
The viewpoints will be shown on the right. On the left, you can see where the camera is located.
Experiment 3 Fall 2008
MVL Space Teleoperation Training


Viewpoints
1
AFT WALL
PORT
Workbench
Experiment 3 Fall 2008
MVL Space Teleoperation Training

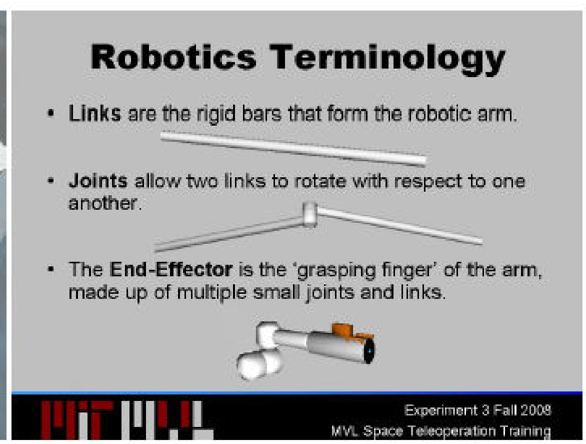

Viewpoints
2
PORT
FORWARD
Experiment 3 Fall 2008
MVL Space Teleoperation Training

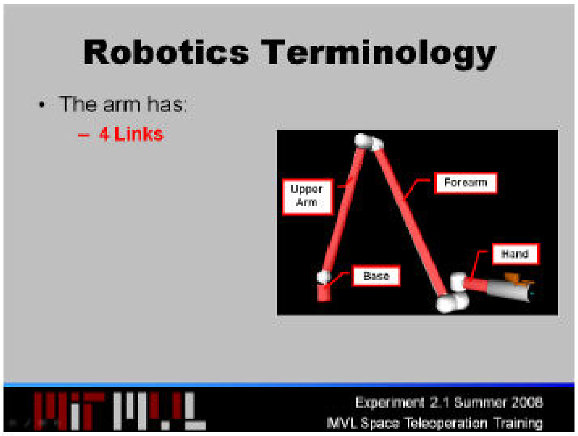

Viewpoints
3
Camera 3 is rotated 90 degrees
STARBOARD
Workbench
WARD
Experiment 3 Fall 2008
MVL Space Teleoperation Training

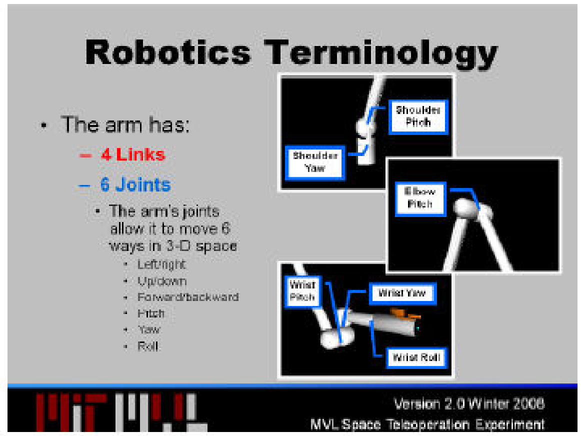

Viewpoints
4
STARBOARD WALL
AFT WALL
Workbench
Experiment 3 Fall 2008
MVL Space Teleoperation Training


Viewpoints
WINDOW
Experiment 3 Fall 2008
MVL Space Teleoperation Training

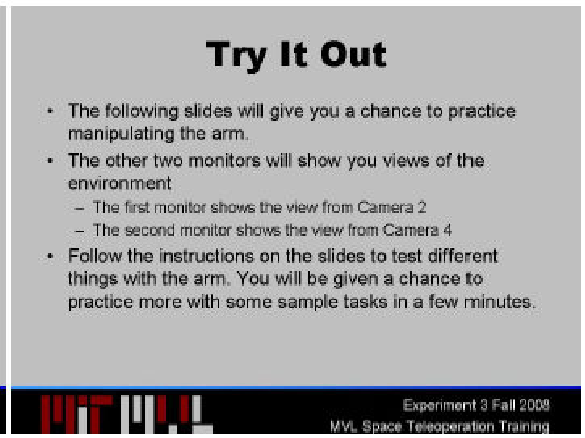

Robotic Arm Operation
The following slides introduce how the arm works and how to operate the hand controller.

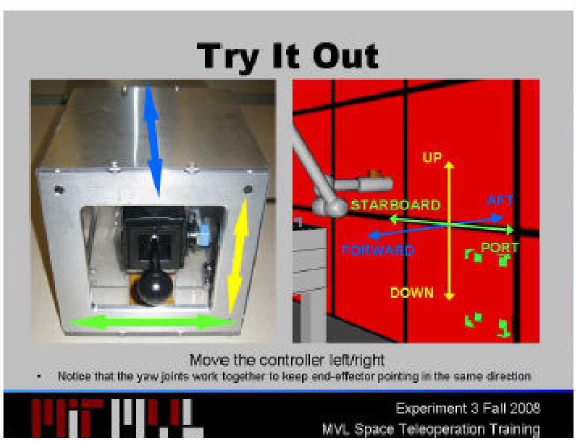

Robotics Terminology
• Links are the rigid bars that form the robotic arm.
• Joints allow two links to rotate with respect to one another.
• The End-Effector is the 'grasping finger' of the arm, made up of multiple small joints and links.
Experiment 3 Fall 2008
MVL Space Teleoperation Training


Robotics Terminology
• The arm has:
– 4 Links
Upper Arm
Forearm
Hand
Base
Experiment 2.1 Summer 2008
MVL Space Teleoperation Training


Robotics Terminology
• The arm has:
– 4 Links
– 6 Joints
• The arm's joints allow it to move 6 ways in 3-D space
• Left/right
• Up/down
• Forward/backward
• Pitch
• Yaw
• Roll
Shoulder Pitch
Shoulder Yaw
Elbow Pitch
Wrist Pitch
Wrist Yaw
Wrist Roll
Version 2.0 Winter 2008
MVL Space Teleoperation Experiment

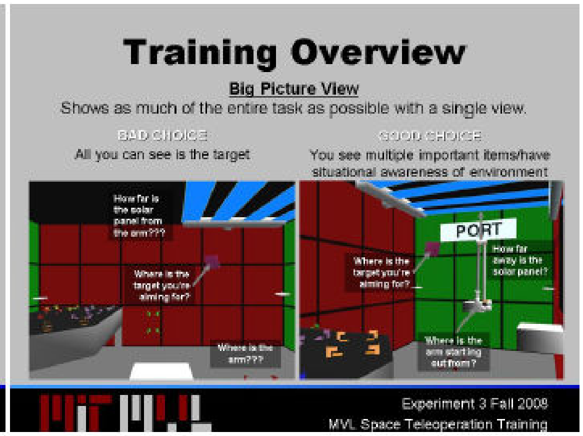

Translational Hand Controller
The translational hand controller allows the arm to move left/right, up/down, and forward/backward.
It does not move the arm's individual joints, it just changes the position of the end-effector tip.
Experiment 3 Fall 2008
MVL Space Teleoperation Training

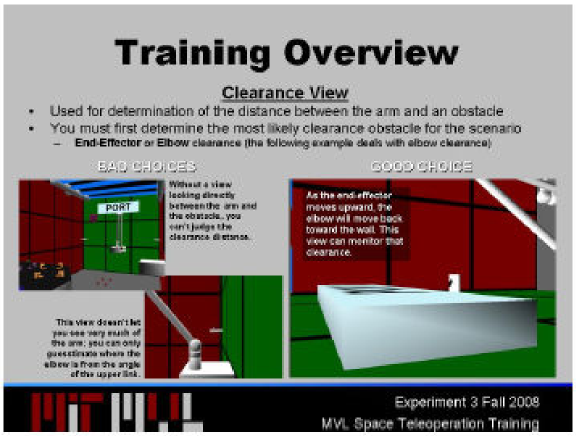

Try It Out
• The following slides will give you a chance to practice manipulating the arm.
• The other two monitors will show you views of the environment
– The first monitor shows the view from Camera 2
– The second monitor shows the view from Camera 4
• Follow the instructions on the slides to test different things with the arm. You will be given a chance to practice more with some sample tasks in a few minutes.
Experiment 3 Fall 2008
MVL Space Teleoperation Training

