SPATIAL ABILITIES AND PERFORMANCE IN ROBOT NAVIGATION

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ABSTRACT

Spatial abilities depend on the comprehension and interpretation of visual information about geometric objects in a given layout. Past research has shown that spatial abilities are a reliable predictor of efficiency in robot navigation in remote environments. This experiment investigated the relationship between spatial abilities and performance in direct line-of-sight and teleoperation courses. Results showed that individuals with higher spatial abilities (particularly spatial orientation) had faster course completion times and fewer collisions. This suggests that increased spatial abilities may play a significant role in effective robot navigation and its implications include using spatial measures as a tool in teleoperator selection.

INTRODUCTION

Spatial abilities play a role in performing commonplace activities, such as driving, sports, and assembling objects (Lunneborg, 1982). Spatial abilities are a higher order of fluid intelligence, which involves the ability to draw inferences and understand the relationships between various objects (Carroll, 1993). Although there are varying opinions about what spatial abilities are and how they are defined, they involve the comprehension and interpretation of visual information as well as the understanding of relations among geometric objects (e.g., Just & Carpenter, 1985). Also referred to as spatial perception ability, this includes the "ability to navigate or manipulate objects in a three-dimensional environment" (Lathan & Tracey, 2002, p. 17). Spatial abilities can be divided into two subcomponents: spatial visualization and spatial orientation (e.g., Ekstrom, French, Harman, and Dermen, 1976; McGee, 1979; Pak, Rogers, & Fisk, 2006). Ekstrom et al. (1976) defined spatial visualization as the mental ability to manipulate a visual image, and spatial orientation as the ability to perceive how one object located in space is organizationally related to other objects.

Although spatial abilities are influenced by genetics (Kelley, 1928; Plomin & Craig, 1997), training and experience may improve these abilities (Brinkmann, 1966; Lunneborg, 1984). This is of particular interest in occupations that use spatial abilities, such as robot operators, who employ visual information to manipulate robots remotely to accomplish various tasks. Since World War II, robots have replaced humans in many tasks (Stassen & Smets, 1997), such as in Urban Search and Rescue (USAR) missions. For example, it was too dangerous and impractical to send humans into the rubble following the September 11, 2001, attacks to look for casualties and structural damage, so USAR robots were deployed instead (Casper & Murphy, 2003). The robot controller used live camera feed from a camera mounted on a robot to view the remote environment, a process known as teleoperation. Teleoperation is essentially the manipulation of a machine at a distance (e.g., Sheridan, 1989), but there are several problems with such remote perception. The greatest of these is destructive mapping, which involves the loss of information when a three-dimensional environment is displayed in two dimensions. Destructive mapping occurs when the proximal and distal stimulus break down, which results in impoverished mental reconstructions of the world, also known as remote perception (Tittle, Roesler, & Woods, 2002).

Relative to direct line-of-sight, the very nature of teleoperation provides significantly fewer sensory and depth cues to operators of remote robotics systems (Woods, Tittle, Feil, & Roesler, 2004). Viewers in direct line-of-sight receive cues about their environment directly from their senses. In teleoperation, however, access to this environmental information is limited and teleoperators may use live camera feed from the machine they are manipulating in order to make judgments about the remote environment. The degraded sensory information available during teleoperation tasks causes difficulty in accurately perceiving the teleoperated robot and the remote environment (Casper & Murphy, 2003). Other problems with remote perception include impoverished tactile senses, a lack of depth information, and a visual mismatch between the remote camera height and the teleoperator's natural eye height (Tittle et al., 2002).

Perceptual challenges and ambiguities make it difficult for teleoperators to establish situation awareness about the remote environment (Burke, Murphy, Coovert, & Riddle, 2004; Woods et al., 2004). In direct line-of-sight, presence is the sensation of immediate proximity in time or space. Teleoperation lacks much of this direct sensory information, but if the teleoperator is sensitive to the robot and its remote environment, operators may feel sufficiently present in that environment; this is known as telepresence (Riley, Kaber, & Draper, 2004; Sheridan, 1989). Teleoperation performance and telepresence are positively correlated- as one's sense of telepresence increases, performance does as well (Riley, Kaber, & Draper, 2004). Recent research on teleoperation and human-machine interfaces suggests ways to improve depth perception. For example, Sekmen, Wilkes, Goldman, and Zein-Sabatto (2003) showed that sonar detection by semi-autonomous robots improves depth perception of remote environments. Also, connecting an operator's visual system with a robot's sonar information can increase telepresence and improve remote perception (Agah & Tanie, 1999).

