Association of Individual Characteristics with Teleoperation Performance

Dan Pan; Yijing Zhang; Zhizhong Li; Zhiqiang Tian

BACKGROUND: A number of space activities (e.g., extravehicular astronaut rescue, cooperation in satellite services, space station supplies, and assembly) are implemented directly or assisted by remote robotic arms. Our study aimed to reveal those individual characteristics which could positively influence or even predict teleoperation performance of such a space robotic arm.

METHODS: There were 64 male volunteers without robot operation experience recruited for the study. Their individual characteristics were assessed, including spatial cognitive ability, cognitive style, and personality traits. The experimental tasks were three abstracted teleoperation tasks of a simulated space robotic arm: point aiming, line alignment, and obstacle avoidance. Teleoperation performance was measured from two aspects: task performance (completion time, extra distance moved, operation slips) and safety performance (collisions, joint limitations reached). The Pearson coefficients between individual characteristics and teleoperation performance were examined along with performance prediction models.

RESULTS: It was found that the subjects with relatively high mental rotation ability or low neuroticism had both better task and safety performance ($|r| = 0.212 \sim 0.381$). Subjects with relatively high perspective taking ability or high agreeableness had better task performance ($r = -0.253$; $r = -0.249$). Imagery subjects performed better than verbal subjects regarding both task and safety performance ($|r| = 0.236 \sim 0.290$). Compared with analytic subjects, wholist subjects had better safety performance ($r = 0.300$). Additionally, extraverted subjects had better task performance ($r = -0.259$), but worse safety performance ($r = 0.230$).

CONCLUSIONS: Those with high spatial cognitive ability, imagery and wholist cognitive style, low neuroticism, and high agreeableness were seen to have more advantages in working with the remote robotic arm. These results could be helpful to astronaut selection and training for space station missions.

KEYWORDS: teleoperation performance, robotic arm, spatial cognitive ability, cognitive style, personality traits.

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With the rapid development of aerospace technology, teleoperation has been widely applied in space exploration. The application of the remote robotic arm on the International Space Station (ISS) is particularly noteworthy. A number of space activities (e.g., extravehicular astronaut rescues, cooperation in satellite services, space station supplies, and assembly) are implemented directly or assisted by remote robotic arms, such as Canadarm2, JEMRMS, and ROKVISS.[34] The mass of a remote robotic arm is huge and the work environment on the space station can be dangerous. Onboard the space station, the error tolerance in the teleoperation process is miniscule.[7] The consequences of an accident are unimaginable. Therefore, teleoperation performance is vital. To some extent, teleoperation performance can be guaranteed by the advanced technology in machinery, electronics, and information science in the early design and development of remote robotic arms. When remote robotic arms come into use onboard the space station, teleoperation performance largely lies on astronauts. Human-related factors, including spatial cognitive ability, cognitive style, and personality traits, may play key roles in the teleoperation process.

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The aircraft laboratory at the Massachusetts Institute of Technology was entrusted by NASA to explore the effects of spatial cognitive ability on teleoperation performance of pickup, docking, and "fly-to" tasks.[16,28] Subjects with higher perspective taking ability performed the pickup task significantly more efficiently, performed the docking task faster, collided less, and performed the "fly-to" task faster, more fluidly, and more effectively.[16,28] Researchers at the China Astronaut Research and Training Centre conducted astronaut training for Shenzhou 9th. Both mental rotation and perspective taking were found to be significantly correlated with manual rendezvous and docking performance.[27,31] Spatial cognitive ability has been found to be positively related to navigation performance,[21] visual scanning performance,[6] and a novice's learning performance on proper positioning of an angled laparoscope.[10] It can be hypothesized that spatial cognitive ability can positively influence teleoperation performance. However, those results are greatly determined by the specific experimental tasks and probably not always right for other complex teleoperations. In addition, the sample sizes in the above studies of simulated space teleoperation were not more than 20[27,28,31] and even as few as 7.[16]

Cognitive style has been found to be related to individuals' cognitive behavior (e.g., information-seeking behavior).[13,26] The matching of cognitive style with task environment (e.g., type of interface, information) influenced work performance. For example, in image retrieval tasks, imagery students significantly outscored verbal students.[1] Personality traits were also found to be significantly correlated to operators' performance, especially when coping with stress under emergency situations.[11] Studies based on the "Big Five" personality factors found that conscientiousness was positively related to academic achievement,[5] driving performance,[24] and performance of experienced operators in complex safety-critical systems.[29] Neuroticism was found to predict driving performance.[24] Accordingly, we have sound reasons to speculate that teleoperation performance could be related to individuals' cognitive style and personality traits. So far as we know, cognitive style and personality traits have not been considered in previous studies of robotic arm teleoperation.