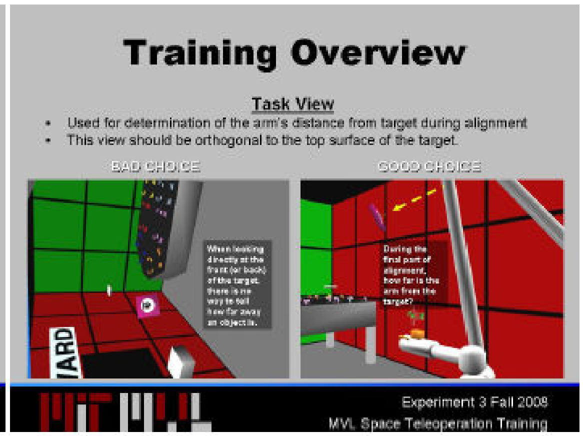

Try It Out
UP
STARBOARD
AFT
FORWARD
PORT
DOWN
Move the controller left/right
• Notice that the yaw joints work together to keep end-effector pointing in the same direction
Experiment 3 Fall 2008
MVL Space Teleoperation Training

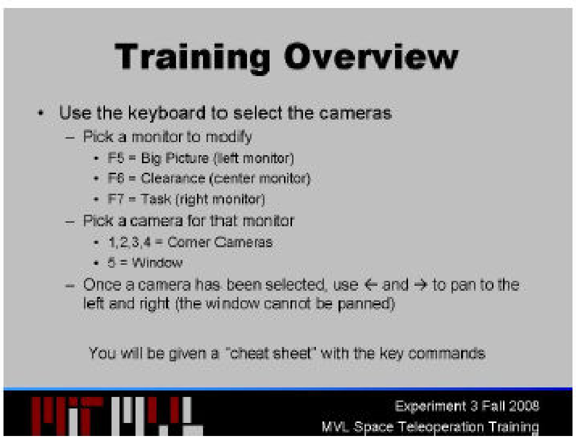

Training Overview
Now that you know how the arm and environment work, the following slides will tell you more about your task.

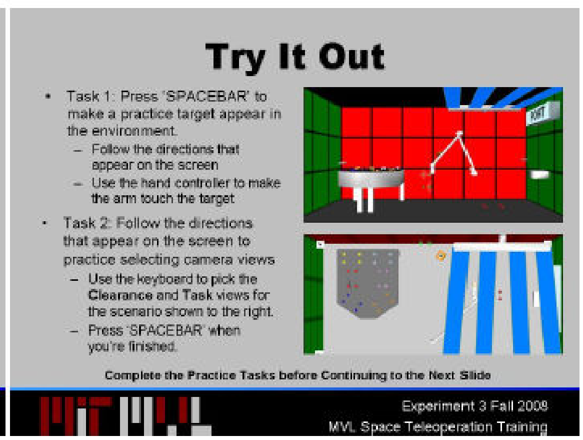

Training Overview
• Learning how to properly select camera views is a big part of the astronauts' robotics training.
• For every task, three types of views are needed:
Big Picture
Clearance
Task
Experiment 3 Fall 2008
MVL Space Teleoperation Training


Training Overview
Big Picture View
Shows as much of the entire task as possible with a single view.
BAD CHOICE
All you can see is the target
GOOD CHOICE
You see multiple important items/have situational awareness of environment
How far is the solar panel from the arm???
Where is the target you're aiming for?
Where is the arm???
PORT
Where is the target you're aiming for?
How far away is the solar panel?
Where is the arm starting out from?
Experiment 3 Fall 2008
MVL Space Teleoperation Training


Training Overview
Clearance View
• Used for determination of the distance between the arm and an obstacle
• You must first determine the most likely clearance obstacle for the scenario
– End-Effector or Elbow clearance (the following example deals with elbow clearance)
BAD CHOICES
GOOD CHOICE
PORT
Without a view looking directly between the arm and the obstacle, you can't judge the clearance distance.
This view doesn't let you see very much of the arm; you can only guesstimate where the elbow is from the angle of the upper link.
As the end-effector moves upward, the elbow will move back toward the wall. This view can monitor that clearance.
Experiment 3 Fall 2008
MVL Space Teleoperation Training


Training Overview
Task View
• Used for determination of the arm's distance from target during alignment
• This view should be orthogonal to the top surface of the target.
BAD CHOICE
GOOD CHOICE
When looking directly at the front (or back) of the target, there is no way to tell how far away an object is.
During the final part of alignment, how far is the arm from the target?
Experiment 3 Fall 2008
MVL Space Teleoperation Training


Training Overview
• Use the keyboard to select the cameras
– Pick a monitor to modify
• F5 = Big Picture (left monitor)
• F6 = Clearance (center monitor)
• F7 = Task (right monitor)
– Pick a camera for that monitor
• 1,2,3,4 = Corner Cameras
• 5 = Window
– Once a camera has been selected, use ← and → to pan to the left and right (the window cannot be panned)
You will be given a "cheat sheet" with the key commands
Experiment 3 Fall 2008
MVL Space Teleoperation Training


Try It Out
• Task 1: Press 'SPACEBAR' to make a practice target appear in the environment.
– Follow the directions that appear on the screen
– Use the hand controller to make the arm touch the target
• Task 2: Follow the directions that appear on the screen to practice selecting camera views
– Use the keyboard to pick the Clearance and Task views for the scenario shown to the right.
– Press 'SPACEBAR' when you're finished.
Complete the Practice Tasks before Continuing to the Next Slide
Experiment 3 Fall 2008
MVL Space Teleoperation Training

Training Overview

- You will complete 3 lessons, and each is made up of 4 trials
  - Step 1: Study the paper maps and click OK only when you are ready to select big picture, clearance, and task views.
  - Step 2: Follow the instructions on the screen to select initial big picture, clearance, and task cameras. Use the information provided by the paper maps to choose the best views.
  - Step 3: Check your initial selections and make changes as necessary in order to get the best set of views possible.
  - Step 4: Press 'SPACEBAR' to lock in your selections. You will be asked what potential clearance problem you were concerned with before the next trial begins.

Experiment 3 Fall 2008
MVL Space Teleoperation Training

Training Overview

- With some scenarios, there may be multiple cameras that all meet the criteria for a view type. Select the one that you feel is best.
- Try not to have important objects (the target, the wall the arm may collide with, etc.) on the very edge of a view. You want to be able to see them as clearly as possible.
- You cannot use any single camera for more than one of the required view types.
- Remember that you are choosing the best cameras for the entire duration of the task, not just for the initial state of the arm

Experiment 3 Fall 2008
MVL Space Teleoperation Training

Training Overview

- There is no time limit for each task, but you are being timed, so work as quickly and accurately as possible.
- After finishing all of the tasks, you will receive a performance rating based on your speed and number of correct selections.

Performance Ratings

1. Corps Applicant (worst)
2. Astronaut Candidate
3. Mission Specialist
4. Flight Engineer
5. Lead Arm Operator (best)

Experiment 3 Fall 2008
MVL Space Teleoperation Training

Appendix E – Experiment 1 Post-Test Questionnaire

Congratulations, you have completed the experiment! We'd like to get some information about your training; please answer each question and, if you wish, add any comments.

1. If you experienced any of the following, please circle your level of discomfort:

EFFECT	NONE				SEVERE
A. Nausea	1	2	3	4	5
B. Dizziness	1	2	3	4	5
C. Disorientation	1	2	3	4	5
D. Eyestrain	1	2	3	4	5
E. Blurred vision	1	2	3	4	5
F. Sweating	1	2	3	4	5
G. Headache	1	2	3	4	5
H. General discomfort	1	2	3	4	5
I. Mental fatigue	1	2	3	4	5
J. Other __________	1	2	3	4	5

2. How enjoyable/interesting was your interaction with the virtual environment?

Boring 1 2 3 4 5 Captivating

Comments?