Spatial abilities play a key role in the early stages of perceptual-motor task learning (Fleishman, 1972) and reliably predict efficiency in robot teleoperation (Sekmen et al., 2003). Thus, effective use of these abilities is very important in teleoperation task performance (Lathan & Tracey, 2002). Spatial abilities are also a key factor in direct line-of-sight tasks. In the military, spatial perception abilities are an important part of mission effectiveness (Alderton, Wolfe, & Larson, 1997; Carey, 1994). There is a strong correlation between cognitive ability and performance in conditions with fewer depth cues (Ackerman, 1987).

Spatial abilities can be assessed by tests that require a subject to comprehend and mentally manipulate visual forms (Kelly, 1928). Lathan and Tracey (2002) found a significant correlation between spatial abilities (as measured by recognition and manipulation tests) and performance in a teleoperation task.

There is little research on robot navigation performance and even less on spatial abilities and performance. Therefore, the purpose of this study was to investigate the relationship between spatial abilities and robot navigation performance in direct line-of-sight and teleoperation courses. Performance was measured by course completion time and the number of course collisions (Lathan & Tracey, 2002; Park, 1998). Since spatial abilities are linked to better understanding and comprehension of objects in an environment, the first hypothesis was that individuals with higher spatial abilities would have better performance in both direct line-of-sight and teleoperation tasks than individuals with lower spatial abilities. Teleoperation provides the machine controller with an impoverished view of the machine's environment, compared to direct line-of-sight in which more environmental cues are available to the operator (Casper & Murphy, 2003; Tittle et al., 2002). This lack of sensory cues causes the teleoperator to rely more on his or her spatial organization and visualization abilities (Sekman et al., 2003) in order to interpret visual information and successfully navigate the robot through the course. Thus, the second hypothesis was that there would be a greater relationship between spatial abilities and teleoperation performance than with direct line-of-sight.

METHOD

Participants

Thirty-one students attending Clemson University participated in this study (11 males, 20 females; age, $M = 21.19$, $SD = 2.1$). All participants received course credit or $10.00 compensation in exchange for their participation. Before starting the experiment, they were tested for normal visual acuity measured binocularly from 6m and self-reported full use of their neck, arms, and hands. Participants also filled out a demographics form concerning their experience with robots and videogames.

Materials and Apparatus

Visuo-spatial abilities were assessed using the Paper Folding Test and the Cube Comparison Test. The Paper Folding Test (Ekstrom et al., 1976) was composed of 20 items. Each item consisted of two to four images depicting how a piece of paper was folded. Once completely folded, a circle depicted where a hole was punched through the entire thickness of the paper. Each folded paper was accompanied by five images of unfolded papers with holes punched in various places in each of the five images. Participants had to decide which of the five images correctly displayed the piece of unfolded paper that contained the newly punched holes.

The Cube Comparison Test (Ekstrom et al., 1976) consisted of 42 items. Each item displayed two six-sided cubes. Each cube had a different design, number, or letter that appeared on each face. For each item, there were two cubes with only three adjacent faces showing. Based solely on this visual information, participants had to decide whether the two cubes were the same or different. In order to prevent participants from guessing in both of the spatial abilities tests, a percentage of the number of incorrect items was deducted from the total score.

The ability to operate a robot was assessed by four robot navigation performance tasks, two in direct line-of-sight and two using teleoperation. The robot used was a radio controlled H_2 Hummer 1:6 (24.5cm x 28cm x 64cm; Figure 1). The robot was chosen because of its sturdy wheelbase, speed, and ability to turn. However, the top of the robot was removed because it came into contact with the wheels when the robot turned, which restricted the robot's turning range. A remote control consisting of two joysticks (one for forward and backward motion, the other for right and left turns) was used to control the movements of the robot (see Figure 1).

