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S.I. : NEW TRENDS ON IMMERSIVE HEALTHCARE

The impact of misaligned idiotropic and visual axes on spatial ability under altered visuospatial conditions

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Abstract

Spatial ability, a critical dimension of human cognition, represents the ability to gather, perceive, and manipulate spatial information to create an accurate and complete mental representation of spatial environments. Previous studies have examined spatial ability in normal spatial conditions of the earth. However, emerging technologies and increasing exploration of hard-to-reach locations are transforming future workplaces into environments with altered visuospatial conditions, which may pose serious challenges to workers' productivity and safety. One such condition is the misalignment of idiotropic and visual axes that may exist in microgravity during space explorations or underwater during deep-sea explorations. In this study, we investigate whether and to what extent misaligned idiotropic and visual axes influence spatial ability. The misalignment was simulated in Virtual Reality (VR) with three conditions: aligned (control group), misaligned (experiment group I), and dynamically misaligned (experiment group II) idiotropic and visual axes. The spatial ability of 99 participants was measured through spatial visualization, relations, and orientation abilities using the Purdue Spatial Visualization Test: Rotations (PSVTR), Mental Cutting Test (MCT), and Perspective-Taking Ability (PTA) test, respectively. For the MCT and PTA tests, the results show no significant differences in response accuracy among the three conditions. The PSVTR test results reflect a statistically significant difference in accuracy among the groups. The three groups did not have significantly different response times for the three tests. The results suggest that the misalignment of the body and visual axes may influence spatial visualization, but may not impact spatial relations or orientation.

Keywords Augmented and virtual reality · Spatial cognition · Spatial ability · Interdisciplinary projects

1 Introduction

The future of work is being transformed by emerging technologies and already involves altered working conditions (He et al. 2021). Future work will explore remote places with unfamiliar environments such as deep space, low Earth orbit (LEO), deep oceans, and polar regions with different climates (Stapleton et al. 2016). To work safely and productively in such conditions, more research is needed for examining and augmenting human cognitive abilities, particularly spatial cognitive ability (Kanas 2015). Numerous studies have shown that spatial ability is not just crucial to perceive a spatial environment but is also important for students' pursuit of STEM education and careers (Marin and Beluffi 2018). Spatial ability is the ability to generate, store, retrieve, and transform visual information to create a complete and accurate mental representation of spatial settings (Lohman 1979). As a result, we can locate objects in space, perceive objects visually, and understand the spatial relationships of objects and surroundings in two and three dimensions (de Bruin Nutley et al. 2016). Human spatial abilities are determined by three key abilities: spatial visualization, spatial orientation, and spatial relations. Spatial visualization is the process of mentally gathering, manipulating, and visualizing spatial information. Mentally rotating an object is one example of a spatial visualization

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task. In 2D or 3D space, mental rotation refers to the ability to change the orientation of an object in our minds. Routine tasks, such as applying makeup in the mirror or combing one's hair and organizing items into a suitcase, utilize mental rotation and visualization abilities (Linn and Petersen 1985; Quasha and Likert 1937). Work-related tasks, such as driving, operating a piece of equipment, or packaging, also use spatial visualization abilities. Spatial relations represent the ability to relate 2-dimensional (2D) projections of a 3-dimensional (3D) shape to form a mental representation of the object. For instance, understanding construction or engineering drawings to create a mental image of a building or object involves spatial relations ability. Spatial orientation ability denotes the ability to imagine positioning at a point and visualizing a particular spatial environment. For instance, mentally aligning a north-up map to egocentric orientation may involve spatial orientation ability. Individuals apply these three abilities in different combinations to perform day-to-day personal and professional tasks safely and efficiently.

It is important to recognize that each of these abilities plays a unique role in a variety of tasks we are likely to encounter in our workplaces or everyday life (Carroll 1993). This involves being able to perceive and visually understand the features, properties, measurements, shapes, positions, and movements of outside objects (Ekstrom et al. 1976). Everyday activities like driving, walking, and climbing stairs are affected by people representing and transforming visuospatial information. Significant research on spatial ability exists in many fields such as STEM education (Buckley et al. 2018; Ha and Fang 2013; Harle and Towns 2011; He et al. 2021; Khine 2017; Li and Wang 2021), science (Ha and Fang 2013; Harle and Towns 2011; He et al. 2021; Khine 2017; Li and Wang 2021; Tracy 1987), mathematics (Casey et al. 1995; Dowker 1996; Fennema 1974; Kyttälä and Björn 2014; Xie et al. 2020), psychology (Annett 1992; Heo and Toomey 2020; Höffler 2010; Lohman 1979) and medicine (Annett 1992; Hegarty et al. 2020; Heo and Toomey 2020; Hier and Crowley Jr 1982; Höffler 2010; Langlois et al. 2020; Sweeney et al. 2014). However, a few studies have been conducted on spatial ability and adjustment to work conditions in hard-to-access locations with altered visuospatial conditions (Jain et al. 2016b; Meirhaeghe et al. 2020; Miiro 2017; Oman 2007). Most experiments on spatial abilities are conducted on Earth in familiar environments and with the presence of not just visual but also gravitational cues. Understanding human spatial abilities in unfamiliar environments with microgravity still needs more research (Park et al. 2021). The altered conditions of workplaces like space and deep ocean comprise altered static or dynamic conditions, including lack of gravity, misalignment of the body axis and visual axis, and lack of frame of reference or visual cues (Alberty 2015; Jenkin et al. 2011; Marin and Beluffi 2018). Such environments may render a workplace unsafe, uncomfortable, and less productive for humans who are not conditioned to work in such settings (Gholami et al. 2022).

The current study used Virtual Reality (VR) to study the effects of altered conditions of misaligned idiotropic and visual axes or frames of reference on human spatial ability when engaged in these environments. The goal is to inform design principles for developing training tools to train the future workforce. Spatial ability is essential to increase future workers' efficiency, reduce human errors, and help them adapt to these situations more quickly and easily, which will potentially make their work safer and more productive.

