The Effects of Task Complexity and Spatial Ability on Teleoperation Performance

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Abstract. This study aims to explore how task complexity and spatial ability on teleoperation performance, especially the interaction effects of task complexity and spatial ability. Three kinds of robotic arm teleoperation task were designed, namely point aiming, line alignment, and cross alignment. They were respectively treated as teleoperation task with low, middle and high complexity. Teleoperation performance were measured from task completion time, rate of extra distance moved, operation slip and collision. Forty subjects were recruited. They were divided into two groups (with high spatial ability and with low spatial ability) based on their scores of the Vandenberg test and the Guay test.

Repeated measures' analyses of variance was carried out to examine the main effects and interaction effects of task complexity and spatial ability on teleoperation performance. The results shown that spatial ability significantly or marginally significantly influenced task completion time ($p = 0.037$), collision ($p = 0.003$), and operation slip ($p = 0.07$). The subjects with high spatial ability performed better than those with low spatial ability. Task complexity significantly affected completion time ($p < 0.001$), rate of extra distance moved ($p < 0.001$), operation slip ($p = 0.028$), and collision ($p < 0.001$). It was also found that the interaction effect of spatial ability and task complexity on collision was marginally significant ($p = 0.069$). Those results implied that spatial ability plays a key role in teleoperation, especially for high complexity tasks. Spatial ability should be considered as an important criterion for tele-operator selection.

Keywords: Task complexity · Spatial ability · Teleoperation performance

1 Introduction

Teleoperation refers to an operation form that remotely control a robot, or system to accomplish a given task [9]. Teleoperation technology has been widely applied in various fields, especially in risky or unknown environment, ranging from search and rescue activities (e.g., search for survivors in the 911 event), underwater adventures, toxic or nuclear material processing to daily industrial and commercial systems such as microsurgery, mineral exploitation [1].

Teleoperation performance is influenced by many factors, such as operators' cognitive characteristics [8], visual interface providing real-time scene [11], and task complexity. Task complexity is an important task characteristic that affecting human

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performance and behavior [6]. No general agreement on the relationship between task complexity and human performance is found. Based on previous studies, Liu et al. [7] summarized four common types to this relationship, namely, negative correlation, positive correlation, inverted U-shaped correlation, and dependent on other factors. In present study, we will tentative explore the relationship between task complexity and teleoperation performance.

Spatial ability is an individual's cognitive ability in the aspect of space or visual imagery [5]. To be specific, spatial ability is an individual's ability in the aspect of identifying, coding, storing, representing, decomposing, and integrating the environment spatial information. It is an important component of an operators' cognitive characteristics. Pan et al. [8] has found that spatial ability played key role in teleoperation. Therefore, the present work will also examine whether the relationship between task complexity and teleoperation performance is dependent on spatial ability, namely the interaction effects between task complexity and spatial ability.

2 Method

2.1 Subjects

Forty male subjects were recruited to participate in this study. They were all undergraduate engineering students, aged from 18–22 years old (mean age = 21.4, SD = 1.3), right handed, and without color blindness. They had no experience on teleoperation even without or only with a little knowledge about teleoperation. Before participating, they were informed about the details of the experiment and voluntarily signed the informed consent form. The experimental procedure was approved in advance by the ethics committee of China Astronaut Research and Training center.

2.2 Teleoperation Tasks

Based on the Virtual Robot Experimentation Platform (VREP), three kinds of simulated robotic arm teleoperations (namely point aiming, line alignment, and cross alignment) were designed. Different shapes were set for the end effector of a simulated robotic arm in different teleoperation tasks. As shown in Fig. 1(I), the end effector and target location were set as a sphere in the point aiming task. This teleoperation was successfully completed when three position deviations (X, Y, Z) satisfying accuracy requirements. As shown in Fig. 1(II), the end effector and target location were set as a cylinder in the line alignment task. This teleoperation was successfully completed when three position deviations (X, Y, Z) and two angle deviations (a, b) reaching accuracy requirements. As shown in Fig. 1(III), the end effector and target location were set as a three-dimensional cross. This teleoperation was successfully completed when three position deviations (X, Y, Z) and three angle deviations (a, b, c) satisfying accuracy requirements.