3. Rate your proficiency on the following items, after going through the Power Point training:

	LOW				EXPERT
- Understanding the Viewpoint types	1	2	3	4	5
- Understanding the Cameras	1	2	3	4	5
- Understanding the Task	1	2	3	4	5

4. Was one of the viewpoint types more difficult than the others?
   - ○ Selecting the Clearance View was the hardest
   - ○ Selecting the Task View was the hardest
   - ○ Selecting the Big Picture View was the hardest
   - ○ Selecting the views were equally difficult

5. Did you try to memorize the layout of the environment during your orientation, or wait and learn it as you went through the tasks?
   - ○ I spent a lot of time studying the pictures of the environment to figure things out
   - ○ I decided to just figure out where things were as I was working with the arm
   - ○ Other: ____

6. Do you have additional suggestions/comments regarding the experiment?

Thank you! Please return this questionnaire to the experimenter.

Appendix F – Experiment 1 Post-Test Questionnaire Results[11]

Subject	Q2	Q3a	Q3b	Q3c	Q4	Q5
1	4	3	4	4	2	1
2	4	4	5	5	1	2
3	3	4	4	4	2	2
4	3	4	4	4	1	2
5	2	2	3	3	1	2
6	3	4	4	4	4	1
7	3	3	5	4	1	1
8	4	3	2	3	4	1
9	3	3	3	3	1	1
10	3	3	2	2	1	1
11	5	4	4	4	3	1
12	5	5	5	5	3	1
13	4	5	4	4	4	1
14	4	4	3	4	1	1
15	4	3	3	3	4	2
16	4	5	5	4	4	1
17	4	4	3	4	4	1
18	3	3	3	4	2	1
19	3	4	3	4	2	1
20	4	3	4	3	1	1
21	4	3	2	4	1	2

[11] Answer Coding
For questions 2 and 3, the value in the table corresponds to the answer marked.
For questions 4 and 5:
1 = first answer option
2 = second answer option
3 = third answer option
4 = fourth answer option

Appendix G – Experiment 1 Trial Design Summary

Trial	Arm Base Location	Clearance Situation
1	Port	Elbow, port wall
2	Forward	EEF, aft wall
3	Port	EEF, aft wall
4	Forward	Elbow, forward wall
5	Port	EEF, table
6	Forward	Elbow, forward wall
7	Port	Elbow, port wall
8	Forward	EEF, aft wall
9	Port	Elbow, port wall
10	Forward	EEF, table
11	Port	EEF, forward wall
12	Forward	Elbow, forward wall

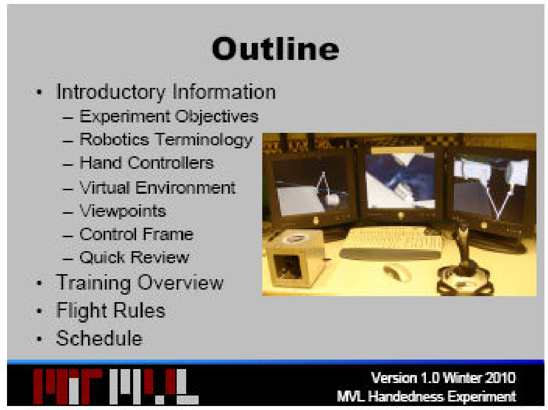
Appendix H – Experiment 2 Basic Subject Data

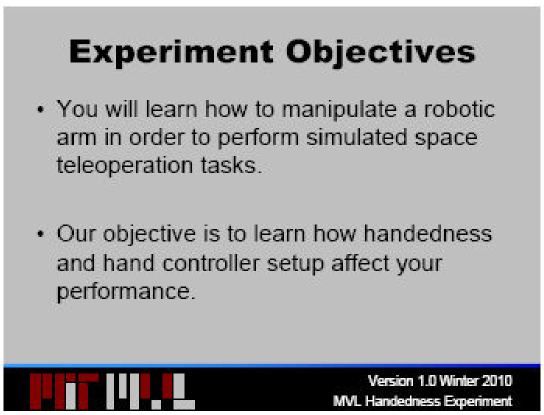
Subject	Gender	MRT	PSVT	PTA
1	F	15	13	21.61
2	M	30	22	17.81
3	M	18	18	21.86
4	M	28	24	26.04
5	M	30	26	20.5
6	M	38	18	23.18
7	M	38	28	25.87
8	M	15	15	18.89
9	M	26	23	26.2
10	F	12	8	15.77
11	M	23	7	15.74
12	M	26	23	21.64
13	F	14	15	15.44
14	M	34	28	25.64
15	M	38	18	23.41
16	M	25	13	21.54
17	M	16	25	20.49
18	M	32	18	22.81
19	F	19	16	18.01
20	M	37	14	23.14

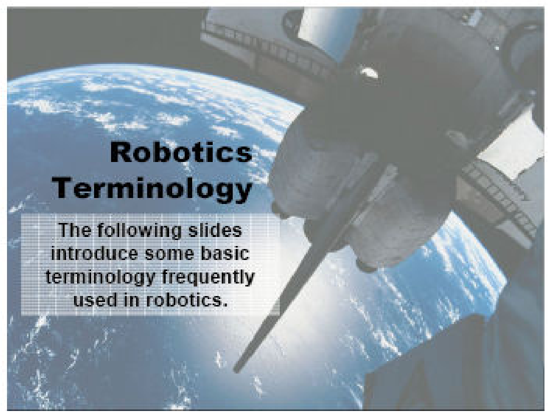
Appendix I – Experiment 2 Pre-Test Questionnaire Results

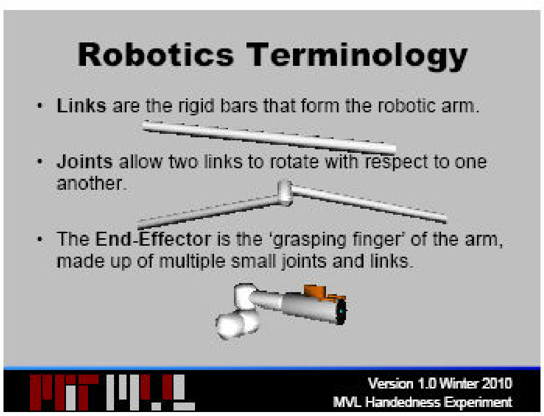
	3-D	3-D Type	Contr Exp?	Exp Type	Comp Hours	Comp Usage	Game Habit?	Game Age	Game Hours	Game Years	Game Recent	Game Type	Prev SA?
1	Y	CAD	N	N/A	3-5	E&D	N	5-12	3-7	5-10	0	Sports	N
2	Y	G&CAD	Y	Video	7+	E&P	Y	5-12	>28	5-10	3-7	FP&RP&Sim	Y
3	Y	G&CAD	Y	Sim&Video	7+	E&P&G	Y	5-12	14-28	5-10	1-3	FP&RP	Y
4	Y	G&CAD	Y	Video	5-7	E&G	Y	5-12	7-14	5-10	1-3	FP&Arc&Sim	Y
5	Y	Sim	Y	Sim	5-7	E&P&G	Y	5-12	14-28	3-5	7-14	FP&RP	Y
6	Y	Games	Y	Video	3-5	E&P	Y	5-12	1-3	5-10	0	RP&Arc&Sports	N
7	Y	G&CAD	Y	Sim&Video	5-7	E&D&P&G	Y	<5	7-14	0-3	7-14	FP&RP&Sim	N
8	Y	CAD	Y	Sim	7+	E&D	Y	12-18	3-7	5-10	1-3	FP&RP	Y
9	Y	CAD	Y	Video	7+	E&D&P	N	5-12	3-7	5-10	1-3	RP	N
10	N	N/A	Y	Video	7+	Email	Y	5-12	1-3	10-15	0	Arc&Sports	N
11	N	N/A	Y	Video	1-3	Email	Y	5-12	1-3	5-10	1-3	Sim&Sports	N
12	Y	Sim	Y	Sim	3-5	E&P	Y	5-12	7-14	5-10	0	FP&Sim	Y
13	N	N/A	Y	Video	7+	E&P	Y	5-12	1-3	10-15	0	FP&Sim&Sports	Y
14	Y	G&CAD	Y	Video	1-3	E&P	Y	5-12	7-14	3-5	1-3		N
15	Y	G&CAD	Y	Sim	7+	E&P&G	Y	5-12	7-14	0-3	3-7	RP&Sim	N
16	Y	CAD	Y	Video	5-7	E&D	N	N/A	N/A	N/A	N/A	FP&RP&Sim	N
17	N	N/A	N	N/A	5-7	E&G	N	N/A	N/A	N/A	N/A	N/A	N
18	Y	CAD	Y	Video	3-5	E&D	N	5-12	1-3	>15	0	Sim&Sports	N
19	Y	Games	Y	Video	5-7	E&P	N	12-18	1-3	10-15	0	RP	N
20	Y	Games	Y	Video	3-5	Email	Y	5-12	7-14	5-10	1-3	FP	Y