Figure 1. The camera-mounted robot and its remote control.

The navigation courses consisted of a series of wood (4 in x 4 in x 2 ft pieces) and cones. They were arranged in a manner that required the controller to make accurate judgments about the organizational layout of the course, object spacing, and depth in order to navigate the course successfully. For example, there were sharp turns, a slalom, and a straightaway that was narrowed in certain parts. The direct line-of-sight and teleoperation courses consisted of one lower complexity course and one higher complexity course. At both complexity levels, participants had to navigate the robot into an alcove (60 cm x 62 cm) at the far end of the course. While teleoperating the robot, participants were asked to identify any object that they saw in the alcove.

In the direct line-of-sight condition, participants had full view of the robot and the course. In the teleoperation condition, participants relied solely on live camera feed from a camera mounted atop the robot in the remote environment. The remote environment was the exact same as the direct line-of-sight environment. The camera used was a Grandtec USA (Dallas, Texas) wireless "Eye See All" security camera system with wireless capability (see Figure 1). The camera system used an RF CMOS USB transmitter and receiver. The receiver displayed live camera feed on a 15 in computer monitor. The resulting image appeared in a 3.5 in x 2.5 in window in the center of the computer screen. The camera was mounted 21 cm above the body of the robot in order to maintain an accurate view of the robot and the course. It was positioned 10 degrees below the horizontal.

Design

This study was a within-subjects design of two visuo-spatial ability assessments and four performance tasks, two in direct line-of-sight and two using teleoperation. The two navigation courses in each of the two performance conditions differed in complexity. The dependent variable measured was performance, as indexed by course completion time and the number of course collisions during navigation.

Procedure

Participants were seated at a desk and asked to complete the two spatial abilities tests. All participants completed the three-minute Paper Folding Test (Ekstrom et al., 1976), followed by the three-minute Cube Comparison Test (Ekstrom et al., 1976). All answers were recorded on a separate score sheet that was graded by the experimenters.

Participants then completed a brief training exercise in order to become familiar with the robot. This training allowed participants to practice basic robot functionality so that they could use the remote controller to move the robot forward and backward, as well as making forward and backward right and left turns. Participants were given as much time as they wanted to practice controlling the robot. After getting accustomed to the robot, they completed the four performance tasks. All participants completed the direct line-of-sight tasks first and the teleoperation tasks second. This was done to imitate real-world procedures in which robot operators would have experience manipulating the robot using direct line-of-sight before navigating it in a remote environment.

In the direct line-of-sight condition, participants faced the course during navigation so that they had full view of the robot and the course. The starting positions were counterbalanced between participants. For example, one participant started on the straightaway and the next participant on the curves. All participants completed the lower complexity course first and the higher complexity course second, so that they would have practice before completing the higher complexity course. When participants navigated the robot into the alcove, they were asked to identify any object that they saw. This was done to add a "search and rescue" element to the task because the job of robot teleoperators is to identify casualties, structural damage, and other such objects in a remote environment. The course completion time and the number of course collisions during navigation were recorded. Collisions were assessed by their severity: minor collisions did not alter the course, moderate collisions altered the course, and major collisions required help from the experiment (e.g., the robot got stuck in a part of the course and needed to be moved).

In the teleoperation condition, participants were seated in front of the computer monitor that displayed live camera feed from the camera mounted atop the robot. The chair was positioned at a fixed 12 in distance from the desk. The seat of the chair was 1.5 ft from the floor. They viewed a brief training video on a 9.5 cm x 7.1 cm screen that demonstrated what it would look like to operate the robot using the computer screen. In order to complete the task and make judgments about the remote environment, participants could rely only on live camera feed, which was projected onto a 9.6cm x 7.2cm window on the 15in computer monitor. The robot's starting position was opposite of the starting position in the direct line-of-sight task. For example, if the robot was positioned to start in the straightaway during the direct line-of-sight tasks, it was placed to start in the slalom for the teleoperation tasks. The course completion time, number of course collisions during navigation, and participants' responses to any object they saw in the alcove were recorded. Upon completion of the experiment, participants were asked if they had any strategies for faster completion times and fewer collisions. Responses were recorded and participants debriefed.