For each teleoperation task, a computer screen provided real-time global view, target view, end effector view, and position and angle deviations of the robotic arm teleoperation situation for the subjects. The subjects were asked to operate two 3DOF

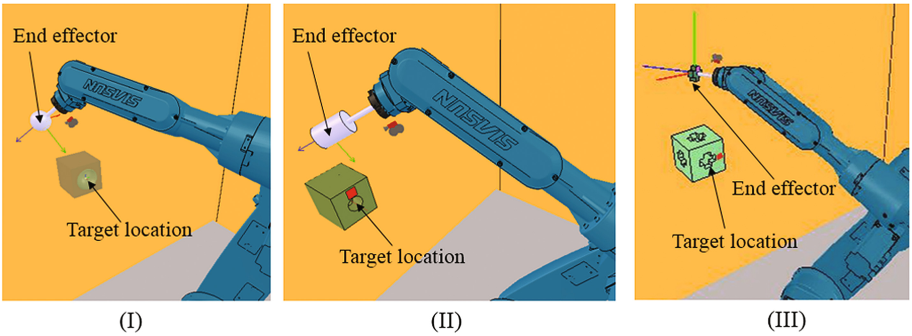

Fig. 1. Teleoperation tasks: (I) point aiming, (II) line alignment, (III) cross alignment

joysticks (Litestar PNX-2013) to control the movements and rotations of the simulated robotic arm's end effector. The position deviations (X, Y, Z) were adjusted by the movements of the end effector in three directions which the angle deviations (a, b, c) were adjusted by the rotations of the end effector along the three axes. After the subjects were introduced the experiment content and familiar with the control mode, they completed each teleoperation task twice. Teleoperation performance of each task was defined as the average performance of these two repeating operations.

During a teleoperation task, the VREP platform recorded the real-time position deviations, angle deviations, and distance moved of the end effector, movements and rotations of two joysticks, number of collision, and task completion time every 0.4 s. When a collision occurred, a prompting window will pop up to alert subjects and told them how many collisions they had made. When a teleoperation task completed successfully, a prompting window will also pop up to inform subjects, and the program automatically stop and return to the original state.

2.3 Dependent Variables

Teleoperation performance were measured from task completion time, rate of extra distance moved, number of operation slip and collision. Their definitions were descripted in Table 1, which were similar to definitions in [8]. Completion time reflects subjects' operation efficiency. Rate of extra distance moved and operation slip reflects subjects' operation effectiveness. Number of collision reflects subjects' operation reliability.

2.4 Independent Variables

Task complexity. This variable has three levels. Based on the different accuracy requirements of successfully completion, three kinds of teleoperation tasks (namely the point aiming, line alignment, and cross alignment) were respectively treated as a teleoperation with low, middle and high task complexity (see details in Sect. 2.2).

Table 1. Definitions of dependent variables [8]

Performance measurements	Definitions
Completion time	How long it took to complete a successful teleoperation. Shorter time indicates higher operation efficiency
Rate of extra distance moved	$\frac{\text{total moved distance} - \text{initial position deviation}}{\text{initial position deviation}}$ Lower ratio indicates better path planning
Number of operation slip	An operation slip was counted when two consecutive operations of joysticks within 2 s were completely opposite, except the residence time between these two operations is longer than the time spends on the first operation. Fewer operation slips indicate higher operation reliability
Number of collision	A collision was counted when any part of the simulated space manipulator collided with the environment or the target cube. Fewer collisions indicate higher operation reliability

In present study, task complexity was a within-subject variable. All subjects were asked to finish three kinds of teleoperation tasks with different task complexity.

Spatial ability. This variable has two levels. It was a between-subject variable. Based on subjects' scores of spatial ability tests, forty subjects were divided into two groups (high ability vs. low ability). Subjects' spatial ability were evaluated from two dimensions, namely mental rotation and perspective taking, separately by the revised Vandenberg test and the adapted Guay test.

The revised Vandenberg test, which has a high internal consistency and test-retest reliability [10], is widely used to evaluate an individual's mental rotation. This test included two sets of 12 items. As shown in Fig. 2(a), each item consists of a criterion figure and four stimulus figures (A, B, C and D). The subjects were asked to find out two figures from A, B, C, D, which matched the criterion figure. They had 4 min for each set.