The present work explores the relationships between different characteristics (spatial cognitive abilities, cognitive style, and personality traits) and teleoperation performance of a remote robotic arm, and aims to identify those characteristics which could positively influence or even predict performance. Furthermore, teleoperation performance is measured objectively from task and safety performance, which respectively reflects operation efficiency and effectiveness, and reliability. The experimental tasks were abstracted tasks (i.e., point aiming, line alignment, obstacle avoidance) based on typical routine robotic arm tasks onboard a space station. Different specific tasks can be treated as the combination of abstracted tasks. For instance, the pickup and "fly to" task in previous studies[16,28] can be treated as point aiming. The spacecraft docking tasks reported by Tian et al.[27] and Wang et al.[31] can be seen as the combination of point aiming and line alignment. Moreover, a larger sample size (>60) is included in the present study to further elucidate the results, which would have broad applications for astronaut selection and training.

METHODS

Subjects

There were 64 undergraduate engineering students who were recruited (mean age = 20.2, SD = 1.02) as subjects for this study. They were all men to avoid the influence of gender, right handed, and without color blindness. They had no or only a little knowledge of space teleoperation with no experience on robotic manipulator operation. They were informed about the details of the experimental protocol and voluntarily signed the informed consent form before participating. The experimental procedure was approved in advance by the ethics committee of the China Astronaut Research and Training Center.

Independent Variables

The individual characteristics in this study that we were particularly interested in included spatial cognitive ability, cognitive style, and personality traits. Spatial cognitive ability was tested using mental rotation and perspective taking, separately, with the revised Vandenberg mental rotation test and adapted Guay's visualization of views test. The revised Vandenberg mental rotation test is a standard set with stimulus figures redrawn from the original Vandenberg and Kuse's set.[18,30] It is one of the most extensively used mental rotation tests with substantial internal consistency (Kuder-Richardson 20 = 0.88) and a test-retest reliability (0.83).[30] It consists of 2 sets of 12 items. The subjects were asked to complete as many of the items as possible in 4 min for each set. Each item had a criterion figure and four stimulus figures (A, B, C, and D). The task required the subjects to rotate figures to identify two stimulus figures which matched the criterion figure. One point was given to the item with two correct answers. In order to avoid guessing, a negative score was given to wrong answers. For example, −1 point was given to the item with two incorrect answers. The adapted Guay's visualization of views test is a standardized test of spatial perspective taking ability.[12] In this paper-and-pencil test, there are 24 items. For each item, an isometric view of a three-dimensional object is depicted in the center of a see-through cube. The same object from a different viewpoint is depicted below the cube. The task is to determine the corner of the cube from which the new view of the object is taken. The item with a correct answer got 1 point. Incorrect answers or no answer got 0 points. The subjects had 8 min to complete as many of the items as possible.

Cognitive style was measured from Verbal/Imagery (V/I) and Wholist/Analytic (W/A) dimensions using the Cognitive Style Analysis (CSA, in Chinese) system. This instrument is simply computer presented and can directly assess an individual's position on two dimensions of cognitive style. It was revised by Li from Riding and Cheema's CSA.[14,20] Li verified its internal consistency and test-retest reliability among Chinese college students.[14] It has also been proved that these two style dimensions tested by CSA are independent of personality and separate from intelligence.[19] The CSA consists of the V/I test and the W/A test, which are simple cognitive processing tasks. They are likely to reflect the underlying cognitive processing of an individual and the way in which an individual habitually represents and organizes information during thinking. The V/I test includes 48 items asking subjects to judge whether a statement is true or false. One half of the statements contain descriptions of conceptual categories (verbal items) while the rest describe appearance relationships (imagery items). The reaction time on verbal items (T_V) and on imagery items (T_I) were recorded. The ratio of T_V and T_I (T_V/T_I) was calculated as the score of the V/I dimension. A low ratio means that a subject tends toward verbal and a high ratio toward imagery. The W/A test includes two subtests and each has 20 items. The first subtest requires subjects to judge whether a pair of complex geometric figures is the same. Half the items are pairs of the same figures and the other half are not. The second subtest requires subjects to determine whether a simple geometric figure is contained in a more complex geometric figure. Half the items are simple figures which are contained and the other half are not. The reaction time on the first subtest (T_W) and on the second subtest were recorded (T_A). The ratio of T_W and T_A (T_W/T_A) was calculated as the score of the W/A dimension. A low ratio means that a subject tends toward wholist while a high ratio means a tendency toward analytic.

