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Investigating the Effects of Frame Disparity on the Performance of Telerobotic Tasks

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Abstract

Teleoperation is a form of telerobotics which refers to human operation of a robotic system over a remote link. The teleoperated robotic arm onboard the Space Shuttle and three more advanced arms onboard the International Space Station (ISS) are essential tools in the continued construction, maintenance, resupply, and scientific operations of this orbiting laboratory. Operating the Shuttle and ISS arms is a highly skilled and delicate task which requires extensive training. An operator typically monitors arm motion using video cameras which are often not ideally located. A major problem associated with using telerobotic arms is the disparity between the direction of joystick movement and the resulting motion of the arm as observed on video monitors. It is known that humans differ in their ability to perform mental rotations or imagine scenes from different perspectives. In some arm control mode and camera configurations, large control/view disparities require difficult mental coordinate transformations. We hypothesized that these differences impact telerobotic operator performance.

In this experiment we investigated the effect of spatial skills, control/view frame disparity, and arm control mode on telerobotic operator performance. A virtual environment was developed to simulate the Basic Operational Robotics Instruction System (BORIS) used for ISS training. Nineteen non-astronaut subjects completed 3 training lessons to learn to operate a 6 Degree of Freedom (DOF) robotic arm. During the training they were presented with several realistic tasks which required them to operate the arm in both high (greater than 90°) and low (less than 90°) control/view disparity scenarios, and in external (environment fixed) and internal (arm fixed) control modes.

We found that spatial abilities correlated with some overall performance metrics in both internal and external modes. In the high control/view disparity condition, Purdue Spatial Visualization of Views Test (PSVT) and a bi-manual control test predicted the number of changes in control inputs.

1. Introduction

The age of improved communications, both in terms of reliability and bandwidth, has allowed for the emergence of remotely controlled robots. Teleoperation is a form of telerobotics where short communication delays allow the human operator to directly control the remote device. Applications have ncluded hazardous material handling [1], [2] and telesurgery [3]. Another high profile application has been in the space industry where teleoperation has been used extensively [4], [5], [6]. Often the operator must control the robot in a coordinate frame not well aligned with their physical or video camera view of the arm.

Crew training for ISS and Shuttle robotic arm usage is an extensive, intensive, and expensive process, requiring hundreds of hours. Recurrent training is required to maintain proficiency. There are large potential benefits from training optimization.

The motivation for this experiment was based on an earlier study carried out by Menchaca-Brandan et al. [7]. They noted that humans differ in their ability to mentally rotate objects and to integrate disparate view perspectives [8]. They identified certain telerobotic performance metrics which correlated with standard tests of spatial ability, and showed that performance decreased in a configuration where the camera angle was 180º away from the control frame

The study described in this paper investigated the effects of spatial skills and control/view frame disparity on telerobotic performance using a more realistic training task, and multiple arm control modes.

2. Hypothesis

The hypothesis behind this experiment was that telerobotic performance depends operator spatial ability and on the angular disparity between the visual (camera view) frame and the control action frame (i.e. the direction of arm movement produced by a joystick movement). We considered two dimensions of spatial ability thought to be important in teleoperation: Mental rotation and perspective taking. Mental rotation is the ability to identify a remembered object after it has been rotated, as measured by the Mental Rotation Test (MRT) [9] and the Cube Comparison Test (CC) [10]. Perspective taking is the ability to imagine a fixed object or scene from different viewpoint, as measured by the Perspective Taking Ability (PTA) [8] test and the Purdue Spatial Visualization of Views Test (PSVT:V) [11].

Teleoperation is usually performed using multiple camera views, so spatial ability may be generally helpful when mentally integrating camera views. Additionally, when the control/view disparity of all views is greater than 90°, operator spatial abilities may be particularly important since the direction of commanded vs. seen arm motion is reversed. We hypothesized that disparities greater than 90º result in reduced performance, particularly among operators with lower spatial abilities. If these hypotheses are confirmed, spatial ability tests could be used to help customize telerobotic operator training.