The adapted Guay test is known as a standardized test for perspective taking ability [3]. This test included 24 items. As shown in Fig. 2(b), each item consists of an

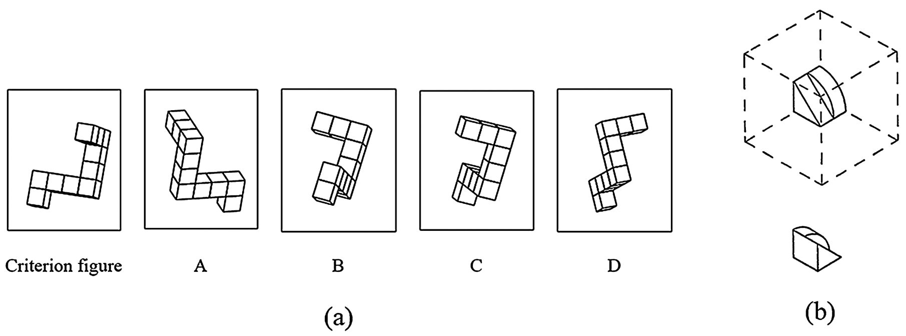

Fig. 2. Examples of spatial ability tests: (a) An example of the revised Vandenberg test; (b) An example of the adapted Guay test

isometric view of a 3-dimensional object depicted in the center of a see-through cube and another view for the same object depicted below the cube which is from a different viewpoint. The subjects were asked to find out the corner of the cube from which the second view of the object is taken. They had 8 min to complete this test.

2.5 Data Analysis

Repeated measures' analyses of variance (repeated ANOVA) was conducted to explore the relationship between task complexity and teleoperation performance, and that whether this relationship dependents on spatial ability. A Mauchly's test of sphericity was performed to guarantee that those data satisfy the assumptions for the repeated measure analysis. A Huynh-Feldt ε correction factor was used when the sphericity was violated ($p < 0.05$). Besides, post-hoc analyses were used to evaluate differences between teleoperation tasks with different complexity.

3 Results

Table 2 shows the descriptive statistic results of teleoperation performance. Table 3 presents the results of repeated ANOVA. Post-hoc analyses' results for task complexity are presented in Table 4.

Table 2. Mean (standard deviation) of performance measurements

		Completion time (s)	Rate of extra distance moved	Operation slip (#)	Collision (#)
Spatial ability	Low	211.04 (18.04)	2.93 (0.38)	16.2 (2.3)	3.5 (0.4)
	High	156.39 (17.58)	2.06 (0.37)	10.3 (2.2)	1.9 (0.4)
Task complexity	Low	104.38 (8.48)	1.21 (0.13)	8.1 (1.1)	0.5 (0.1)
	Middle	201.44 (14.88)	1.56 (0.19)	15.8 (2.3)	4.5 (0.6)
	High	245.33 (29.09)	4.72 (0.65)	15.8 (3.2)	3.1 (0.4)

Table 3. Results of repeated measures ANOVA

	Huynh-Feldt ε	Spatial ability		Task complexity		Spatial ability × Task complexity	
		F	*p*	F	*p*	F	*p*
Completion time (s)	.699	4.707	.037	15.684	<0.001	1.005	.347
Rate of extra distance moved	.599	2.689	.110	28.841	<0.001	.400	.568
Operation slip (#)	.743	3.477	.070	4.310	.028	.640	.486
Collision (#)	.828	10.180	.003	26.656	<0.001	2.958	.069

Table 4. Post-hoc analyses' results for task complexity (p value)

Task complexity		Completion time (s)	Rate of extra distance moved	Operation slip (#)	Collision (#)
Low	Middle	<0.001	.081	<0.001	<0.001
Low	High	<0.001	<0.001	.024	<0.001
Middle	High	.167	<0.001	.999	.049

3.1 Completion Time

From the results of repeated measures ANOVA in Table 3, it was found that both spatial ability and task complexity significantly influenced completion time ($p = 0.037$, $p < 0.001$). From the post-hoc analyses' results for task complexity in Table 4, it was found that the difference of completion time between the low complexity teleoperation and middle complexity teleoperation, and between the low complexity teleoperation and high complexity teleoperation were significant ($ps < 0.001$).