Statistical analysis

Scores from the two visuo-spatial tests were combined into one aggregate score. Course completion times were recorded in seconds and collisions coded by their severity and calculated into one aggregate score. Correlation measures analyzed the relationship between visuo-spatial abilities and performance in the four navigation tasks.

RESULTS

Visuo-spatial abilities scores and performances in the four navigation courses were analyzed using correlation measures. There was a significant negative correlation between spatial abilities and total completion time (r = -0.496, p < .01; Figure 2) as well as between spatial abilities and total number of collisions (r = -0.416, p < .05; Figure 3). Table 1 shows the correlations of spatial abilities to course completion times and the number of collisions, relative to the type of performance condition and complexity.

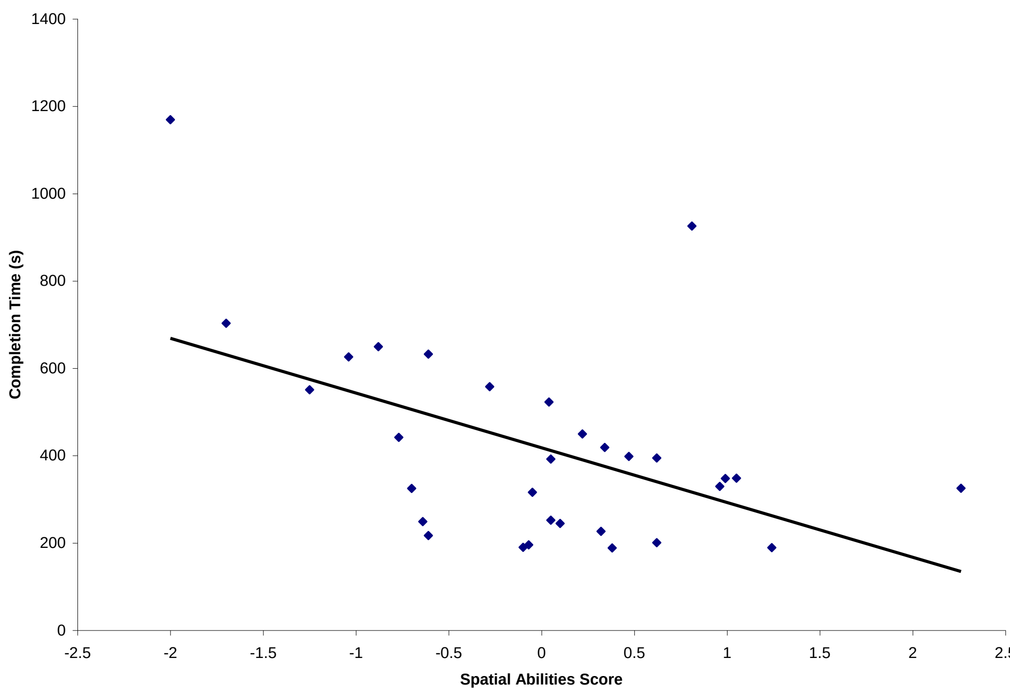

Figure 2. Total course completion time as a function of spatial abilities.