Personality traits are unique and stable thinking patterns and behavior styles of conscious and unconscious thoughts, actions, and emotions give rise to the ways people respond to their environment.[15] Personality traits appear to be stable among working-age adults. For example, the mean-level changes in the "Big Five" personality traits are small and do not vary substantially across age groups.[8] Among various tests of assessing personality traits, the most commonly used include the Enneagram typing system, the Myers-Briggs Type Indicator, the "Big Five" personality traits, and Cattell's 16 Personality Factors. The former two are mainly used by professional psychologists, human resources, recruitment consultants, and sociologists.[2] Each type of personality trait had different relationships with people's job attitudes, cognitions, and occupational choice.[25] The latter two separately evaluate personality traits from 5 and 16 aspects. They are commonly used to evaluate occupational suitability in personnel selection of various domains, such as aviators.[3,4] In this study, personality traits were assessed from extraversion, agreeableness, conscientiousness, neuroticism, and openness to experience using the "Big Five" Personality Index questionnaire. The assessment structure of this questionnaire, reasonably representing the personality dimensions of an individual, has been accepted by most researchers.[22] The questionnaire consists of 44 items stating a number of general descriptions. Each item has five options from strongly disagree to strongly agree where the score is ranged from 1 to 5. The score of each dimension is the average value of relevant items.

Equipment

In this study, the virtual reality environment of a space manipulator was constructed based on the Virtual Robot Experimentation Platform, which is a powerful robot simulation and modeling software developed by Coppelia Robotics Company. As shown in **Fig. 1**, the simulated remote robotic arm has an

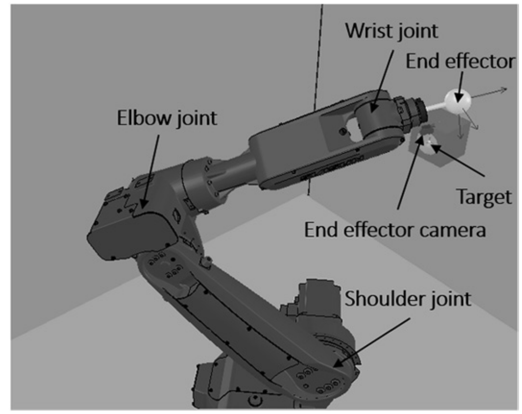

Fig. 1. Simulated space robotic arm.

end effector (a device at the end of a robotic arm) and three joints similar to the shoulder, elbow, and wrist of a human being. Each joint has pitch and yaw angles which will change with the movement or rotation of the end effector. The target was one face of a cube which was located on either the left or right wall. The subjects operated two 3-degrees-of-freedom joysticks (Litestar PNX-2013) to control the end effector. The left hand was in charge of position movement of the end effector while the right hand was in charge of angle adjustment. Four cameras located in the virtual workplace separately provided global, end effector, and left/right target views for the subjects (**Fig. 2**). The global and target cameras were fixed in the workplace while the end effector camera was installed on the end effector and moved with the end effector (Fig. 1). Meanwhile, two numerical panels provided real-time position and angle deviation, pitch and yaw angles of each joint, and their limitations.

During a task, when any joint angle limitation was reached, or any collision or out of workspace boundary occurred, a prompting window would pop up to alert subjects. When a task was completed successfully, a prompting window would also pop up to inform subjects. At the same time, the program automatically stopped and returned to the original state. The platform recorded the position deviation, angle deviation, joystick movement and rotation, moving distance, number of collisions, out of boundary, joint limitation reach, and task completion time every 0.4 s.

Experimental Task and Procedure

The experimental task was to perform three kinds of teleoperation tasks, including point aiming, line alignment, and obstacle avoidance tasks. The end effector of the simulated remote robotic arm was set to different shapes for different tasks. As shown in **Fig. 3A**, the end effector and target of point aiming task were abstracted into a sphere. The subjects were asked to control the remote robotic arm and make the center of the end effector aim at the center of the target. The task was considered successfully completed when the subjects made the three position deviations within the accuracy requirement. As shown in **Fig. 3B**, the end effector and target of line alignment task were abstracted into a cylinder. The subjects