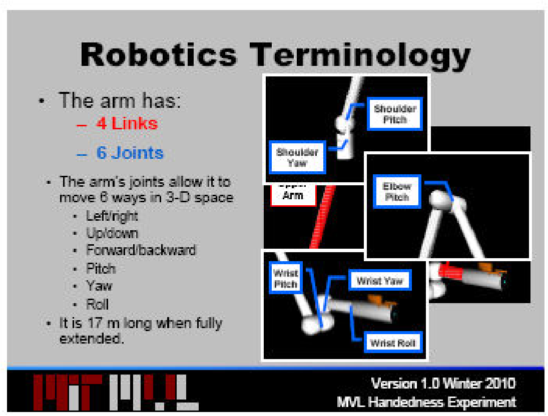
Appendix J – Experiment 2 Training (Day 1)

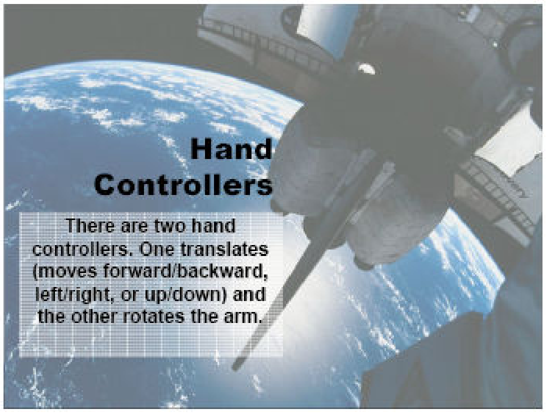


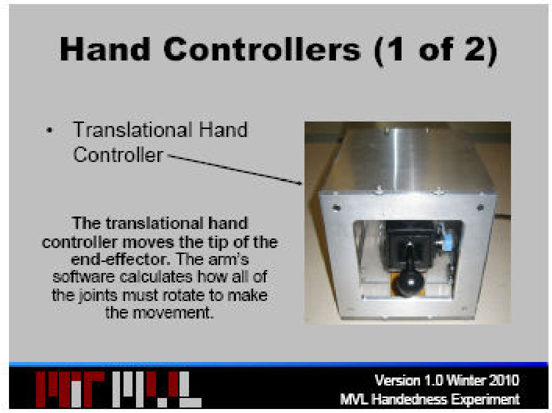




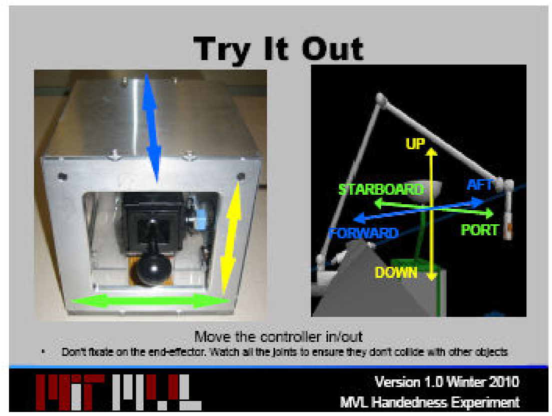





Hand
Controllers
There are two hand controllers. One translates (moves forward/backward, left/right, or up/down) and the other rotates the arm.


Hand Controllers (1 of 2)
• Translational Hand Controller
The translational hand controller moves the tip of the end-effector. The arm's software calculates how all of the joints must rotate to make the movement.
Version 1.0 Winter 2010
MVL Handedness Experiment


Hand Controllers (1 of 2)
It is important to make smooth movements with the hand controller. Quick motions could damage a robotic arm.
It is often desirable to move in more than one axis at once. This is called multi-axis control.
Version 1.0 Winter 2010
MVL Handedness Experiment


Try It Out
UP
STARBOARD
AFT
FORWARD
PORT
DOWN
Move the controller in/out
• Don't fixate on the end-effector. Watch all the joints to ensure they don't collide with other objects
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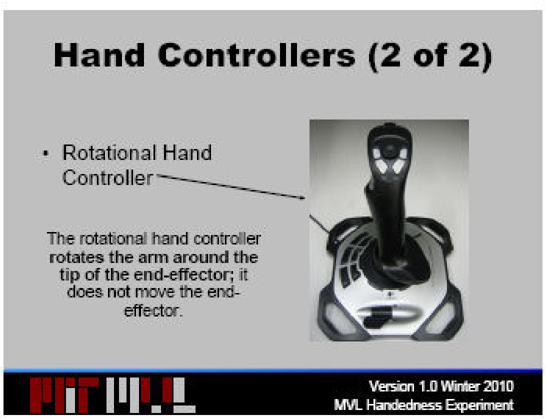
MVL Handedness Experiment


Hand Controllers (2 of 2)
• Rotational Hand Controller
The rotational hand controller rotates the arm around the tip of the end-effector; it does not move the end-effector.
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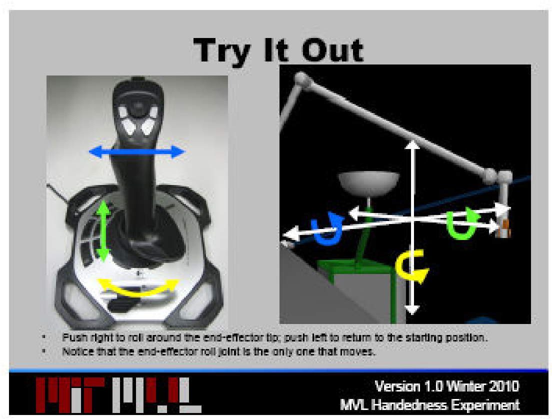
Try It Out
• Push right to roll around the end-effector tip; push left to return to the starting position.
• Notice that the end-effector roll joint is the only one that moves.
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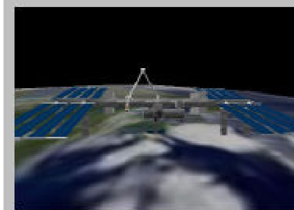
Virtual Environment



International Space Station (ISS)

- Components
  - Core Modules
  - Truss & Solar Arrays
  - Robotic Arm
  - Targets

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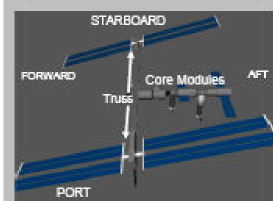
International Space Station



- Core Modules
  - The Core Modules make up the habitable space of the station.
  - They are located on the forward/aft axis of the ISS
- Truss and Solar Arrays
  - The truss is mounted at the forward end of the Core Modules.
  - It is located on the port/starboard axis of the ISS

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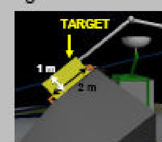
International Space Station

- Anatomy of the Truss

- Targets



- The target is 2 m x 1 m x 1 m in size.