3. Methods

We created a virtual environment to mimic the Basic Operational Robotic Instructional System (BORIS) used during ISS and Shuttle Generic Robotics Training (GRT) to train astronauts in the basic skills of operating a robotic arm. The environment was developed on a Microsoft Windows XP graphics workstation using the Vizard Virtual Reality Toolkit (WorldViz, Santa Barbara, CA) and AC3D, a 3D model modeling program (Inivis Limited, Ely, UK). Robot arm motions were computed using RRG Kinematix v.4, a kinematic software library plug-in for Vizard (Robotics Research Group, University of Texas).

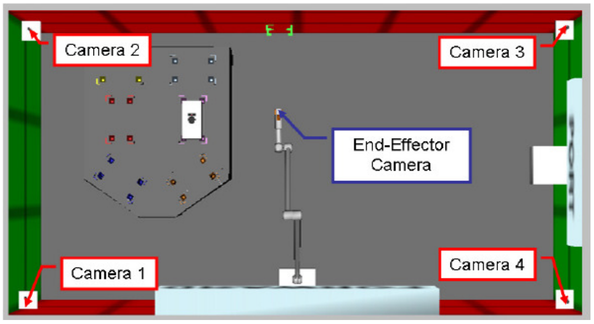


Fig 1. *A plan view of the environment, showing the locations of the fixed cameras and the EE camera. Solar panel not shown.*

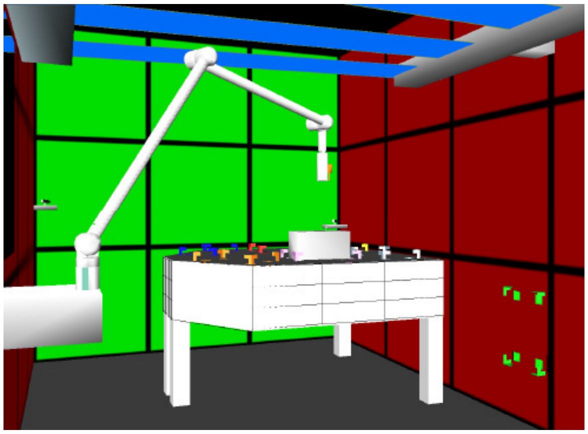


Fig 2. *A view from inside the environment, showing the arm aligned above the target box, and the solar panel above.*

As shown in ***Fig 1*** and ***Fig 2*** the environment consisted of a generic spacecraft payload bay with 4 walls that were color coded (green walls represent port and starboard while the red walls represent forward and aft). Each wall was marked with a 5m square grid to help the user with size estimation. There was a table on one side of the room. A solar array formed a ceiling over the other half of the room and constrained arm movement. As in the BORIS training system, operators manipulated a generic two boom, 6 Degree of Freedom

(DOF) telerobotic arm similar to that on Shuttle, and shown in ***Fig 3***.

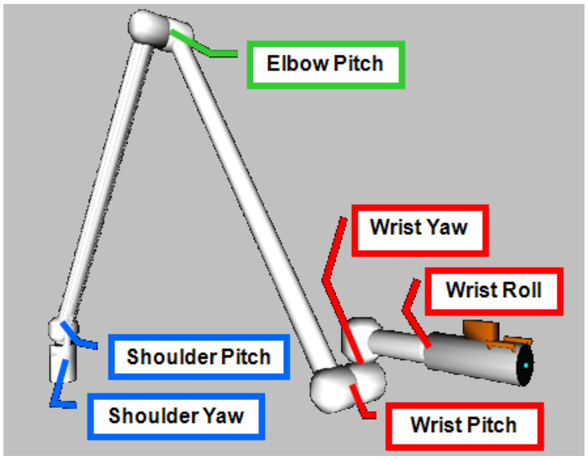


Fig 3. *Robot arm with each joint identified.*

The arm was operated using two different control frame modes, internal (egocentric) and external (exocentric). These modes describe the control frame of reference from which movements are made. In external mode, the control axes are fixed with respect to the environment, whereas in internal mode, control axes move, and are aligned with the end effector (EE) camera.

Subjects used three 17 inch LCD monitors to observe arm motion. The center monitor displayed a view from a camera located on the arm's end EE. The other two monitors showed views from cameras fixed in the corners of the environment. Control/view disparity was manipulated by requiring the operator to use two different combinations of EE and fixed cameras, as shown in ***Table 1***.