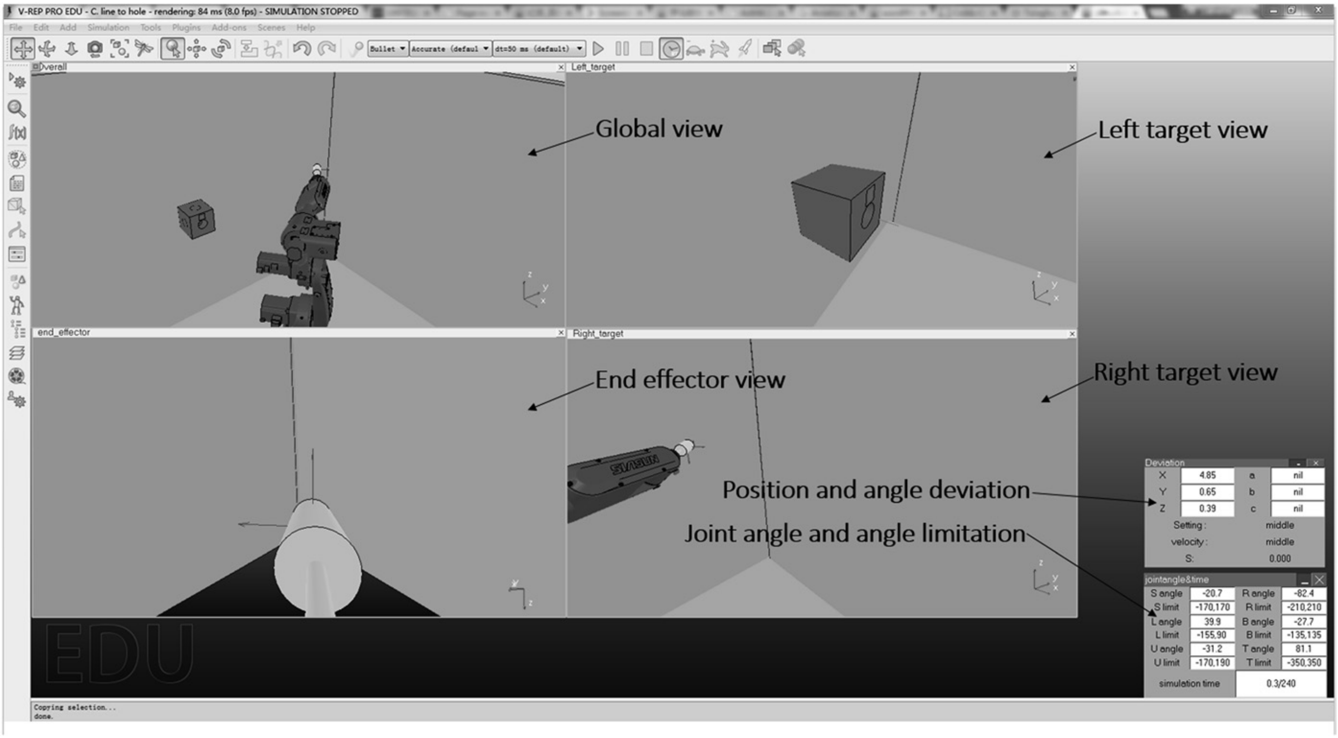

Fig. 2. Teleoperation interface.

were asked to control the remote robotic arm and make the axis of the end effector align with the axis of the target, starting from an initial orientation perpendicular to the target face. The task was designated successfully completed when the subjects made three position deviations and two angle deviations within the accuracy requirements. The obstacle avoidance task was similar with the point aiming task, but two obstacle sticks were placed between the remote robotic arm and the target cube (**Fig. 3C**).

The experiment procedure was as follows: first, a pilot study was conducted to test the experimental platform and train experimenters. Next, the subjects were asked to take several tests assessing their spatial cognitive ability, cognitive style, and personality, and to learn about the tasks, including what information the interface provided and how to use the joysticks. After that was the teleoperation experiment, which consisted of a practice session and a test session. The subjects practiced each task once to be familiar with operating two joysticks and be clear on the task requirements. Finally, the subjects were asked to finish each task twice, once with the target cube located on the left wall (Fig. 3A), and once with it located on the right wall (Fig. 1). The order of the three tasks was balanced among the subjects.

Dependent Variables

Teleoperation performance was assessed from a task and safety performance perspective. Task performance reflected operational efficiency and effectiveness in terms of completion time, extra distance moved, and operation slip. Safety performance was measured based on behaviors which may reduce teleoperation reliability or even cause an accident. Collision and joint limitation reach were considered measures of safety performance.

1) Completion time: This refers to how much time a subject took to complete a task successfully. Completion time reflected operational efficiency and a short time indicates good task performance.

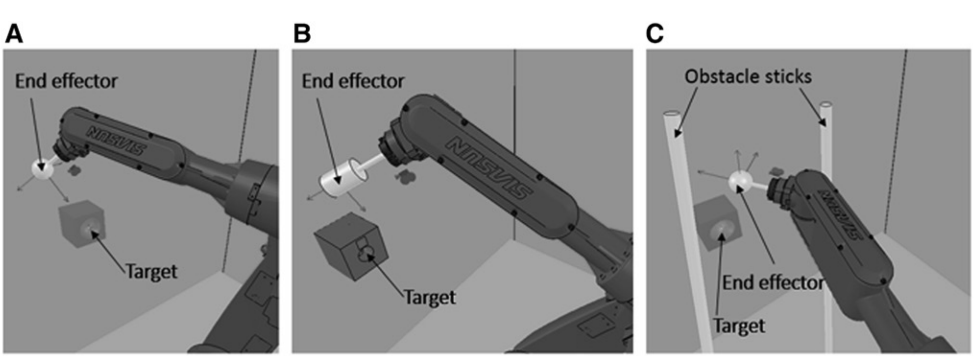

Fig. 3. Abstracted tasks of robotic arm teleoperation. A) Point aiming; B) line alignment; C) obstacle avoidance.

2) Extra distance moved: This was defined as the ratio between total moved distance minus initial position deviation and initial position deviation, i.e., [extra distance moved = (total moved distance – initial position deviation)/initial position deviation]. The ratio reflects operational effectiveness and a small ratio indicates good path planning.