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International Space Station

- Now you can spend a moment navigating through the environment.
  - Use the hand controllers to move about the environment.
  - Try both rotation and translation.
- Things to practice:
  - Use both hand controllers simultaneously – this is called **bimanual control.**
  - Move in more than one axis at a time on each controller – this is called **multi-axis control.**

Watch how different joint angles change together to achieve different movements.

Look around the environment to get an idea of potential hazards. This will be discussed in a later section about clearance and flight rules.

If you get stuck, press 'r' to reset.

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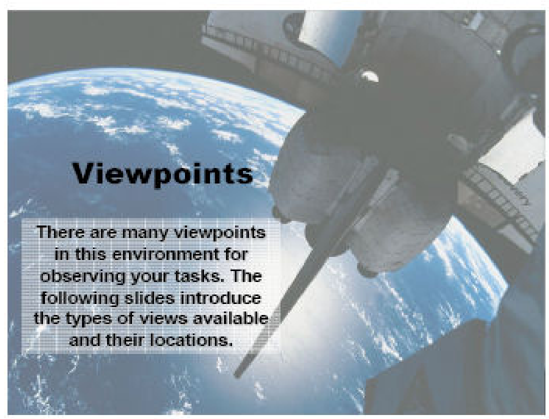

Viewpoints

- The three monitors give different views of the environment and can show any of 5 viewpoints:
  - Four from cameras on the Truss
  - One from a camera placed at the arm's end effector
- The viewpoints in this experiment will be selected for you.

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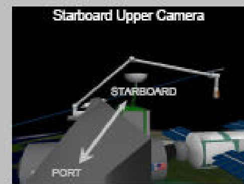
Viewpoints



- Both of the cameras on the lower side of the truss are mounted upside down.
- The pictures above show the views from the starboard upper and starboard lower cameras.

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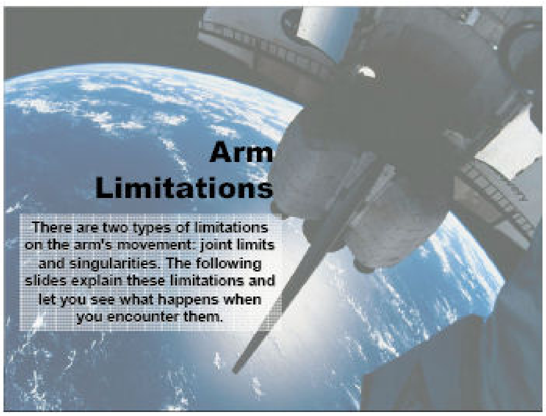


Arm Limitations

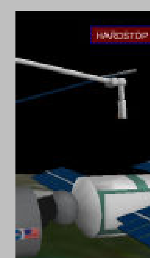
There are two types of limitations on the arm's movement: joint limits and singularities. The following slides explain these limitations and let you see what happens when you encounter them.

Joint Limits

- It's very important that you pay attention to what each of the arm's joints is doing, not just to where the end-effector is going.
- The arm has physical limits, which are called hardstops.
  - Hardstops are the limits on how far a joint can rotate.
  - This notice is displayed on the screen when you encounter a hardstop:

HARDSTOP

  - Move in the reverse direction to free the arm



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Singularities

The arm also has software limitations. It cannot guide movements in particular positions, known as singularities.

When the Elbow Pitch joint is at 0°, all of the arm's joints lock up and a notice is displayed on the screen.

When the Wrist Yaw joint is near ±90°, the arm attempts to avoid the singularity by moving other joints, bringing the joints very close to hardstop. Be very careful to avoid this singularity.

When the Wrist Roll joint is at ±90°, only two of the rotational hand controller's three directions will function. Move the joint away from ±90° to get back normal functionality.

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Try It Out – Singularities

- These steps will let you see what happens when you reach the elbow pitch singularity:
  - Push the translational hand controller to the left and hold it there.
    - Watch the arm move until it hits the singularity.
    - Notice the warning displayed on the screen (ignore the 'clearance violation' at this point).
  - Push the controller to the right to recover and return to the starting position.

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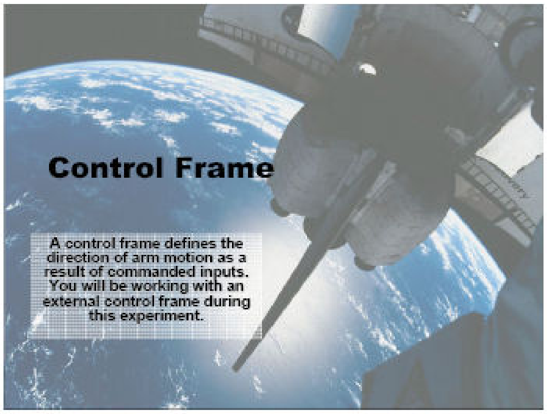
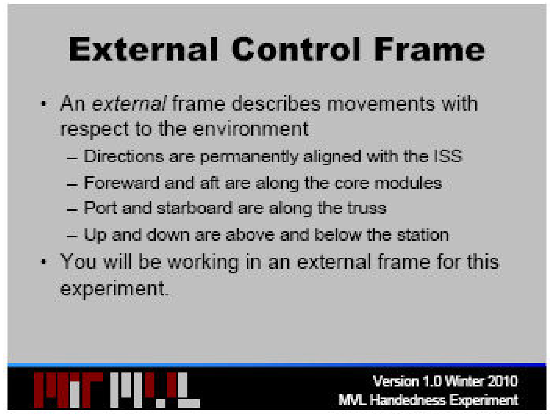

Control Frame
A control frame defines the direction of arm motion as a result of commanded inputs. You will be working with an external control frame during this experiment.


External Control Frame
• An *external* frame describes movements with respect to the environment
– Directions are permanently aligned with the ISS
– Foreward and aft are along the core modules
– Port and starboard are along the truss
– Up and down are above and below the station
• You will be working in an external frame for this experiment.
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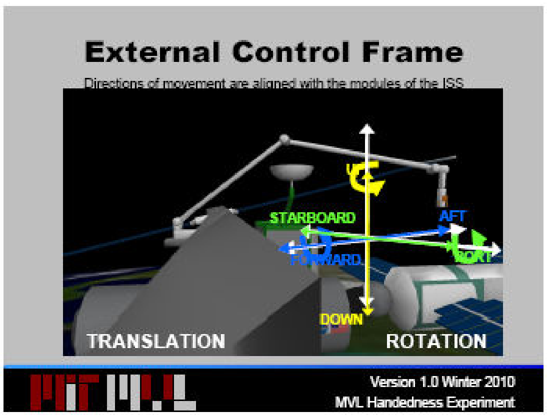
External Control Frame
Directions of movement are aligned with the modules of the ISS
STARBOARD
AFT
PORT
DOWN
TRANSLATION
ROTATION
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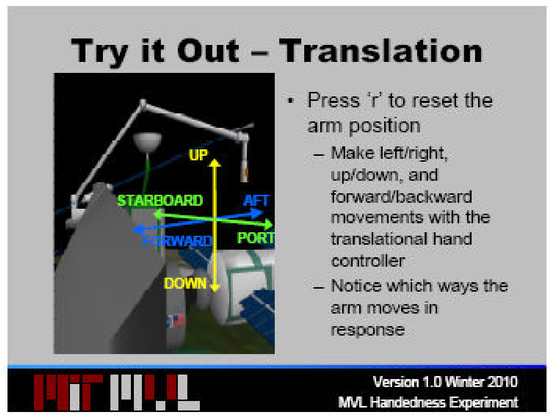
MVL Handedness Experiment