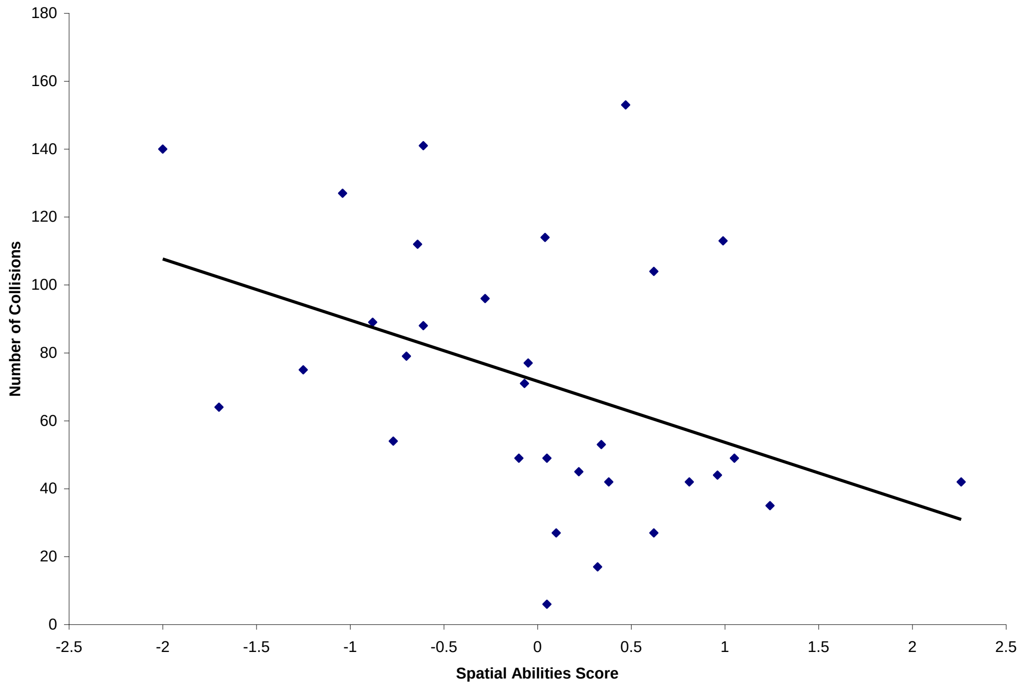

Figure 3. Total number of collisions as a function of spatial abilities.

Table 1

Correlation between spatial abilities and performance

Performance Measure	Spatial Abilities Score
Total time	-0.496**
Direct line-of-sight time	-0.483**
Teleoperation time	-0.475**
Lower complexity time	-0.49**
Higher complexity time	-0.474**
Total collisions	-0.416*
Direct line-of-sight collisions	-0.361*
Teleoperation collisions	-0.388*
Lower complexity collisions	-0.342
Higher complexity collisions	-0.42*

Notes: * $p < 0.05$ level (two-tailed);
** $p < 0.01$ level (two-tailed)

Further analyses revealed that participants had faster course completion times and fewer collisions in the teleoperation condition than in the direct line-of-sight condition. This pattern of performance was also evident in the lower complexity condition compared to the higher complexity condition (Table 2). In regard to direct line-of-sight and teleoperation, a paired-samples t-test revealed that the difference in the number of collisions was significant ($t = 2.816$, $p < .01$) but the difference in the course completion times was only marginally significant ($t = 1.883$, $p = .069$). With respect to complexity, participants were significantly faster in the lower complexity course than in the high complexity course ($t = -6.946$, $p < .001$), but the difference in the number of collisions was only marginally significant ($t = -1.807$, $p = .081$).

Table 2

Measures of performance

	Course Completion Time		Number of Collisions	
Condition	Mean	SD	Mean	SD
Overall	418.95	228.02	71.74	38.98
Direct line-of-sight	221.92	139.77	41.19	25.83
Teleoperation	197.03	95.77	30.54	17.73
Lower complexity	189.15	112.61	33.29	19.27
Higher complexity	233.02	118.43	38.55	22.7

Additional correlation analyses revealed that there was a stronger correlation between performance and scores on the Cube Comparison Test than on the Paper Folding Test. Gender and previous video game experience did not influence navigation performance.

DISCUSSION

The purpose of this study was to investigate the relationship between visuo-spatial abilities and performance in direct line-of-sight and teleoperation. The results supported the prediction that participants with higher spatial abilities showed better overall performance in both direct line-of-sight and teleoperation tasks than participants with lower spatial abilities. This suggests that successful course navigation, as indexed by completion time and the number of errors (Lathan & Tracey, 2002; Park, 1998), relied partly on spatial abilities (Lathan & Tracey, 2002; Sekmen et al., 2003). Performance may also have depended on fluid intelligence (Carroll, 1993), specifically on the interpretation and comprehension of visual information and object relations in a particular layout (Just & Carpenter, 1985).