1.1 Background

Emerging technologies have revolutionized the way we live, work, and interact over the past decade, from how people make phone calls to how companies run. Considering this, it is likely that the working environment will change in coming decades. As a result of rapidly changing and expanding technology, the nature of work, working dynamics, and the notion of the workplace are also transforming (Stapleton et al. 2016). So, it should not be a surprise that technological advancements are making it easier for humans to explore the deep oceans, deep space, and polar regions never before reached (Clement et al. 2015). However, the conditions in these work environments may alter human spatial cognitive processing. When people are immersed in such environments, altered visuospatial conditions can adversely affect spatial cognitive processing and eventually the ability to work safely (Kincl et al. 2003) and productively.

1.2 Spatial ability

Spatial cognitive processing is an integral part of human cognition, governing our understanding of spatial environments. Spatial ability is one facet of spatial cognition and has been defined in a variety of ways. Lohman (1979) defines it as the ability to generate, store, retrieve, and transform well-structured visual images. Linn and Petersen's framework (Linn and Petersen 1985) explain it as the ability to represent, transform, generate, and extract symbols and non-verbal information. They suggest three components of spatial ability: visual perception, mental rotation, and spatial imagination. As described by Garg et al. (1999), spatial ability is also the ability to comprehend three-dimensional objects and their position as they are manipulated. Overall, spatial ability is defined as the human capacity for generating, visualizing, memorizing, remembering, and transforming any type of visual information such as pictures, maps, and 3D images. Although researchers have defined spatial ability differently, consensus designates it as a natural ability helping individuals solve tasks involving visual and spatial perception (Lin and Suh 2021). Liao and Dong (2017) define it as an ability that indicates human intelligence and argue it is not a single ability but an aggregated result of several spatial ability components. Consequently, components or subfactors of spatial ability have been proposed and studied. For instance, McGee categorized spatial perception and spatial orientation as two main subfactors of spatial ability (McGee 1979). Likewise, Lohman divided spatial ability into spatial visualization, spatial orientation, and speeded rotation components (Lohman 1988). Similarly, Carroll identified five components: visualization, spatial relations, closure speed, flexibility of closure, and perceptual speed (Carroll 1993). Recently, Harris et al. (2021) studied spatial reasoning under mental rotation, spatial visualization, and spatial orientation abilities. However, several studies (Carroll 1993; Contero et al. 2005; Fatemah et al. 2020; Katsioloudis et al. 2014; Liao et al. 2014; Lin and Suh 2021; Maeda and Yoon 2011; Miyake et al. 2001; Park et al. 2020; Pittalis and Christou 2010; Rahmawati and Wulandari 2021; Wulandari et al. 2021) agree on three key dimensions of spatial ability: spatial visualization, spatial orientation, and spatial relations. These dimensions may help us understand how people perceive and mentally manipulate objects.

1.3 Dimensions of spatial ability: spatial visualization, relations, and orientation

Spatial ability is manifested both directly (our responses to how words, numbers, or letter-like forms are arranged on a page) and indirectly (how structured information is organized and presented). Three key dimensions of spatial ability—spatial visualization, orientation, and relations—have been discussed in the literature. Spatial visualization measures the ability to visualize and mentally rotate, turn, or twist an object in a specified sequence (Alberty 2015; Marin and Beluffi 2018; Park et al. 2021). Tests measuring this dimension of spatial ability require participants to mentally manipulate (rotate, turn, or twist) an object as per explicit guidelines on the nature and sequence of manipulation, then identify its new appearance, location, or position from a set of given options. Tests measuring spatial visualization of rotation include the Purdue Spatial Visualizations Test: Visualization of Rotations (P SVT: R), Shepard-Metzler Mental Rotation Test (MRT), and Vandenberg and Kuse Mental Rotations Test, a modified version of MRT (Ernst et al. 2017; Maeda and Yoon 2013; Samsudin et al. 2011). Lowrie et al. (2019) defined spatial visualization as an ability to “mentally transform and manipulate spatial properties of an object.” They mention the Paper Folding Test and Form Board Test as tests to measure spatial visualization. Spatial relations ability, also known as speeded rotation, evaluates a participant’s ability to mentally rotate a 2D figure (simpler one-step rotation) (Kozhevnikov and Hegarty 2001). Such ability can be measured with the Cards Rotation Test or Cube Comparison Test (Fehringer 2021; Kozhevnikov and Hegarty 2001; Long et al. 2011). It may also involve mentally rotating a 2D object and relating it to orthographic projections of its 3D object (Alberty 2017; Marin and Beluffi 2018). This dimension of spatial ability can also be measured with the Mental Cutting Test (MCT), which requires participants to imagine the 2D cross section of a 3D object cut by an inclined plane and to match the cross section to a set of given 2D shapes (Katsioloudis and Jovanovic 2014). A participant’s ability to imagine and create a mental image of a spatial setting from different standpoints is evaluated by spatial orientation (Alberty 2015; Marin and Beluffi 2018). This dimension of spatial ability can be measured by the Perspective-Taking Ability (PTA) test and Guilford-Zimmerman Spatial Orientation Test (Contero et al. 2005; Kozhevnikov and Hegarty 2001).

1.4 Virtual reality (VR) in spatial cognition research

Virtual Reality (VR) uses computer graphics and several sensory inputs in real-time to create a more "intuitive and naturalistic" experience so users can immerse themselves into a simulated physical environment and interact with it more intuitively and naturally (Schulteis and Rothbaum 2002). In multiple studies, VR technology has been used to simulate physical conditions and evaluate spatial cognition (Clément 2011; Harris et al. 2011, 2010; Li et al. 2020). Tibor analyzed the interaction time of a group of students who took a virtual reality test of spatial ability. A study by this author concluded that males with Gear VR were more likely to experience a significant increase in interaction time during the Mental Rotation Tests, whereas males with desktop displays were more likely to experience a significant decrease (Guzsvinecz et al. 2022). VR has been particularly effective in simulating environments that are difficult to experience first-hand. For instance, using VR, Shebilske et al. (2006) and Guo et al. (2016) simulated a multi-module space station and found that spatial tests can be used to predict work and navigation performances. In a similar vein, Jain et al. (2016a) developed a VR simulation of scuba diving in a fully immersive manner and found that a variety of underwater sensations can be produced in virtual environments. In VR, Schneider et al. (2018) created mockups to outline design principles for a training game aimed at teaching important scuba procedures. Additionally, VR has successfully simulated extreme environments and provided a similar physiological response as microgravity (Jain et al. 2016a; Miiro 2017; Shebilske et al. 2006). As a cost-effective and safer alternative to conventional parabolic flights and drop towers, VR simulations have been recommended for testing and training astronauts (Kanas and Manzey 2008; Miiro 2017). By creating VR-based crew training, astronauts eliminate several problems such as spatial orientation and navigation, motion sickness, and disorientation (Oman 2007; Shebilske et al. 2006). In various educational environments and at all levels, VR has been used to support teaching–learning processes. In fact, it is possible to create learning environments that hold great promise using a virtual reality (VR) platform. Mikropoulos and Natsis (2011) reviewed over 50 papers, spanning 10 years, concerning the use of VR in the design of educational virtual environments (EVE).