It can be seen from Table 2 that the subjects with high spatial ability significantly spent 25.9% less time than those with low spatial ability ($Mean_{\text{high spatial ability}} = 156.39$ s, $Mean_{\text{low spatial ability}} = 211.04$ s). Meanwhile, subjects spent 48.2% less time on the low complexity teleoperation (i.e., point aiming) than on the middle complexity teleoperation (i.e., line alignment) ($Mean_{\text{low complexity}} = 104.38$ s, $Mean_{\text{middle complexity}} = 201.44$ s), and spend 57.5% less time on the low complexity teleoperation than on the high complexity teleoperation (i.e., cross alignment) ($Mean_{\text{low complexity}} = 104.38$ s, $Mean_{\text{high complexity}} = 245.33$ s).

3.2 Rate of Extra Distance Moved

From the results presented in Table 3, it can be found that task complexity significantly influenced the rate of extra distance moved ($p < 0.001$). From the post-hoc analyses' results for task complexity in Table 4, it was found that the difference of the rate of extra distance moved between the low complexity teleoperation and high complexity teleoperation, and between the middle complexity teleoperation and high complexity teleoperation were significant ($ps < 0.001$). Meanwhile, the difference of the rate of extra distance moved between low complexity teleoperation and middle complexity teleoperation were marginally significant ($p = 0.081$).

3.3 Operation Slip

As shown in Table 3, the number of operation slip was marginally significantly affected by spatial ability ($p = 0.070$), and was significantly affected by task complexity ($p = 0.028$). From the post-hoc analyses' results for task complexity in Table 4, it was found that the difference of operation slip between the low complexity teleoperation and middle complexity teleoperation, and between the low complexity teleoperation and high complexity teleoperation were significant ($p < 0.001$, $p = 0.024$).

It can be seen from Table 2 that the subjects with high spatial ability significantly made 36.4% fewer operation slips than those with low spatial ability ($Mean_{\text{high spatial ability}}$ = 10.3, $Mean_{\text{low spatial ability}}$ = 16.2). Meanwhile, subjects made 48.7% fewer operation slips in the low complexity teleoperation (i.e., point aiming) than in the middle complexity teleoperation and in the high complexity teleoperation (i.e., line alignment, cross alignment) ($Mean_{\text{low complexity}}$ = 8.1, $Mean_{\text{middle complexity}}$ = 15.8, $Mean_{\text{high complexity}}$ = 15.8).

3.4 Collision

As the results presented in Table 3, the number of collision was significantly influenced by both spatial ability and task complexity ($p = 0.003$, $p < 0.001$). Meanwhile, the interaction effect between spatial ability and task complexity on the number of collision was marginally significant ($p = 0.069$). From the post-hoc analyses' results for task complexity in Table 4, it was found that the difference of collision between the low complexity teleoperation and the middle complexity teleoperation, between the low complexity teleoperation and the high complexity teleoperation, and between the middle complexity teleoperation and the high complexity teleoperation were all significant ($p < 0.001$, $p < 0.001$, $p = 0.049$).

It can be seen from Table 2 that the subjects with high spatial ability significantly made 45.7% fewer collisions than those with low spatial ability ($Mean_{\text{high spatial ability}}$ = 1.9, $Mean_{\text{low spatial ability}}$ = 3.5). Meanwhile, subjects made 88.9% fewer collision in the low complexity teleoperation (i.e., point aiming) than in the middle complexity teleoperation (i.e., line alignment), and made 83.9% fewer collisionin the low complexity teleoperation than in the high complexity teleoperation (i.e., cross alignment) ($Mean_{\text{low complexity}}$ = 0.5, $Mean_{\text{middle complexity}}$ = 4.5, $Mean_{\text{high complexity}}$ = 3.1).

4 Discussion and Future Work

From Fig. 3, we can see that with the increase of task complexity, the difference of teleoperation performance (namely, completion time, rate of extra distance moved, operation slip, collision) between subjects with high and low spatial ability were also increasing. Those results implies that spatial ability plays a key role in teleoperation, especially for high complexity tasks. The actual teleoperation tasks, such as space robotic arm teleoperation, are much more complex than the simulated robotic arm teleoperation in present study. Therefore spatial ability should be considered as an important criterion for tele-operator selection.