The number of collisions, but not course completion time, accurately predicted a greater relationship between spatial abilities and teleoperation performance than with direct line-of-sight. One reason for this is that in the teleoperation tasks, participants were asked to identify any object that they saw in the alcove. They did not have to do so in the direct line-of-sight tasks, so this object identification may have increased course completion times. Interestingly, participants did not have a rear camera view of the course, so there may have been a greater reliance on spatial abilities to navigate the course successfully. Since the number of rear collisions was not recorded, future research could relate spatial abilities to the number of front and rear collisions in teleoperation in order to validate this proposition.

There were faster completion times and fewer collisions in teleoperation than in direct line-of-sight. This most likely was the result of practice with the robot, and mirrored the training procedures of actual teleoperators. To improve their performance, real-world teleoperators work with robots in direct line-of-sight before facing the greater challenges of remote environments. Also, completing the second half of the direct line-of-sight course required mirror image navigating that may have been mildly disorienting to the operator. However, the mirror image may have caused people to rely more on their spatial abilities, thereby providing a possible explanation for the stronger correlation between spatial abilities and performance in direct line-of-sight than in teleoperation. During teleoperation, the camera feed provided one straightforward view of the course and no mirror-image view, so it may have been easier for participants to control the robot.

Feelings of telepresence may also have improved teleoperation performance (Agah & Tanie, 1999; Riley, Kaber, & Draper, 2004; Sekman et al., 2003; Sheridan, 1989). Moreover, the lack of teleoperator feedback may also explain why performances in teleoperation exceeded those in direct line-of-sight. Feedback increases human performance in a virtual environment (Burdea, Richard, & Coiffet, 1996), but the lack of feedback in the present experiment may have caused people to rely more on their spatial abilities in order to make judgments about the remote environment. Augmented reality improves perception of the remote environment so that participants have even more sensory information for their spatial abilities to use, which may have been another factor in the stronger teleoperation performance (Lawson, Pretlove, Wheeler, & Parker, 2002).

Spatial abilities play a role in the efficiency of robot navigation and can be broken divided into the subcategories of spatial visualization and spatial orientation (Ekstrom et al., 1976; McGee, 1979). The two spatial abilities tests, however, were not measures of pure spatial abilities, so people may have incorporated other skills that the assessments did not consider in order to complete the tests. Interestingly, scores on the Cube Comparison Test correlated more strongly with performance than scores on the Paper Folding Test, which suggests that robot operation abilities may require higher spatial orientation ability than spatial visualization ability (see also Pak et al., 2006).

Although spatial abilities have a genetic factor (Kelley, 1928; Plomin & Craig, 1997), there was not a significant correlation between performance and gender (Tan, Czerwinski, & Robertson, 2006). Previous video game experience was not significantly correlated with spatial abilities, either. However, a larger sample may show gender or previous video gaming experience effects (Brinkmann, 1966; Lunneborg, 1984). Wider fields of view seem to improve navigation performance in a three-dimensional virtual environment and narrow the gender-based ability differences (Tan, Czerwinski, & Robertson, 2006), suggesting that gender may not be the only factor that influences human performance.

One limitation of this study was the small area in which to work. Creating a bigger and longer course with various types of obstacles (e.g., inclines, uneven terrain) as well as comparing mirror image to non mirror image performance may increase the reliability of the role that spatial abilities plays in performance. In addition, a battery of spatial ability tests could be used better to assess spatial abilities and identify the specific subcomponents that have a greater role in robot navigation (Alderton, Wolfe, & Larson, 1997).

This experiment shed light on the factors that influence performance by comparing robot navigation in direct line-of-sight and teleoperation. These findings have implications for the possibility of using spatial measures as tools in the selection of teleoperators in general, more specifically in "search and rescue" missions (Burke, Murphy, Coovert, & Riddle, 2004; Casper & Murphy, 2003). Spatial abilities also have a significant effect on one's ability to learn a motor task in a simulated environment and transfer that knowledge to a real-world task (Tracey & Lathan, 2001). This suggests that spatial ability testing using simulators may play an important role in training operators for complex motor tasks. Future studies could investigate the role of spatial abilities in navigating the robot through larger courses, various types of obstacles, mirror imaging manipulations, multiple camera views (e.g., side and rear views), recording the number of front and rear collisions, and incorporating feedback during teleoperation.

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