2 Materials and methods

2.1 Research goal and objectives

The main goal of this study is to understand how altered visuospatial conditions found in extreme microgravity environments may affect human spatial ability. This goal is reached through the following research objectives:

- Simulate altered visuospatial conditions by developing VR settings embedded with spatial ability tests.
- Measure spatial visualization, relations, and orientation dimensions of participants' spatial ability under different altered conditions that may exist in a microgravity environment.
- Examine if and to what extent statically or dynamically misaligned idiotropic and visual axes may influence spatial ability.

2.2 Participants

Although this study focuses on people who work in extreme conditions, such as astronauts, divers, and polar researchers, to avoid bias in spatial testing, they were excluded because they have already undergone rigorous training or have extensive experience in altered conditions (*NASA Extreme Environment Mission Operations* https://www.nasa.gov/mission_pages/NEEMO/index.html; Sandor et al. 2016; Strauss 2004). The study included 99 participants (27 females), all with normal or corrected-to-normal vision. Participants were recruited from the Texas A and M University student population through email announcements sent through the university's email system. The participants' age ranged from 18 to 52 years with an average age of 24.45 years and a standard deviation of 6.156663. The Institutional Review Board (IRB) of the university approved the study and all subjects provided written consent before the study began (Table 1).

Table 1 Participants' information

Age	Min: 18/max: 52	Mean: 24.45
Major	Engineer: 44	Non-engineer: 55
Gender	Female: 27	Male: 72
Video game	Gamers: 44	Non-gamers: 55

2.2.1 Instruments

The three dimensions of spatial ability were measured and evaluated using three instruments. To evaluate spatial relations as well as visualization ability, the Mental Cutting Test (MCT) (part of the Special Aptitude Test in Spatial Relations) was used (Katsioloudis et al. 2014). The perspective-taking ability (PTA) test assessed spatial orientation ability. To evaluate spatial visualization ability, the Revised Purdue Spatial Visualization Test (PSVTR) was applied.

2.2.1.1 Mental Cutting Test (MCT) The Mental Cutting Test was developed in the USA in 1979 as an entrance examination to assess the spatial ability of students at all levels (CEEB 1939). Participants are asked to mentally cut an item and visualize its sectional views (Németh 2007; Quaiser-Pohl 2003). All 25 problems on the standard MCT consist of a 3D test object cut by a 2D plane marked in the VR setting. From a list of five possible cross-sectional 2D views, participants are then asked to choose one that represents the accurate cross section. The maximum score is 25 (Tsutsumi et al. 2008).

2.2.1.2 Purdue Spatial Visualization Tests: Visualization of Rotation (PSVT: R) The Purdue Spatial Visualization Test (PSVT), a 12-item test developed by Guay in 1976, consists of three sections: Developments, Rotations, and Views. The Purdue Spatial Visualization Tests: Visualization of Rotation (PSVT: R) measures a person's ability to rotate mentally in three dimensions. The 30 items in PSV T: R consist of 13 symmetrical and 17 nonsymmetrical figures presented as 3D objects (Maeda and Yoon 2011). Figure 1 illustrates an example item. Participants are presented with an example object and its rotated view. They are then asked to find a rotated view of the test object with the same rotation as the example object. They select the accurate rotated view from a set of five options.

2.2.1.3 Perspective-Taking Ability (PTA) We applied PTA to measure how participants imagine a view from another viewpoint (Hegarty and Waller 2004). The test stimulus includes 6–7 routine objects positioned in the VR

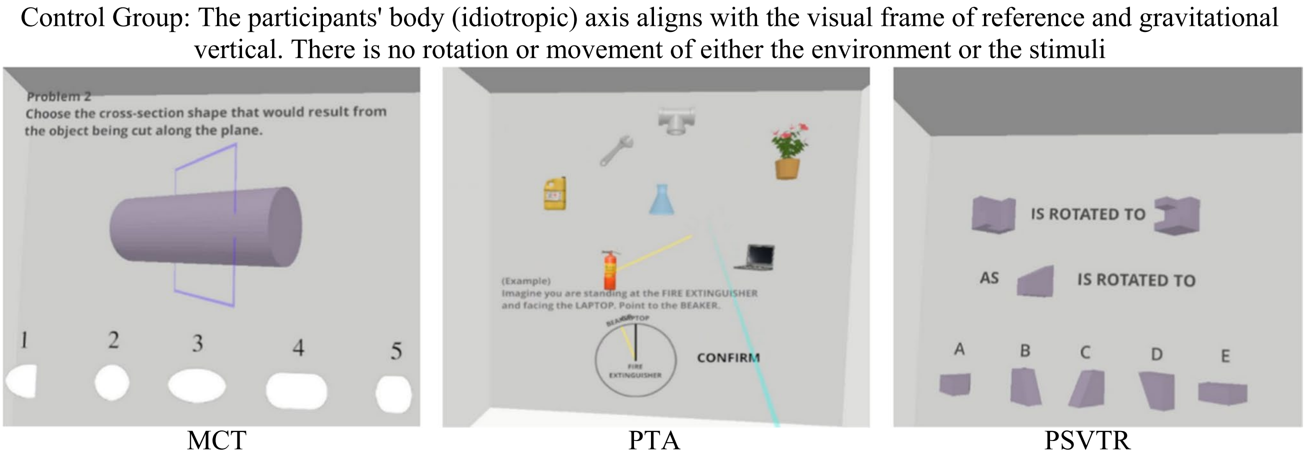

Fig. 1 Tests and respective stimuli examples under the control group condition

environment on a surface. Participants are asked to imagine themselves situated in the place of one of the objects facing another object. They are then asked to point in the direction of a third object. Scores are based on how far an individual's answer deviates from the correct direction in sexagesimal degrees. In other words, a lower value means a smaller deviation and a higher score on the PTA task. Understanding how an environment looks from different perspectives requires different skills than being able to transform individual objects spatially.