Disparity	*Cameras Used*
Low	Camera1/EE Camera /Camera4
High	Camera2/EE Camera /Camera3

Table 1

As in BORIS, subjects manipulated the robotic arm using 2 hand controllers, one for rotational movements and the other for translational movements (*Fig 4*). The control axes corresponded to those on Shuttle and ISS.

Fig 4. *Experiment workstation featuring the 2 hand controllers and 3 monitors*

Nineteen subjects (ages 18-60, including 6 females) were recruited from the MIT community. The experiment consisted of 3 separate training sessions; the first lasted 2 hours and the other two lasted one hour each. In the first session, the subjects completed the 4 spatial ability tests described above; CC, MRT, PSVT and PTA. The subjects read a standardized briefing presentation, which included information about the environment, tasks and terminology. At the end of Session 1, subjects practiced moving the arm in each of the two control modes.

Subjects completed Task Sets 1 and 2 in Session 2 and Task Sets 3 and 4 in their final Session. Each of the first three task sets contained 4 similar tasks; the fourth set contained 6 tasks from Sets 1 and 2. The subjects navigated the robotic arm from one corner of the environment to a location 1.5 m above a target box (as illustrated in *Fig 2*). To complete the task the operator aligned the EE with an alignment guide mounted on the target box. The target position, control frame, and control/view disparity varied between tasks.

For the purpose of analysis each task was split into two sections: "Fly-To" and "Alignment". During the Fly-To segment the arm traversed the room and stopped prior to alignment. During the Alignment section the operator moved the arm to 1.5 m from the target and used the target guide to adjust EE orientation. At the end of each task, subjects were given an overall rating on their performance.

Performance metrics analyzed included those shown in ***Table 2***. Additional details are provided in Sect. 4.

Performance Metrics	
Completion Time	# Changes in Direction
% Time Spent Moving	# Singularities
# Clearance violations	Alignment accuracy
# Collisions	# Hard stops
# Continuous Moves	Path Error

Table 2

At the end of each session subjects completed a Bi-Manual Control (BMC) test. Subjects used the internal control mode and the EE camera view to move the arm around an elliptic path as quickly and accurately as possible (***Fig 5***). The task, which is similar to a NASA GRT exercise, required bimanual coordination of both rotational and translational hand controller inputs.

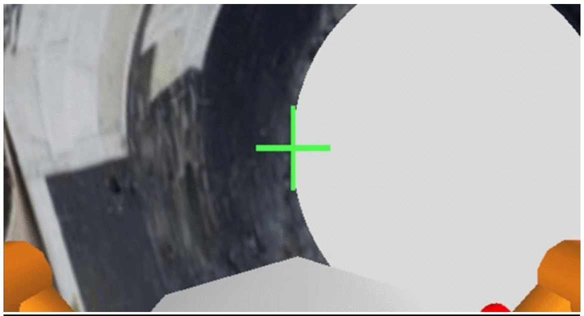
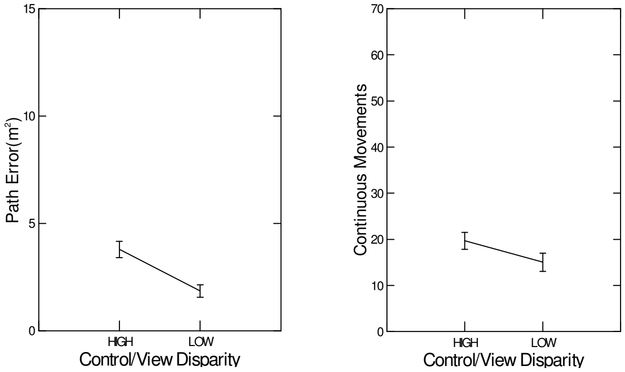


Fig 5*. EE camera view of Bi-Manual Control (BMC) task. The subjects were required to trace the EE camera crosshairs around the ellipse while keeping the vertical bar tangent to the edge.*

4. Results

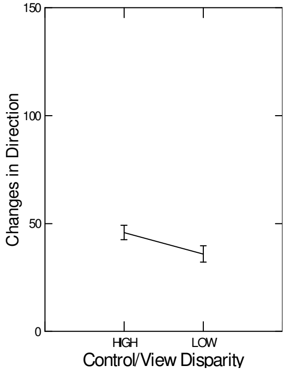
We used mixed regression models (Systat v.12, Systat Software, San Jose, CA) to statistically analyze the relationships between performance, spatial ability, and control/view disparity.