Try it Out – Translation
UP
STARBOARD
AFT
FORWARD
PORT
DOWN
• Press 'r' to reset the arm position
– Make left/right, up/down, and forward/backward movements with the translational hand controller
– Notice which ways the arm moves in response
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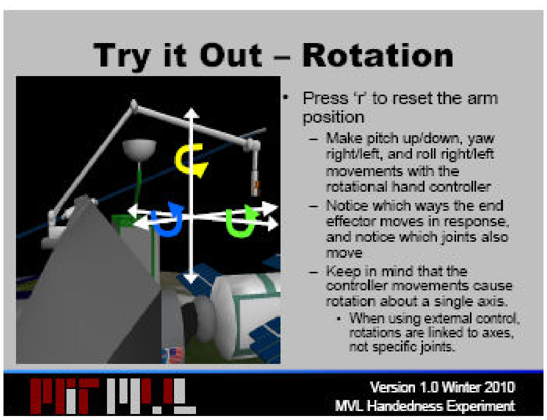
Try it Out – Rotation
• Press 'r' to reset the arm position
– Make pitch up/down, yaw right/left, and roll right/left movements with the rotational hand controller
– Notice which ways the end effector moves in response, and notice which joints also move
– Keep in mind that the controller movements cause rotation about a single axis.
• When using external control, rotations are linked to axes, not specific joints.
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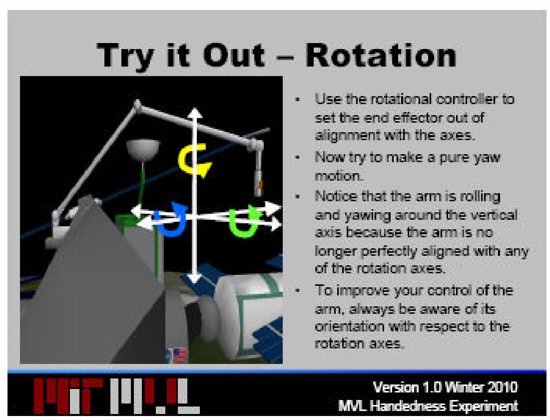
Try it Out – Rotation
• Use the rotational controller to set the end effector out of alignment with the axes.
• Now try to make a pure yaw motion.
• Notice that the arm is rolling and yawing around the vertical axis because the arm is no longer perfectly aligned with any of the rotation axes.
• To improve your control of the arm, always be aware of its orientation with respect to the rotation axes.
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MVL Handedness Experiment

Quick Review

The following slide reviews some important concepts. If there's something you don't understand, feel free to ask the experimenter questions or re-read the slides on that material.

Review of Important Concepts

- Camera Viewpoints
  - The ISS environment has 5 viewpoints
    - Four from cameras on the Truss
    - One from a camera placed at the arm's end effector
- Hand Controllers
  - Two kinds:
    - Translational (box)
    - Rotational (joystick)
  - Use both at the same time, and move in multiple axes simultaneously when possible.
- Arm Limitations
  - Hardstops are the limit on how far a joint can rotate.
  - Limitations in the arm's software cause three types of singularities.
- Control Frame
  - External: directions are relative to the ISS
  - Rotation depends on orientation relative to ISS axes

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MVL Handedness Experiment

Training Overview

Now that you know how the ISS arm and environment work, the following slides will tell you more about what you'll be doing in the experiment.

Training Overview

- Training
  - The training will allow you to practice tasks similar to those you will encounter in the trials. You will perform two fly-to maneuvers from a starting position to the target.
  - Then you will practice getting the arm in the final alignment condition.
- Trials
  - Over the two sessions, you will perform 48 trials (24 today, and 24 at your next session).
  - 24 of the trials will be with your dominant hand performing rotation, and 24 will be with your non-dominant hand performing rotation.
  - Your score will be determined by:
    - Trial time
    - The efficiency of your path
    - Coordination of multi-axis movement and bimanual control
    - Final position and alignment
    - Number of resets of the arm position
    - Adherence to flight rules, described in the next section

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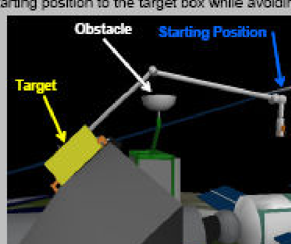
MVL Handedness Experiment

Training Task – Step 1

You will train on how to perform a <u>Fly-To</u> task, and will move the arm from its starting position to the target box while avoiding obstacles.



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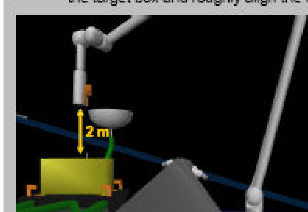
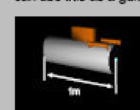
Training Task – Step 2

You will be asked to move the end effector to a location <u>2 meters</u> above the target box and roughly align the end effector with the target



Hint: The last component of the end-effector is 1 m long; you can use this as a guide.



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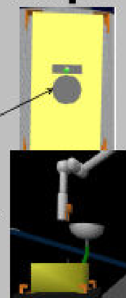
Training Task – Step 3

- When the end-effector is 2 meters above the target box, fine tune its alignment.
  - There are two tools to help you:
    1. A gray circle and a gray rectangle on the target
    2. A big picture view of the angle between the target surface and the end effector
  - Follow these steps to align the end-effector with the target:
    1. Make sure that the gray circle is below the gray rectangle on the target and that the green crosshairs are above the white pin.
    2. Make sure that the end effector is perpendicular to the target surface.
  - Your goal is to be within 20 degrees of perpendicular and 2 meters from the target surface.
- When you are happy with the end-effector's alignment and positioning, you will press SPACE BAR to end the task.



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Flight Rules

- Overall clearance limitation: 2 ft (0.6m) between the arm and all obstacles
  - A warning will be shown on the screen when any part of the arm comes within this limit:

    Clearance Violation

  - Look for what has caused the clearance violation and move away to remove the warning.
- You must avoid collisions between the arm and obstacles or with itself
  - If a collision occurs, this warning will be displayed on the screen:

    COLLISION

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Things to Be Aware Of

Cameras
- Use all of your viewpoints, observe clearances, monitor the task.

Frame
- Think carefully about how to move the arm in the external control frame.

Joints
- Be aware of location of joint angle limits and arm singularities.

Alignment
- The final position you should get to is:
  - 2 meters above the target
  - +/- 20 degrees from perpendicular with the target

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MVL Handedness Experiment

Strategies

- Collision/Clearance Limit Avoidance
  - Monitor the both the elbow and the end effector's position and clearance.
  - Keep checking all of the camera views for potential clearance concerns.
- Reducing Task Time
  - Move in more than one direction at once and perform both rotational and translational movements together in order to finish the task more quickly.
  - Look for the shortest path between the start position and the target and follow that line as best you can.

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Strategies

- Moving the Arm to the Target
  - Plan ahead. Before you start working, think about the movements required for the best route and how to avoid obstacles.
    - i.e. Where will the elbow be if you move the end-effector toward the port side? Will it be too close to a nearby object?
    - When you begin moving the arm, make sure it's doing what you expected. If not, think about what happened and why before moving again.
  - Talk out loud about what you're doing or planning to do while you're working.
    - e.g. "I'm pulling the translational hand controller back; I expect the arm to move forward away from the base. The elbow is going to get closer to the truss, but it won't violate the clearance limit."
    - If what you're planning to do doesn't make sense, you may be able to realize it in advance through hearing yourself say it out loud.

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Strategies

- Arm Alignment
  - Use the edges of fixed objects such as the targets or the trusses to determine when the arm is vertical or horizontal
  - Look at all of your views when you are trying to align the arm with the target. In most situations, you CANNOT get all of the information you need from a single view.
- Distance Estimation
  - Remember that the last component of the end-effector is 1m long. You can use it as a guide to ensure that you don't violate the clearance limit and to position the end-effector correctly.
- Maneuvering
  - If you end up with the arm locked up in a hardstop or trapped due to collisions, try to move in the opposite direction to escape the hardstop. If you cannot escape it, reset the arm to its original position by pressing 'r'. Be aware that resets will count against your overall score.

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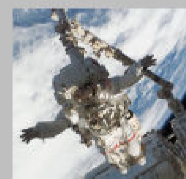
Training Schedule

- This is the schedule for how your training will progress.