2.3 Study environment

A Unity 3D game engine was used to create the VR environments with spatial test stimuli to depict the three conditions (Hier and Crowley Jr 1982). The first condition denoted an earth-like setting with the participants' body (idiotropic) axis aligned with the visual frame of reference and vertical. The second and third conditions simulated visual environments that may exist under microgravity conditions. In the second condition, the idiotropic axis was misaligned statically at a random angle either in the X, Y, or Z axis. In the third condition, however, the misalignment was dynamic. In other words, the misalignment kept changing with the spatial environment randomly rotating around the X, Y, or Z axis. Participants tested under the first condition were designated as the *control group (CG)*, whereas those under the second and third conditions were the *experiment group I (EG 1)* and *experiment group II (EG2)*, respectively. The alignment of the visual and idiotropic axes distinguished the control from the two experiment groups. Figures 1, 2 and 3 show screenshots of the three VR settings with test stimuli. In each session, participants were seated upright on a swivel chair, although the stimuli and the spatial environment rotated either statically or dynamically in VR. The axes were aligned in the control group, *CG*, but not in the experiment

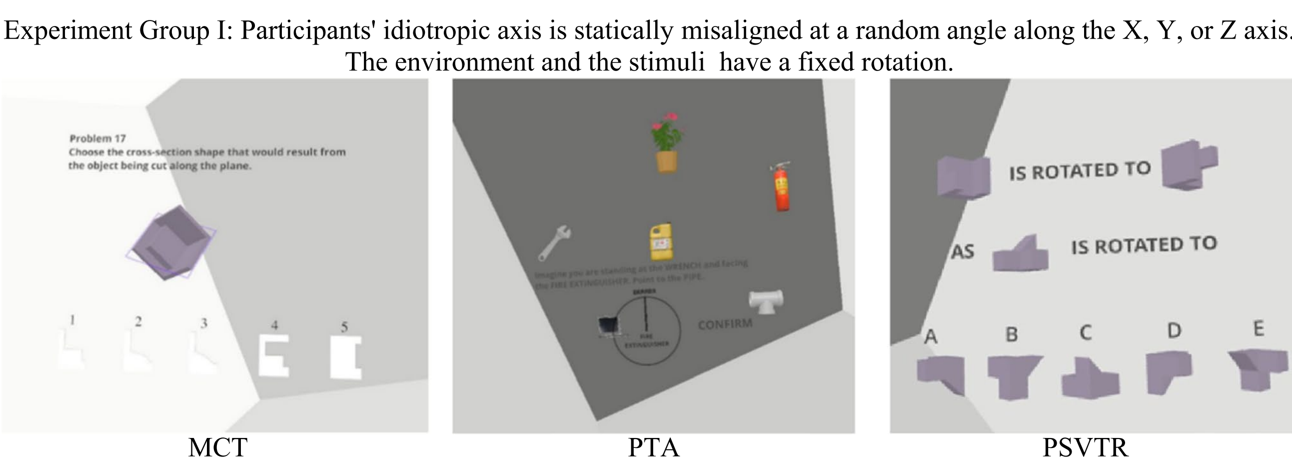

Fig. 2 Tests and respective stimuli examples under the Experiment Group I condition

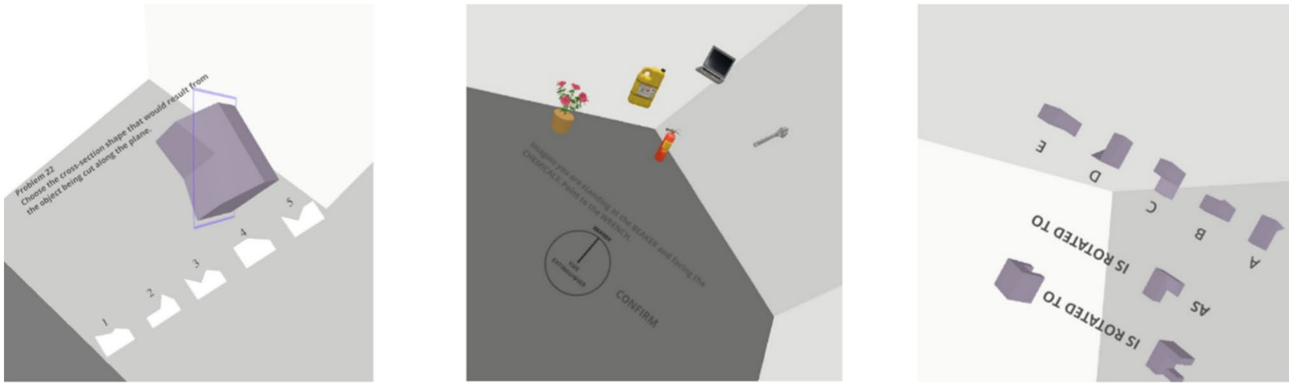

Fig. 3 Tests and respective stimuli examples under the Experiment Group II condition

Table 2 Spatial tasks for different experiments

	CG1	EG1	EG2
PSVT: R	N1	N2	N3
MCT	N2	N3	N1
PTA	N3	N1	N2

groups. *EG1* represents a static non-alignment of axes, whereas *EG2* is a dynamic misalignment of axes; Table 2 shows the number and types of spatial tasks for experiment and control groups. Participants were randomly divided into the three groups, as shown in Table 2 (e.g., N1, N2, and N3) and a group was randomly assigned to each of the control and experiment groups to prevent participants from working on the same spatial task repetitively. None of the participants repeated a test under the three conditions.