3) Number of operation slips: For each direction or angle

control, if the directions of two consecutive operations within 2 s were opposite to each other, then it is defined as an operation slip, except when the residence time between these two operations is longer than the time spent on the first operation. The number of operation slips reflected operational effectiveness and few slips indicate good task performance.

4) Collision: A collision was counted when any part of the simulated space manipulator collided with the environment or the target cube. Few collisions indicated good safety performance.

5) Joint limitations reached: A reach of joint limitations was counted when any pitch or yaw angle of the three joints reached their limitations. Reaching a joint limitation may cause potential damage to hardware systems. The number of joint limitations reached also reflected operational fluency and situation awareness. Few joint limitation reaches indicated good safety performance.

Data Analysis

When checking the collected data set, subjects #4 and #7 were deemed to be outliers since several of their performance measures deviated from the means by more than three times the standard deviations. After excluding the outliers, none of the subjects had a performance measure more than three times the standard deviation above or below the mean. Thus all results reported in the next section were based on the data of 62 subjects. Firstly, a normality test of all variables based on the Q-Q plot was conducted. After all variables were considered to be approximately distributed normally, the Pearson coefficient was used to explore the correlation between individual characteristics and performance measures. The value of a Pearson coefficient reflects the strength of the association between two variables.[17] Stepwise linear regression was used in the final analysis to determine the effects of spatial cognitive ability, cognitive style, and personality on performance measures of three types of teleoperation using a statistical significance of 0.05. All data analyses were performed using SPSS 20 and MS Excel 2013.

RESULTS

As shown in **Table I**, mental rotation ability was significantly related to extra distance moved in the point aiming task ($r = -0.326$, $P = 0.005$), completion time, extra distance moved, collision in the line alignment task ($r = -0.235$, $P = 0.033$; $r = -0.212$, $P = 0.049$; $r = -0.381$, $P = 0.001$, respectively), and collision in the obstacle avoidance task ($r = -0.281$, $P = 0.013$). These results indicate that the subjects with high mental rotation ability had both better task performance (i.e., less extra distance moved and shorter completion time) and better safety performance (i.e., fewer collisions) than those with low. Perspective taking ability was found to be significantly related to extra distance moved in both the point aiming task and the line alignment task ($r = -0.288$, $P = 0.012$; $r = -0.253$, $P = 0.024$, respectively), and the operation slip of the obstacle avoidance task ($r = -0.243$, $P = 0.028$). Subjects with high perspective taking ability had better task performance (i.e., less extra distance moved and fewer operation slips) than those with low.

As shown in Table I, the verbal/imagery dimension was significantly related to completion time, operation slip, and joint limitation reach in the point aiming task ($r = -0.278$, $P = 0.014$; $r = -0.236$, $P = 0.032$; $r = -0.290$, $P = 0.011$, respectively), and collision in the obstacle avoidance task ($r = -0.226$, $P = 0.039$). Imagery subjects were found to have both better task performance (i.e., shorter completion time, fewer operation slips) and safety performance (i.e., fewer joint limitations reached and collisions) than verbal subjects. The wholist/analytic dimension was only significantly related to collision in the point aiming task ($r = 0.300$, $P = 0.009$), indicating wholist subjects had fewer collisions than analytic subjects. No significant relationship was found between cognitive style and performance measures in the line alignment task.

As shown in Table I, extraversion was significantly related to completion time in the line alignment task ($r = -0.259$, $P = 0.021$) and joint limitations reached in the obstacle avoidance task ($r = 0.230$, $P = 0.036$). Extraverted subjects completed the task in shorter time, but caused more joint limitation reaches than introverted subjects. Agreeableness was significantly related to operation slip in the line alignment task ($r = -0.249$, $P = 0.026$). The subjects with high agreeableness had fewer operation slips than those with low. Conscientiousness was significantly related to completion time in the obstacle avoidance task ($r = 0.301$, $P = 0.009$). The subjects with high conscientiousness spent a longer time on the obstacle avoidance task. Neuroticism was significantly related to completion time, extra distance moved, and collision in the obstacle avoidance task ($r = 0.228$, $P = 0.037$; $r = 0.262$, $P = 0.020$; $r = 0.305$, $P = 0.008$, respectively). The subjects with low neuroticism had both better task performance (i.e., shorter completion time and less extra distance moved) and better safety performance (i.e., fewer collisions). No significant relationship was found between personality traits and performance measures in the point aiming task.

Stepwise regression analysis was conducted separately for the three tasks, with performance measures serving as the criterion and spatial cognitive ability, cognitive style, and personality traits serving as predictive variables. The results are given in **Table II**, **Table III**, and **Table IV**. Only those that are statistically significant are reported here.