Furthermore, as shown in Fig. 3(d), not only for the subjects with high spatial ability but also for the subjects with low spatial ability, they had more collisions in line alignment teleoperation than in cross alignment teleoperation. In the simulated robotic arm teleoperation of present study, collisions usually occurred in the fine-tuning stage. In the fine-tuning stage of line alignment, the subjects need to adjust the Z position deviation in a wide range keeping two angle deviations (a, b) unchanged. This is an action with strict constraints. During this kind of action, it is very easy to collide. But in point aiming and

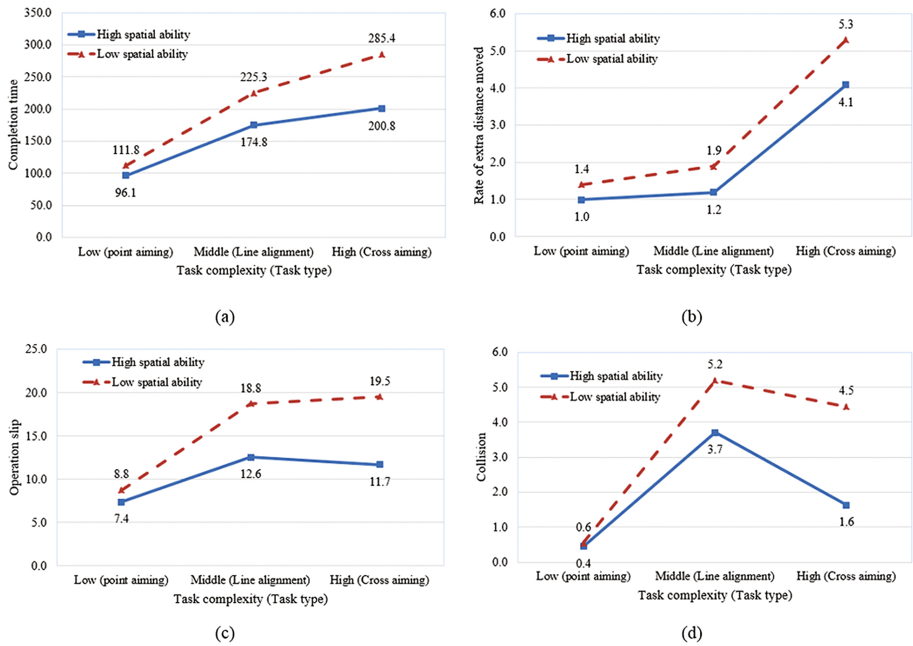

Fig. 3. The interaction effects of spatial ability and task complexity on teleoperation performance

cross alignment, this kind of action does not exist. This result indicated that apart from accuracy requirement but the teleoperation process (i.e., the number of actions with constraints) should be also taken into account in the evaluation of teleoperation complexity.

According to reference [6], the conceptualization, identification, and measurement of task complexity is really complicated. It can be speculated that it is the same to teleoperation complexity. The present study is a tentative exploration on teleoperation complexity, and its relationship with teleoperation performance, especially for operators with different spatial ability. In future work, more research should be conducted to the measurement of teleoperation complexity. Moreover, the inverted U-shaped correlation between task complexity and performance is an important theoretical assumption [2, 4, 12]. If this assumption is proved in teleoperation. It will be a tremendous contribution for teleoperation design since an individual performs best in teleoperation with appropriate complexity based on the inverted-U shaped correlation. Therefore, empirical research is really necessary for this theoretical assumption in future work.

5 Conclusion

The present work found spatial ability significantly or marginally significantly influenced task completion time, collision, and operation slip in simulated robotic arm teleoperation. The subjects with high spatial ability performed significantly better than those with low spatial ability. That implies that spatial ability plays a key role in teleoperation. Furthermore, task complexity significantly affected completion time, extra distance moved, operation slip, and collision in the simulated teleoperation of present study. It was also found that the interaction effect of spatial ability and task complexity on collision was marginally significant. Compared to low complexity teleoperation, the performance difference between the subjects with low spatial ability and those with high spatial ability were larger in high complexity teleoperation. Therefore, spatial ability should be considered as an important selection criterion for tele-operators, especially those operators for high complexity teleoperation.

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