2.4 Procedures and data collection

A schematic flow diagram of the experiment procedures is shown in Fig. 2. To familiarize participants with the tests, apparatus, and experiment instructions, an introductory session was conducted ahead of the test. After they consented to participation, they were given two surveys. In the first one, they provided demographic and other information such as their major and hobbies. During the second survey, they provided a prediction of how they would feel during the test, such as if they expected headaches or fatigue to occur. They assigned a score between 0 and 5 for each question. All experiments were conducted in a room with white walls at a set temperature and humidity. Through Virtual Environments (VE) created in Unity 3D, the participants sat upright in a swivel chair and completed the three tests in VR by wearing an integrated HTC VIVE Pro Eye Head-Mounted Display (HMD). All tests required participants to choose from a set of options and record their choices via a hand-held controller. During each test, data were collected by trained graduate students. For the tests, correct/incorrect answers and response time were collected automatically in a spreadsheet through a programming script. Participants' responses to the two surveys were also gathered in a spreadsheet. Graduate students ensured that both the hardware and software functioned properly during the sessions. After the Intervention, the survey was again administered to participants so their responses could be compared before and after the test. Team members removed the participants' headsets and caps and gave them wipes and napkins to clean up. Cleaning supplies, such as soaps, hand sanitizers, and paper towels were provided.

2.5 Data analysis

A total of 27 females and 72 males participated in the study. Some participants missed answering all the questions, with most missing less than 8% of the questions on a test. Three participants missed 8%, 16%, and 56% of the questions on a test; the participant missing 56% was removed from the data set. Statistical differences and correlations were computed between the control and experiment groups, as well as between gender and age subgroups. The difference in test scores between control and experiment groups by age and gender was determined with an independent-samples t-test or Mann–Whitney U test (when two subgroups existed) and a one-way ANOVA or Kruskal–Wallis H Test (if more than two subgroups existed). Correlation analysis of the six test conditions was performed as well as one of the test parameters (e.g., rotation angle versus response time). On the MCT and PSVTR tests, there were 25 tasks with options.

Participants received 1 for each correct answer and 0 for each incorrect answer. Each PTA test consisted of 36 tasks, and the angular distance from the correct answer was calculated for each response. The mean of the 36 angular distances was calculated as a factor reflecting the participant's performance on the test. The lower the mean, the more accurate the performance. Response time was defined as the amount of time spent on each test.

2.6 Limitations

There are certain limitations of the presented research. First, participants may tire of wearing VR headsets for a long time; this issue may moderate results, which is not examined in this study. Also, despite the dominance of immersive VR settings of microgravity, participants still received gravitational feedback, which could have a minor effect on results. Second, the controlled laboratory setting might limit the ecological validity of the findings, as real-world spatial challenges often involve dynamic and unpredictable elements not present in the study's controlled environment. Other spatial features such as light quality, shadow pattern, and spatial objects typically present in real-world settings (e.g., wires, pipes, airlocks, handles on International Space Station) may also confound the results. These limitations must be addressed in future research. Finally, the sample size of 100 participants may not enable generalization of results.

3 Results

The collected data were first analyzed for significant differences in the response accuracy of the control group, experiment group I, and experiment group II in MCT, PSVTR, and PTA tests. A one-way analysis of variance (ANOVA) can determine whether there are statistically significant differences among the means of three independent groups in each test when the required assumption of the test is met. As seen in Fig. 3, no outliers exist in any independent variable group in the MCT test. The Shapiro–Wilk Test results indicate that the dependent variable is normally distributed in each group since all p values are greater than 0.05. Levene's test results show that the assumption of homogeneity of variances is met since the p value is greater than 0.05.

As Table 3 represents, no statistically significant differences exist among the MCT scores of participants from the control and the two experiment groups as determined by one-way ANOVA ($F(2,96) = 2.390$, $p = 0.097$). This means that the misalignment of idiotropic and visual axes may not influence spatial relations and visualization performance as determined by the MCT test.

As Fig. 4 shows, no outliers exist in any independent variable group in the PSVTR test. However, the Shapiro–Wilk Test results indicate that the data significantly deviate from a normal distribution since two p values are below 0.05.

This means all required assumptions of one-way ANOVA are not met. As a result, the required assumption for Kruskal–Wallis H Test was checked. According to

Table 3 Checking for significant differences in the response accuracy of the three groups in the three tests

Spatial visualization test	Statistical test	*P* value	Post hoc test	Sample 1–sample 2	*P* value
MCT	One-Way ANOVA	.097	N/A	N/A	N/A
PSVTR	Kruskal–Wallis H Test	0.002	Dunn's Post Hoc Test	Experiment group II–Control group	.086
				Experiment group II–Experiment group I	.000
				Control group–Experiment group I	.074
PTA	Kruskal–Wallis H Test	0.016	Dunn's Post Hoc Test	Control group–Experiment group I	.155
				Control group–Experiment group II	.004
				Experiment group I–Experiment group II	.147

Fig. 4 Experiment procedures

the Levene's test results, the assumption of equality of variances is met since the p value is greater than 0.05. The Kruskal–Wallis H test showed a statistically significant difference in accuracy score of the PSVT: R test among the three groups ($\chi^2(2) = 12.267$, $p = 0.002$) (Table 3) with a mean rank accuracy score of 49.83 for the control, 62.44 for the experiment group I (static misalignment), and 37.73 for the experiment group II (dynamic misalignment). Dunn's post hoc test results indicate only a statistically significant difference between the accuracy mean rank of experiment group I and II: the corresponding p value is below 0.05 (Table 3). Surprisingly, no statistically significant differences were found in the pairwise comparison of the control group with both experiment groups. The pairwise comparison, however, shows that experiment group I answered the questions more accurately than did experiment group II (Fig. 1, supplementary).