The performance prediction model of the point aiming task is shown in Table II. The verbal/imagery cognitive style dimension was a significant predictor of completion time ($P = 0.028$), accounting for 6.2% of the variance. Mental rotation ability was a significant predictor of extra distance moved ($P = 0.010$), accounting for 9.1% of the variance. The wholist/analytic cognitive style dimension was a significant predictor of collisions ($P = 0.018$), accounting for 7.5% of the variance. The verbal/imagery cognitive style dimension was a significant

Table I. Pearson Correlations Between Individual Characteristics and Performance.

	SPATIAL COGNITIVE ABILITY		COGNITIVE STYLE		PERSONALITY TRAITS				
PERFORMANCE MEASURES	MR	PT	V/I	W/A	E	A	C	N	O
Point aiming									
Task performance									
Completion time (s)	−0.171	−0.168	−0.278*	0.017	−0.126	0.114	0.120	0.112	−0.105
Extra distance moved	−0.326**	−0.288*	−0.184	0.011	−0.054	0.009	0.012	0.116	−0.054
Operation slip (#)	−0.068	−0.195	−0.236*	−0.029	0.058	−0.073	0.042	0.054	0.017
Safety performance									
Collision (#)	−0.162	−0.138	−0.122	0.300**	0.051	−0.049	0.042	0.017	−0.103
Joint limitation reach(#)	−0.057	−0.069	−0.290*	0.025	0.008	0.078	−0.024	−0.008	0.028
Line alignment									
Task performance									
Completion time (s)	−0.235*	−0.155	−0.060	−0.099	−0.259*	−0.089	0.025	0.118	−0.132
Extra distance moved	−0.212*	−0.253*	−0.089	−0.117	−0.209	−0.190	−0.007	0.124	−0.066
Operation slip (#)	−0.200	−0.102	−0.199	0.032	−0.042	−0.249*	−0.113	0.119	−0.085
Safety performance									
Collision (#)	−0.381**	−0.054	0.068	0.039	−0.114	−0.121	−0.047	0.085	−0.138
Joint limitation reach(#)	−0.162	−0.189	−0.057	−0.179	−0.162	−0.037	0.007	−0.121	−0.167
Obstacle avoidance									
Task performance									
Completion time (s)	−0.106	−0.038	0.202	−0.082	−0.084	−0.028	0.301**	0.228*	0.064
Extra distance moved	−0.173	−0.188	0.019	−0.142	−0.047	−0.078	0.188	0.262*	0.109
Operation slip (#)	−0.064	−0.243*	−0.015	−0.174	0.116	−0.109	0.201	0.091	0.186
Safety performance									
Collision (#)	−0.281*	−0.139	−0.226*	0.158	−0.085	−0.087	0.038	0.305**	0.014
Joint limitation reach(#)	−0.121	−0.010	0.141	−0.096	0.230*	0.114	0.148	−0.074	0.042

** $P < 0.01$; *$P < 0.05$ (one-tailed). MR: mental rotation; PT: perspective taking; V/I: Verbal/imagery; W/A: wholist/analytic; E: extraversion; A: agreeableness; C: conscientiousness; N: neuroticism; O: openness to experience.

predictor of joint limitation reach ($P = 0.022$), accounting for 6.9% of the variance.

As shown in Table III, for the line alignment task, extraversion was a significant predictor of completion time ($P = 0.042$), accounting for 5.1% of the variance. Perspective taking ability was a significant predictor of extra distance moved ($P = 0.047$), accounting for 4.8% of the variance, while mental rotation ability was a significant predictor of collision ($P = 0.002$), accounting for 13.1% of the variance.

Table IV presents the performance prediction model of the obstacle avoidance task. Conscientiousness and neuroticism were significant predictors of completion time ($P = 0.001$; $P = 0.003$), accounting for 7.5% and 11.4% of the variance, respectively. Conscientiousness and neuroticism were significant predictors of extra distance moved ($P = 0.016$; $P = 0.005$), accounting for 7.5% and 5.3% of the variance, respectively. Mental rotation ability and neuroticism ($P = 0.040$; $P = 0.024$) were significant predictors of collision, separately accounting for 4.9% and 7.8% of the variance, respectively.

DISCUSSION

Spatial cognitive ability has received much attention in the virtual environment area. Empirical studies were carried out to examine the effect of spatial cognitive ability on task performance in various areas, such as surgery,[10] navigation,[21] and space exploration,[31] where spatial judgment is needed. It was suggested that understanding spatial information about the scene and making cognitive judgments are the basis for performing teleoperations.[23] In the present study,

Table II. Summary of Stepwise Regression Results (Point Aiming).