- Session 1:
  - ☑ Spatial Ability Tests
  - ☑ Training
  - ☐ First 12 Trials
  - ☐ Second 12 Trials
- Session 2:
  - ☐ Spatial Ability Test
  - ☐ Quick Review
  - ☐ Third 12 Trials
  - ☐ Last 12 Trials

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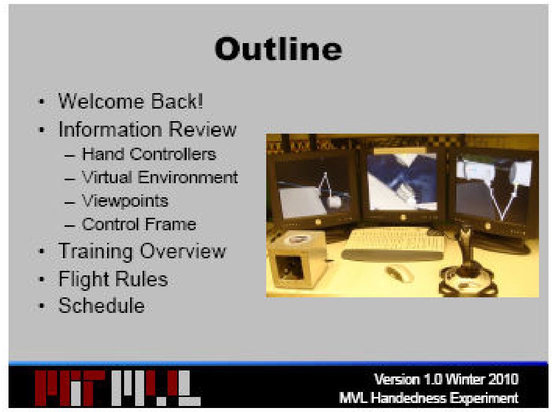
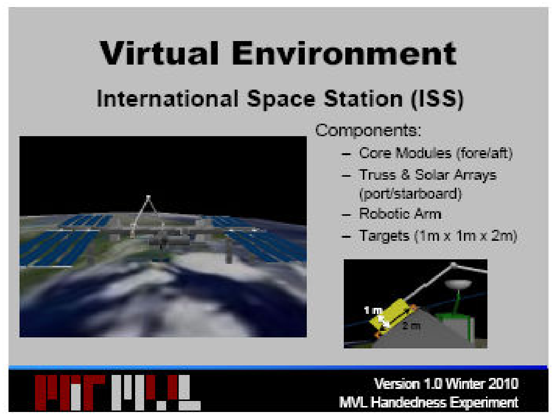
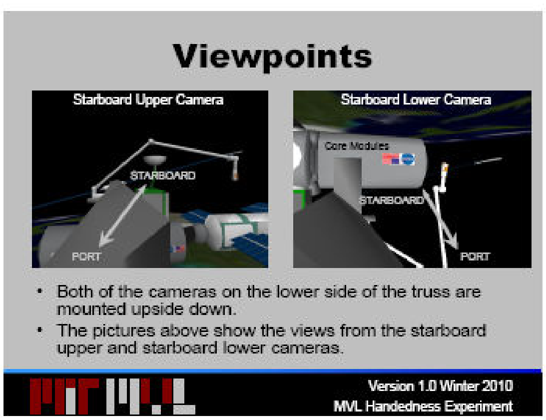
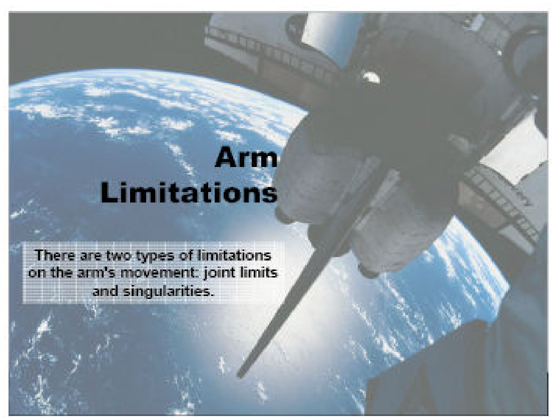
Appendix K – Experiment 2 Training (Day 2)







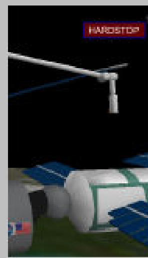


Joint Limits

- It's very important that you pay attention to what each of the arm's joints is doing, not just to where the end-effector is going.
- The arm has physical limits, which are called hardstops.
  - Hardstops are the limits on how far a joint can rotate.
  - This notice is displayed on the screen when you encounter a hardstop:

    HARDSTOP

  - Move in the reverse direction to free the arm



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Singularities

The arm also has software limitations. It cannot guide movements in particular positions, known as **singularities**.

When the Elbow Pitch joint is at 0°, all of the arm's joints lock up and a notice is displayed on the screen.

When the Wrist Yaw joint is near ±90°, the arm attempts to avoid the singularity by moving other joints, bringing the joints very close to hardstop. Be very careful to avoid this singularity.

When the Wrist Roll joint is at ±90°, only two of the rotational hand controller's three directions will function. Move the joint away from ±90° to get back normal functionality.

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External Control Frame

- An *external* frame describes movements with respect to the environment
  - Directions are permanently aligned with the ISS
  - Foreward and aft are along the core modules
  - Port and starboard are along the truss
  - Up and down are above and below the station
- You will continue working in an external frame for this experiment.

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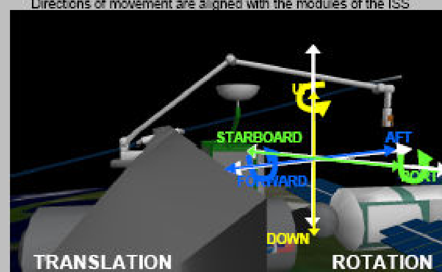
External Control Frame

Directions of movement are aligned with the modules of the ISS



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Trials Overview

- Review
  - As a quick review, you will perform two fly-to maneuvers from a starting position to the target.
  - Then you will review getting the arm in the final alignment condition (within 20 degrees of perpendicular and 2 meters from the target surface).
- Trials
  - In today's session, you will perform 24 trials (12 with your non-dominant hand performing rotation, and 12 with your dominant hand performing rotation).
  - Your score will be determined by:
    - Trial time
    - The efficiency of your path
    - Coordination of multi-axis movement and bimanual control
    - Final position and alignment
    - Number of resets of the arm position
    - Adherence to flight rules, described in the next section

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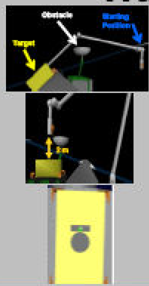
Training Review



Step 1: You will move the arm from its starting position to the target box while avoiding obstacles.

Step 2: You will move the end effector to a location 2 meters above the target box and roughly align the end effector with the target.

Step 3: Fine tune the alignment. Make sure that the gray circle is below the gray rectangle and that the end effector is perpendicular to the target surface. Align the green crosshairs with the white pin.

Remember this reference length:

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Flight Rules and Tips

- Clearance limitation: 0.6m between the arm and all obstacles
  - Look for what has caused the clearance violation and move away to remove the warning.
- You must avoid collisions between the arm and obstacles/walls or with itself
- Cameras: Use all of your viewpoints, observe clearances, monitor the task.
- Frame: Think carefully about how to move the arm in the external control frame.
- Joints: Be aware of location of joint angle limits and arm singularities.
- Alignment: The final position you should get to is:
  - 2 meters above the target
  - +/- 20 degrees from perpendicular with the target

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Strategies

- Collision/Clearance Limit Avoidance
  - Monitor the both the elbow and the end effector's position and clearance.
  - Keep checking all of the camera views for potential clearance concerns.
- Reducing Task Time
  - Move in more than one direction at once and perform both rotational and translational movements together in order to finish the task more quickly.
  - Look for the shortest path between the start position and the target and follow that line as best you can.

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Strategies

- Moving the Arm to the Target
  - Plan ahead. Before you start working, think about the movements required for the best route and how to avoid obstacles.
    - i.e. Where will the elbow be if you move the end-effector toward the port side? Will it be too close to a nearby object?
    - When you begin moving the arm, make sure it's doing what you expected. If not, think about what happened and why before moving again.
  - Talk out loud about what you're doing or planning to do while you're working.
    - e.g. "I'm pulling the translational hand controller back; I expect the arm to move forward away from the base. The elbow is going to get closer to the truss, but it won't violate the clearance limit."
    - If what you're planning to do doesn't make sense, you may be able to realize it in advance through hearing yourself say it out loud.