Figure 5 shows outliers in all three subgroups in the PTA test, which means all required assumptions of one-way ANOVA are not met. As a result, the required assumption for Kruskal–Wallis H Test was checked. Levene's test results show the assumption of the equality of variances is met since the p value is greater than 0.05. The Kruskal–Wallis H test shows a statistically significant difference in the angular distance mean of the PTA test among the three groups ($\chi^2(2) = 8.245$, $p = 0.016$) (Table 3) with a mean rank accuracy score of 39.88 for the control, 49.94 for the experiment group I (static misalignment), and 60.18 for the experiment group II (dynamic misalignment). Dunn's post hoc test results indicate only a statistically significant difference between the angular distance mean rank of the control group and experiment group II: the corresponding p value is below 0.05 (Table 3). The pairwise comparison, however, shows that the control group answered the questions more accurately than did the experiment group II (Fig. 2, supplementary) (Figs. 6, 7).

Next, the data were analyzed to determine any significant differences in the response times of the control group, experiment group I, and experiment group II on the MCT, PSVTR, and PTA tests. Similarly, the one-way ANOVA or Kruskal–Wallis H Test was used to answer this question. Since all required assumptions of one-way ANOVA were not met for all three tests, the required assumption for Kruskal–Wallis H Test was checked. The Kruskal–Wallis H test shows no statistically significant difference in the response times among the different groups in the MCT test, $\chi^2(2) = 3.077$, $p = 0.215$ (Table 4). The Kruskal–Wallis H test further indicates that the response time on P SVT:R test did not differ significantly across the three groups ($\chi^2(2) = 2.848$, $p = 0.241$) (Table 4). According to the results of the Kruskal–Wallis H test for the PTA response times, no statistically significant differences exist among the three groups ($\chi^2(2) = 5.198$, $p = 0.074$) (Table 4). The results indicate the misalignment of the idiotropic and visual axes may not influence response times on the three tests. The study further examined interconnectedness between the participants' accuracy/angular distance and response times on MCT, PSVTR, and PTA tests. The Pearson's correlation