Consistent with our hypothesis and [7], our analysis confirmed that even ignoring mode and control/view disparity manipulations, spatial ability correlated significantly with some measures of teleoperation performance. For example, scores on the PSVT correlated to Path Error during both the Fly-To and Alignment segments ($p = 0.023$, $p = 0.021$). Path Error measured how efficiently subjects navigated to and aligned with the target using the shortest possible route. This was expected since, even when controlling using the EE camera and internal control mode, operators must be able to efficiently integrate information provided by the environmentally fixed cameras.



a. Average Squared Error from the Best Path to the Target

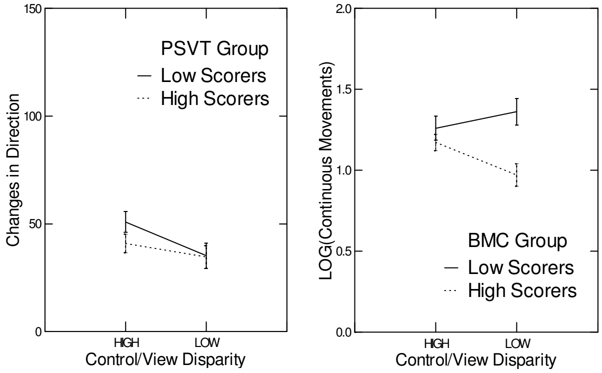
b. Number of Continuous Arm Movements



c. Number of Changes in Direction

Fig 6*. Performance Results with High and Low View Disparity Cases (Fly-To Segment, External Control)*

Furthermore, we found that the high visual disparity condition adversely affected certain performance measures that we expected to be sensitive either to control reversals that result from misperception of the state of the arm, or to the relationship between joystick and arm movement. For example, ***Fig 6*** shows several measures of Fly-To segment performance using the external control mode. As shown in ***Fig 6*****a**, subjects had significantly ($p < 0.001$) larger path errors in the high disparity condition. ***Fig 6*****b** illustrates that subjects made more continuous movements – starting and stopping the arm – in the high disparity condition ($p = 0.023$). That number indicates how smoothly the arm was controlled. Smooth control with fewer starts and stops was encouraged during training because on Shuttle and ISS, sudden inputs can lead to arm oscillations. ***Fig 6*****c** demonstrates that subjects made significantly ($p = 0.002$) fewer changes in direction of motion in the low disparity condition. Making more direction changes usually reflects a more discrete style of route planning or a higher number of control reversals. We expected that in the high disparity condition, where control/view relationships are reversed, subjects would be more prone to initially rotate or translate in the wrong direction (e.g. left instead of right) before correcting the motion.



a. Number of Changes in Direction by PSVT Score

b. Log(# Continuous Movements) by Bi-Manual Control Score

***Fig 7**. Performance Results by Test Score (Fly-To Segment, External Control)*

To assess the interaction of ability and view disparity on operator performance, each subject's ability test score was classified as high (or low) depending on whether it was above (or below) the average for the subject group.

Only one of the spatial ability tests showed a significant cross-effect with disparity condition. As expected (***Fig 7*a**), in the high disparity condition, subjects with lower PSVT scores made significantly ($p = 0.002$) more changes in direction than subjects with high PSVT scores did. In the low disparity condition, however, there were no significant performance differences between high and low scoring subjects. Also, subjects with high BMC scores made a significantly ($p = 0.046$) lower number of continuous movements in the low disparity condition, as shown in ***Fig 7*b**. There was, however, there was no significant difference in between high and low BMC subjects in the high disparity case.