	COMPLETION TIME			EXTRA DISTANCE MOVED			COLLISION			JOINT LIMITATION REACH		
VARIABLES	B	β	*P*	B	β	*P*	B	β	*P*	B	β	*P*
Constant	175.92		<0.001	2.21		<0.001	−0.48		0.272	3.95		0.002
MR				−0.06	−0.33	0.010						
V/I	−87.21	−0.28	0.028							−3.11	−0.29	0.022
W/A							0.89	0.30	0.018			
	Adjusted $R^2 = 6.2\%$			Adjusted $R^2 = 9.1\%$			Adjusted $R^2 = 7.5\%$			Adjusted $R^2 = 6.9\%$		
	$F = 5.042$			$F = 7.126$			$F = 5.950$			$F = 5.518$		
	$P = 0.028$			$P = 0.010$			$P = 0.018$			$P = 0.022$		

Note: MR: mental rotation, V/I: Verbal/imagery, W/A: wholist/analytic.

Table III. Summary of Stepwise Regression Results (Line Alignment).

	COMPLETION TIME			EXTRA DISTANCE MOVED			COLLISION		
VARIABLES	**B**	β	***P***	**B**	β	***P***	**B**	β	***P***
Constant	309.27		<0.001	2.45		<0.001	10.24		<0.001
MR							−0.34	−0.38	0.002
PT				−0.05	−0.25	0.047			
factor E	−41.36	−0.26	0.042						
	Adjusted R^2 = 5.1%			Adjusted R^2 = 4.8%			Adjusted R^2 = 13.1%		
	F = 4.306			F = 4.104			F = 10.177		
	P = 0.042			P = 0.047			P = 0.002		

Note: MR: mental rotation, PT: perspective taking, E: extraversion.

the teleoperation process involved activities such as image information retrieval, understanding, integration and transformation, formation of mental models, and judgment of spatial position and orientation. These activities cause a demand on spatial cognition. We found that the subjects with relatively high mental rotation ability performed remote robotic arm tasks significantly more quickly (line alignment task), more effectively (point aiming and line alignment tasks), and more reliably (line alignment and obstacle avoidance task). Mental rotation ability explained 9.1% of the extra distance moved variance in the point aiming task, 13.1% of the collision variance in the line alignment task, and 4.9% of the collision variance in the obstacle avoidance task. The subjects with relatively high perspective taking ability performed all three tasks more effectively. Perspective taking ability explained 4.8% of the extra distance moved variance in the line alignment task. Therefore, it can be concluded that spatial cognitive ability positively influences task and safety performance of typical robotic arm teleoperations and thus should be considered in astronaut selection and training. This is consist with previous studies on specific and complex tasks.[16,28,31] Additionally, considering the limited variance spatial cognitive ability explained, it is also important for future studies to identify other factors that would contribute to the variance of task and safety performance in teleoperation tasks.

With regard to cognitive style, the verbal/imagery style dimension describes the preferred way in which an individual would represent knowledge in memory, either verbally or in mental pictures.[19] The present study found that imagery subjects performed the point aiming task more quickly, effectively, and reliably, and performed the obstacle avoidance task more reliably than verbal subjects. This is reasonable since the camera views presented real-time images, which was good for imagery subjects to represent information in memory. The wholist/analytic dimension describes the consistent way in which an individual would organize and process information, either in part or as a whole.[19] Wholist subjects were found to perform the point aiming task more reliably than analytic subjects. Since wholist subjects could be good at combining various information, and learn better from experience,[33] they could better avoid collisions. Based on the above results, imagery and wholist operators are recommended for remote robotic arm tasks rather than verbal and analytic operators. Again, although the influence was significant, the variance explained by either the verbal/imagery or wholist/analytic dimensions were limited (less than 10%).

Nevertheless, it was not found that cognitive style was significantly related to performance measures of the line alignment task. This was probably because of the specific task requirements. Fine-tuning is really important for the success of the line alignment task because of the requirement of angle accuracy. In contrast, path planning is the main process of the point aiming and obstacle avoidance tasks since there were no requirements for angle accuracy. This probably indicates that division of the whole teleoperation process is necessary for task analysis and training since different process stages have requirements for different aspects of cognitive ability or style. For example, the whole process should be divided into path planning, an implementation stage, and a fine-tuning stage. Future work may address this problem, exploring the possible interaction between the teleoperation process and cognitive style.

Table IV. Summary of Stepwise Regression Results (Obstacle Avoidance).

	COMPLETION TIME			EXTRA DISTANCE MOVED			COLLISION		
VARIABLES	**B**	β	***P***	**B**	β	***P***	**B**	β	***P***
Constant	−163.353		0.038	−2.008		0.059	0.241		
MR							−0.109	−0.252	0.040
factor C	47.842	0.431	0.001	0.458	0.316	0.016			
factor N	46.017	0.377	0.003	0.592	0.371	0.005	0.896	0.279	0.024
	Adjusted R^2 = 18.9%			Adjusted R^2 = 12.8%			Adjusted R^2 = 12.7%		
	(7.5% for C; 11.4% for N)			(7.5% for C; 5.3% for N)			(4.9% for MR; 7.8% for N)		
	F = 8.103			F = 5.466			F = 5.450		
	P = 0.001			P = 0.007			P = 0.007		

Note: MR: mental rotation, C: conscientiousness, N: neuroticism.