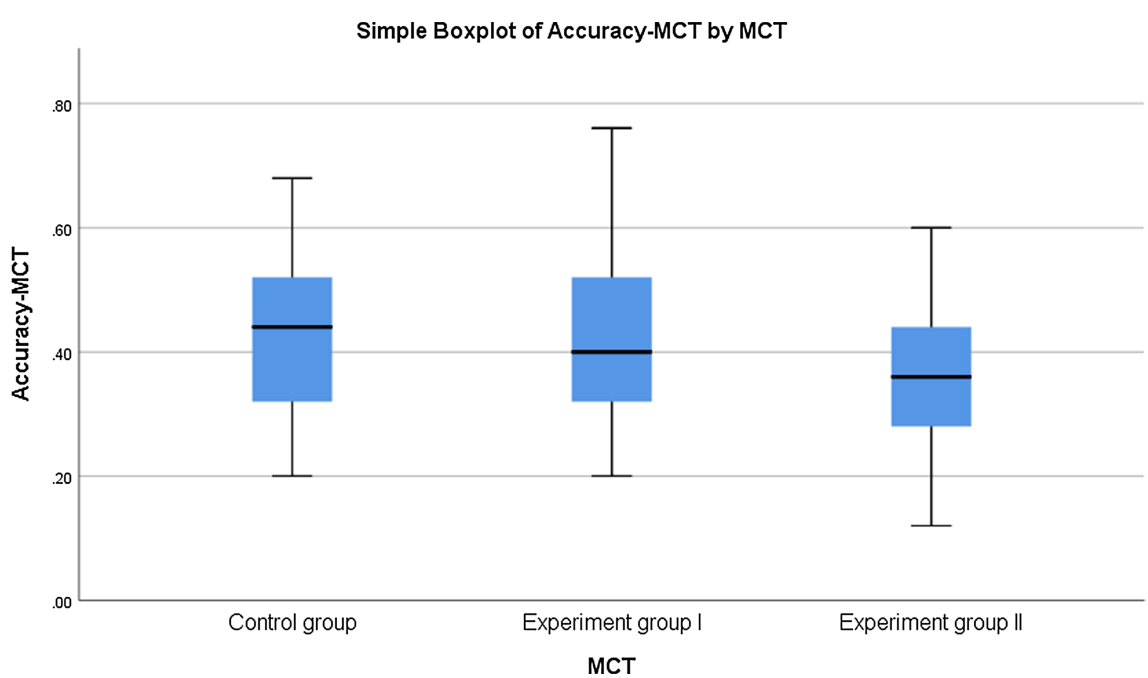

Fig. 5 Boxplots for each independent variable group in the MCT test

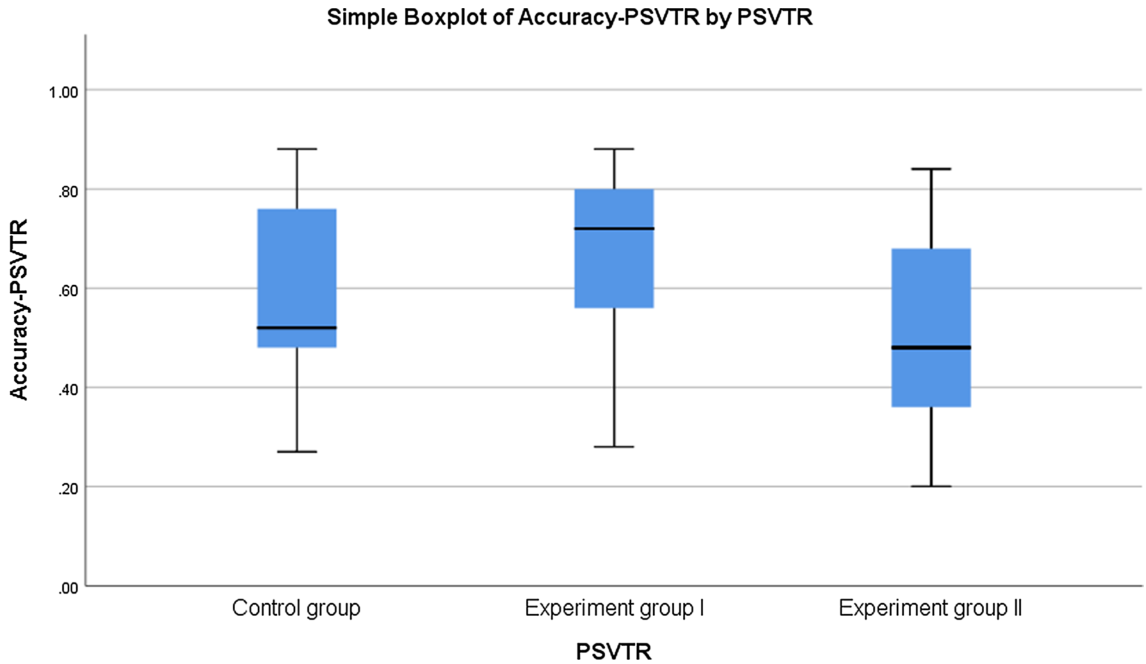

Fig. 6 Boxplots for each independent variable group in the PSVTR test

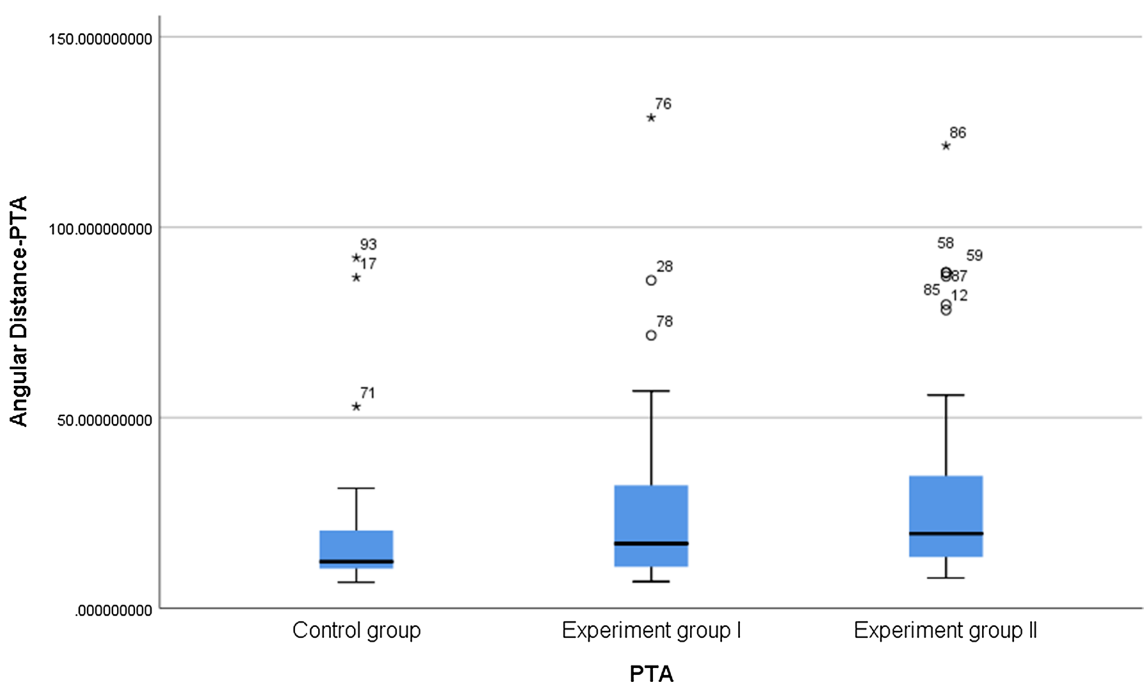

Fig. 7 Boxplots for each independent variable group in the PTA test

could be used to understand whether there is an association between accuracy/angular distance and response time. It is only appropriate to use Pearson's correlation if the data pass the four assumptions required for Pearson's correlation to give a valid result. As shown in Figs. 3–5, supplementary, there is no linear relationship between the accuracy/angular distance and participants' response times in MCT, PSVTR, and PTA tests. As a result, there is no reason to use Pearson's correlation to measure the strength and direction of associations that do not exist between the two variables.

Table 4 Checking for significant differences in the response time of the three groups in the three tests

Spatial visualization test	Statistical test	*P* value
MCT	Kruskal–Wallis H Test	.215
PSVTR	Kruskal–Wallis H Test	.241
PTA	Kruskal–Wallis H Test	.074

Next, data were examined to see if this interconnectedness of accuracy/angular distance and response time differs within groups, across different tests, and between control and experiment groups. Similarly, Pearson's correlation could be used to understand whether there is an association between accuracy/angular distance and response times within groups, across different tests, and across experiment groups. As shown in Figs. 6–14, supplementary, there is no linear relationship between accuracy and participants' response times in the control group, experiment group I, and experiment group II in the MCT test, PSVTR test, and the PTA test. While none of the scatterplots are similar, they all indicate no linear relationship between accuracy and response times within groups, across different tests, and between experiment groups.

We also analyzed gender effects on participants' performance. A point-biserial correlation can be used to determine any association between participants' accuracy scores and gender. A point-biserial correlation is a special case of Pearson's correlation, applied when one variable is continuous and the other is measured on a dichotomous scale. The Point-biserial correlation results indicate no statistically significant association between participants' accuracy scores in the MCT test and gender since the p value is greater than 0.05 (Table 5). For the PSVTR test, since all the required assumptions of Point-biserial correlation are not met, either the independent-samples t-test or the Mann–Whitney U test should be used to compare differences between genders. However, the normal distribution of the dependent variable for each independent variable group is one of the required assumptions of the independent-sample t-test, which is not met. As a result, the required assumption for the Mann–Whitney U test was checked. Levene's test results show that the assumption of the equality of variances is met since the p value is greater than 0.05. The Mann–Whitney U test shows no statistically significant difference in accuracy between genders in the PSVTR test, $p = 0.128$ (Table 5). For the PTA test, the assumptions of neither the point-biserial correlation nor the independent-samples t-test are met. However, the required assumption for the Mann–Whitney U test is met. Levene's test results show the equality of variances is met since the p value is greater than 0.05. The Mann–Whitney U test results indicate males' performance was statistically significantly better than females' in the PTA test ($U = 650.000$, $p = 0.011$) (Table 5).