5. Discussion

Previous studies (e.g. [7] and [10]) have shown a significant effect of gender on spatial ability scores and telerobotic performance. A further analysis of the spatial ability score data from [10] showed that female astronaut subjects scored significantly lower on the MRT ($p < 0.001$) and PSVT ($p = 0.001$). However, in our MIT test population, we found no significant gender differences on any of our spatial ability tests. We found significant gender effects in only one performance metric (alignment segment completion time).

We found that for certain measures, such as the percentage of time spent moving, performance decreased in the high disparity condition while using internal control mode ($p < 0.001$). Although the control/view disparity angle cannot be considered fixed since with internal mode the control frame orientation is constantly changing, it is not surprising that the environment cameras used affected performance. In order to perform the Fly-To segment of a task successfully in the internal mode, the operator must constantly update their mental map of the control frame's position and orientation. With all three target locations, the disparity between the control and view frames using internal mode was normally less (or greater) than 90° when using the low (or high) disparity camera pair. As would be expected, subjects spent a lower percentage of their time moving with the high disparity cameras and a higher percentage of their time moving with the low disparity cameras.

6. Conclusion

In this experiment, we found that spatial ability correlated with some performance metrics in both external and internal control modes. The high control/view disparity condition negatively affected performance, particularly of the low ability subjects. Perspective taking and bi-manual control abilities influenced responses to control/view disparity manipulations.

Actual flight telerobotics are normally performed by a team of astronauts. One acts as the arm operator, and another assists as a secondary operator, helping the primary operator plan the task, monitor clearance, adjust camera views, and maintain overall situational awareness. The next step in our research is an experiment investigating the effect of spatial abilities on secondary operator performance. NASA often designates its high performing astronaut trainees as primary operators, while lower performing trainees are assigned as secondary operators. We are testing whether high spatial ability scores also correlate with strong performance when monitoring clearance and detecting other problems.

7. Acknowledgements

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8. References

[1] Kress, R.L., W.R. Hamel, P. Murray, K. Bills, "*Control Strategies for Teleoperated Internet Assembly",* IEEE/ASME Transactions on Mechatronics, 2001.

[2] Hamel, W.R, P. Murray, "*Observations Concerning Internet-Based Teleoperations for Hazardous Environments*", International Conference on Robotics & Automation, 2001.

[3] Rovetta, A. "*Telerobotic Surgery Control and Safety*", IEEE International Conference on Robotics & Automation, 2000.

[4] Backes, P.G., M.K. Long, R.D. Steele, "*The modular telerobot task execution system for space telerobotics*", Proceedings, IEEE International Conference on Robotics and Automation, 1993.

[5] Gennery, D., T. Litwin, B. Wilcox, B. Bon. "*Sensing and perception research for space telerobotics at JPL*", Proceedings, IEEE International Conference on Robotics and Automation, 1987.

[6] Kim, W.S. "Graphical Operator Interface for Space Telerobotics", 1993.

[7] Menchaca-Brandan, M., A. M. Liu, C. M. Oman and A. Natapoff, "*Influence of perspective-taking and mental rotation abilities in space teleoperation*". 2nd ACM/IEEE Conference on Human-Robot Interaction (HRI 07), Washington, DC. 2007.

[8] Kozhevnikov, M., M.A. Motes, B. Rasch, and O. Blajenkova, "*Perspective-Taking vs. Mental Rotation Transformations and How They Predict Spatial Navigation Performance".* Appl. Cognit. Psychol. 20: p. 397-417, 2006.

[9] Vandenberg, S.G. and A.R. Kuse, "*Mental rotations, a group test of three dimensional spatial visualization",* Perceptual and Motor Skills,. 47: p. 599 – 604, 1978.

[10] Ekstrom, R.B., J.W. French, H.H. Harman, and D. Derman, "*Manual for Kit of Factor-Referenced Cognitive Tests",* Educational Testing Service: Princeton, NJ. 1976.

[11] Guay, R.B., "*Purdue Spatial Visualization Tests*", Purdue Research Foundation: West Lafayette, IN, 1977.

[12] Oman, C.M., A.M. Liu, A. Natapoff. "*Efficient Individualized Teleoperation Training via Spatial Ability Assessment."*, Final Report, National Space Biomedical Research Institute, 2008.