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Strategies

- Arm Alignment
  - Use the edges of fixed objects such as the targets or the trusses to determine when the arm is vertical or horizontal
  - Look at all of your views when you are trying to align the arm with the target. In most situations, you CANNOT get all of the information you need from a single view.
- Distance Estimation
  - Remember that the last component of the end-effector is 1m long. You can use it as a guide to ensure that you don't violate the clearance limit and to position the end-effector correctly.
- Maneuvering
  - If you end up with the arm locked up in a hardstop or trapped due to collisions, move in the opposite direction to try to escape the hardstop. If you cannot escape, reset the arm to its original position by pressing 'r'. Be aware that resets will count against your overall score.

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Training Schedule

- This is the schedule for how your training will progress.

- Session 1:
  - ☑ Spatial Ability Tests
  - ☑ Training
  - ☑ First 12 Trials
  - ☑ Second 12 Trials
- Session 2:
  - ☑ Spatial Ability Tests
  - ☑ Quick Review
  - ☐ Third 12 Trials
  - ☐ Last 12 Trials

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Appendix L – Experiment 2 Post-Test Questionnaire

Congratulations, you have completed the experiment! We'd like to get some information about your training; please answer each question and, if you wish, add any comments.

1. If you experienced any of the following, please circle your level of discomfort:

EFFECT	NONE				SEVERE
A. Nausea	1	2	3	4	5
B. Dizziness	1	2	3	4	5
C. Disorientation	1	2	3	4	5
D. Eyestrain	1	2	3	4	5
E. Blurred vision	1	2	3	4	5
F. Sweating	1	2	3	4	5
G. Headache	1	2	3	4	5
H. General discomfort	1	2	3	4	5
I. Mental fatigue	1	2	3	4	5
J. Other __________	1	2	3	4	5

2. How enjoyable/interesting was your interaction with the virtual environment?

Boring 1 2 3 4 5 Captivating

Comments?

3. Rate your proficiency on the following items, after going through the Power Point training:

		LOW				EXPERT
- Understanding the movement of the arm	1	2	3	4	5	
- Understanding the Cameras		1	2	3	4	5
- Understanding the Task	1	2	3	4	5	

4. Which joystick configuration did you prefer to perform the task?
   - ○ Translation Hand Controller on Left, Rotational Hand Controller on the Right
   - ○ Rotational Hand Controller on Left, Translational Hand Controller on the Right

5. Which of the following did you consider the most difficult?
   - ○ Integrating the camera views
   - ○ Understanding the movement of the arm
   - ○ Using multi-axis/bimanual movements with the hand controllers
   - ○ Other: ____

6. Do you have additional suggestions/comments regarding the experiment?

Thank you! Please return this questionnaire to the experimenter.

Appendix M – Experiment 2 Post-Test Questionnaire Results[12]

Subject	Q2	Q3a	Q3b	Q3c	Q4	Q5
1	4	4	4	5	2	2
2	4	4	4	4	2	3
3	5	3	4	4	1	3
4	4	5	5	5	1	3
5	5	4	4	5	1	2
6	5	4	4	5	2	2
7	4	5	5	5	1	2
8	3	3	2	3	2	1
9	5	3	5	5	1	2
10	2	3	2	4	2	3
11	3	3	3	4	1	3
12	4	4	4	4	2	1
13	3	3	3	4	1	3
14	5	4	3	5	1	3
15	4	3	4	5	1	3
16	5	2	4	5	2	3
17	4	3	3	4	1	3
18	3	4	4	4	2	3
19	3	3	3	5	1	2
20	4	4	3	4	2	1

[12] Answer Coding

For questions 2 and 3, the value in the table corresponds to the answer marked.

For questions 4 and 5:

1 = first answer option

2 = second answer option

3 = third answer option

4 = fourth answer option

Appendix N – Experiment 2 Trial Design Summary[13]

Trial #	Target Position (relative to ISS truss)	Target Orientation[14]
0	Below	No offset
1	Below	Roll Offset
2	Above	Pitch Offset
3	Above	Roll Offset
4	Above	Roll and Pitch Offset
5	Above	No Offset
6	Above	Roll and Pitch Offset
7	Below	Roll and Pitch Offset
8	Above	Roll Offset
9	Below	Roll and Pitch Offset
10	Below	Roll Offset
11	Below	Pitch Offset

[13] Four sets of these 12 trials were done per subject, alternating between Dominant and Non-Dominant joystick configurations.

[14] Offsets were +/- 30 degrees

Appendix O – Experiment 2 Handedness Questionnaire and Results

Activity	Preference[15]				
Writing	AL	UL	NP	UR	AR
Throwing	AL	UL	NP	UR	AR
Scissors	AL	UL	NP	UR	AR
Toothbrush	AL	UL	NP	UR	AR
Knife (w/o fork)	AL	UL	NP	UR	AR
Spoon	AL	UL	NP	UR	AR
Match (when striking)	AL	UL	NP	UR	AR
Computer Mouse	AL	UL	NP	UR	AR

The laterality quotient was calculated using the formula:

$$LQ = \frac{(R - L)}{(R + L)} * 100$$

"No preference" responses are ignored and total right and left responses are counted separately, counting "always" responses double. (Technically a LQ between -50 and 50 would be classified as a "mixed-hander." These subjects were included as part of the left-handed group in Experiment 2).

[15] AL = Always Left
UL = Usually Left
NP = No Preference
UR = Usually Right
AR = Always Right

Appendix P – Experiment 2 Handedness Questionnaire Results

Activity	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10
Writing	AL	AR	AR	AR	AR	AL	AL	AR	AR	AL
Throwing	UL	AR	AR	AR	AR	AL	AL	AR	AR	UL
Scissors	NP	UR	AR	AR	AR	AR	UL	AR	AR	UL
Toothbrush	AL	UR	UR	AR	AR	AR	AL	UR	AR	AL
Knife (w/o fork)	UL	AR	AR	UR	AR	AL	UL	AR	AR	UL
Spoon	AL	UR	AR	UR	AR	AL	AL	AR	AR	AL
Match (when striking)	AL	AR	AR	AR	AR	AL	UL	AR	AR	AL
Computer Mouse	NP	AR	AR	UR	AR	AR	AR	AR	AR	AR
Laterality Quotient	-100	100	100	100	100	-25	-69	100	100	-69

Activity	s11	s12	s13	s14	s15	s16	s17	s18	s19	s20
Writing	AL	AL	AR	AR	AR	AR	AL	AR	AR	AL
Throwing	AL	AL	AR	AR	AR	AR	AL	UR	UR	AL
Scissors	AL	AL	AR	AR	AR	UR	AL	AR	AR	AR
Toothbrush	AL	AL	AR	AR	AR	UR	AL	AR	AR	AL
Knife (w/o fork)	AL	NP	AR	AR	AR	AR	AL	UR	UR	UL
Spoon	AL	AL	AR	AR	AR	AR	AL	AR	AR	AL
Match (when striking)	AL	AL	AR	AR	AR	AR	UR	AR	AR	AL
Computer Mouse	UR	AR	AR	AR	AR	AR	AR	AR	AR	AR
Laterality Quotient	-87	-71	100	100	100	100	-60	100	100	-47

Appendix Q – Description of Experiment Vizard (v3.0) Scripts

Experiment 1

- Familiarizationv3.py
  - Co-requisite program for the PowerPoint orientation (Appendix D). Ran on two screens only and consisted of the MVL DST environment and arm. Allowed subjects to practice moving the arm, determine (with hands-on interaction) the purpose of clearance and task views, and practice setting up cameras for a trial.
  - Did not record any performance data
- MVL-DST-v.6.12.py
  - Main data-taking program for the experiment. Was used for all three lessons; the experimenter inputted the lesson number at startup so that the program would import the correct files.
  - Recorded Summary Data Files for each lesson.

Experiment 2

- TutorialFinalv3.py
  - Co-requisite program for the PowerPoint orientation (Appendix J). Consisted of the virtual ISS environment, robotic arm, and a target. Allowed subjects to practice moving the arm with the translational and rotational hand controllers
  - Did not record any performance data
- Combined_v9_FINAL.py
  - Main data-taking program for the experiment. Was used for all four sessions; the experimenter inputted the session number at startup so that the program would import the correct targets.
  - Recorded Summary Data Files for each session.