Personality traits play a role in the way people respond to their environment. The present study found that extraverted subjects performed the line alignment task more quickly, but performed the obstacle avoidance task less reliably than introverted subjects. That is reasonable since extraverted individuals prefer to pursue initiative and stimulus, but introverted subjects tend to deliberate.[9] Thus, extraverted subjects completed tasks faster while introverted subjects performed more reliably, which indicated that the priority of the task and safety performance should be considered when selecting astronauts tending to extraversion or introversion. In addition, the subjects with low neuroticism performed the obstacle avoidance task more quickly, effectively, and reliably. Neuroticism explained 11.4% of the completion time variance, 5.3% of the extra distance moved variance, and 7.8% of the collision variance. People with high neuroticism are emotionally reactive, vulnerable to stress, and often in a bad mood,[32] which could negatively influence their performance. Besides, the subjects with relatively high conscientiousness performed the obstacle avoidance task more slowly. Conscientiousness explained 7.5% of both completion time and extra distance moved variances. The subjects with relatively high agreeableness performed the line alignment task more effectively. In short, four of the "Big Five" factors were found to be significantly related to teleoperation performance. Although with limited variance explained, personality traits, especially extraversion, neuroticism, and conscientiousness, should not be ignored in astronaut selection.

Finally, mental rotation ability had a stronger correlation with teleoperation performance than other individual characteristics studied in the present work, and mental rotation ability was the only one which could significantly predict performance measures of all three teleoperation tasks (Tables II, III, and IV). As shown in Table I, two significant Pearson coefficients between mental rotation ability and teleoperation performance were larger than 0.3, which means a medium strength of association[17] (**Fig. 4**). This probably indicates that mental rotation ability should have a priority in astronaut selection.

In conclusion, spatial cognitive ability and imagery cognitive style positively influenced both task and safety performance. Wholist cognitive style had positive impact on safety performance. Moreover, extraverted subjects had better task performance, but worse safety performance. Those with relatively low neuroticism and high agreeableness seemed to have more advantages in working with the remote robotic arm. It is recommended to consider these characteristics in astronaut training and selection.

However, these conclusions are tentative. There are still several directions that should be explored in future research. Since spatial cognitive ability, V/I–W/A cognitive style, and the "Big Five" personality traits provided limited explanation of the performance variance (less than 20%), future work should attempt to identify other factors that may have significant influence or interaction with individual characteristics, such as the interaction between cognitive style and information display format. In addition to male subjects, future studies should collect data from female subjects as more women are included in space programs.

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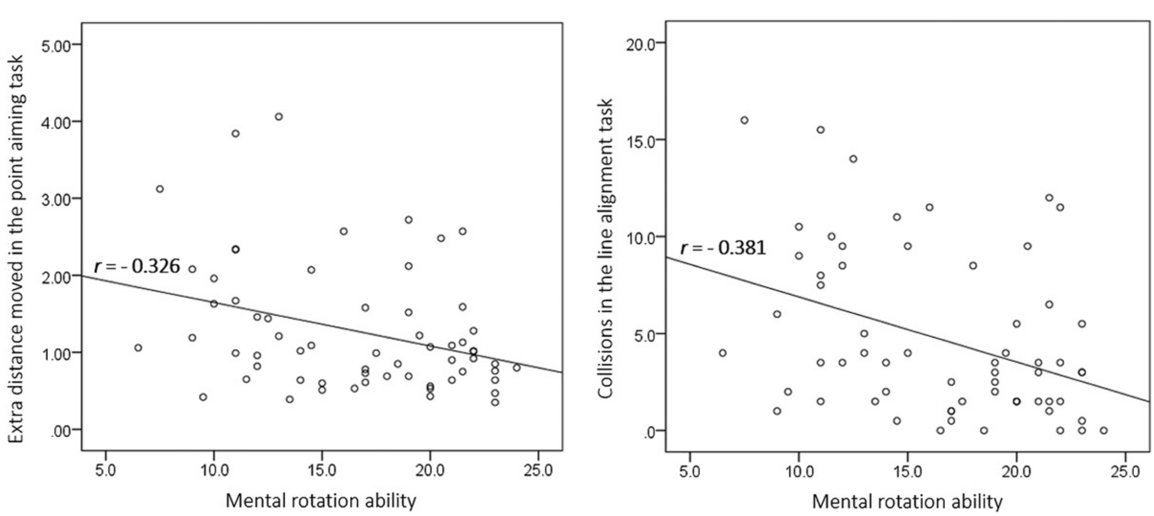

Fig. 4. Plots of the correlation between mental rotation ability and extra distance moved in the point aiming task, and the correlation between mental rotation ability and collisions in the line alignment task.

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