We also examined whether individual differences such as age affected participants' performance. Pearson's correlation could be used to measure any association between participants' accuracy scores and age. As shown in Figs. 15–17, supplementary, no linear relationship exists between participants' accuracy and age in MCT, PSVTR, and PTA tests. As a result, there is no point in using Pearson's correlation to measure the strength and direction of associations that do not exist between the two variables. Finally, we tested whether participants' age group affects their performance. The Terrell-Scott rule determines the number of intervals (age groups): at least (2n)^1/3 class intervals are required, where n is the total number of data values. As a result, the number of age groups was considered 5: $(2 \times 33)^{(1/3)} = 4.04$. The age groups were set as follows: (18–24), (25–31), (32–38), (39–45), and (46–52). Based on the data characteristics, the one-way ANOVA or Kruskal–Wallis H Test was used to determine any statistically significant differences among the means of the five age groups in each test. For all three tests, since the required assumption of one-way ANOVA was not met, the required assumption for Kruskal–Wallis H Test was checked. The Kruskal–Wallis H test shows no statistically significant difference in accuracy scores among the different age groups in the MCT test ($p = 0.133$), PSVT:R test ($p = 0.217$), and the PTA test ($p = 0.737$) (Table 6).

Table 5 Checking for significant differences in the response accuracy between genders in the three tests

Spatial visualization test	Statistical test	*P* value	Angular distance mean rank	
MCT	Point-biserial correlation	.203	N/A	
PSVTR	Mann–Whitney U Test	0.128	N/A	
PTA	Mann–Whitney U Test	.011	Male	45.53
			Female	61.93

Table 6 Checking for significant differences in the response accuracy between different age groups

Spatial visualization test	Statistical test	*P* value
MCT	Kruskal–Wallis H Test	0.133
PSVTR	Kruskal–Wallis H Test	0.217
PTA	Kruskal–Wallis H Test	0.737

4 Discussion

The results of this study indicate no statistically significant differences among the control and the two experiment groups' performance on the MCT test. However, participants' performance on the PSVT: R and PTA tests show statistically significant differences among the three groups. Pairwise comparison demonstrates that experiment group I performed better than experiment group II on PSVT: R tasks. On the other hand, the control group outperformed experiment group II on the PTA test. Understanding these results through the nature of the tests is important. For instance, the three tests differ in terms of frame of reference (FOR) in that the PSVT: R and MCT tests are object based, whereas the PTA test applies an egocentric encoding (Lowrie et al. 2017; Tito et al. 2021). The relationship of objects and spatial environment (or visual FOR) changes in mental rotation tasks, such as those in the PSVT: R tests, may be affected more by the transformation of the visual FOR. This may help explain why participants' performance on static misaligned FOR was better than the dynamic misalignment, which continually changes the object-FOR relationship. This might also illuminate why there was no statistically significant difference in the performance of the control group and the experiment group, both of which have a fixed stimulus-FOR relationship.

The results suggest males outperform females in PTA tasks, whereas no gender difference was found in PSVT: R and MCT tasks. Gender differences have been found in several studies examining large-scale and small-scale spatial abilities (Nagy-Kondor and Esmailnia 2022; Yuan et al. 2019). For instance, tasks such as spatial orientation and navigation involve a person applying spatial cognitive processing in large-scale environments; such tasks, therefore, require large-scale spatial abilities. In large-scale tasks, a participant's viewpoint changes (Tito et al. 2021; Yuan et al. 2019), whereas in small-scale tasks they apply the same viewpoint to envision different spatial representations of 2-D and 3-D objects. Studies have found that gender differences in large-scale spatial tasks are greater than in small-scale tasks favoring males in spatial performance. Our results agree with these findings as no statistically significant differences were found in the accuracy scores of males and females for PSVT: R and MCT tasks that represent small-scale tasks (Castro-Alonso and Atit 2019). However, in the case of the PTA test, which measures spatial orientation ability, males seem to outperform females in the present study. It has also been reported that small-scale spatial ability shows a much smaller gender difference than for large-scale tasks (Nagy-Kondor and Esmailnia 2022; Yuan et al. 2019), which corroborates our findings of no impact of gender on spatial performance for PSVT: R and MCT tests. On the contrary, females tend to apply an egocentric processing suitable for large-scale tasks. Consequently, their performance on large-scale tasks should be better; however, this is not reflected in this study and may require further research. Yuan et al. (2019) and Gabriel et al. (2011) note this may be due to females' vulnerability to spatial anxiety and their parahippocampal gyrus working "less efficiently than males." Allocentric processing is considered more suitable for small-scale tasks, and females applying egocentric processing to such tasks may result in inferior performance. The results of this study show no gender differences in PSVT: R and MCT test scores, which may also need further investigation. However, it is important to note that males and females may apply diverse spatial strategies (egocentric vs. allocentric) and may show a varied level of performance on both large-scale and small-scale tasks ranging from no gender difference to either males or females performing better (Gabriel et al. 2011; Hoffman et al. 2011; Newell et al. 2011; Rilea 2008; Yuan et al. 2019).

The results of this study indicate no impact of statically or dynamically misaligned idiotropic and visual axes on the spatial ability of spatial relations as measured by the MCT test. This misalignment, however, influenced the spatial visualization and orientation abilities measured using the P SVT:R and PTA tests, in which participants in the dynamically misaligned group (experiment II) performed more poorly than the static misalignment (experiment I) and control groups, respectively. Studies such as Dyde et al. (2009) and Dye et al. (2009) have examined how the perceptual vertical is impacted by different orientations of visual backgrounds in altered gravitational conditions produced during lying supine and parabolic flights. Their results indicated that the impact of visual background orientations on the perceptual upright was less in microgravity conditions than in normal conditions. This might explain our finding of no significant differences in the results of the control group and the experiment groups I and II for the PSVT: R, a small-scale spatial test. Jenkin et al. (2011) studied perceptual upright in microgravity, hypo-gravity, hyper-gravity, and normal conditions under static and dynamic visual cues. The dynamic orientation cues were provided through a video clip, whereas static cues were given through a static frame drawn from the video clip. Their study found that gravity conditions did not influence the visual effect. Dynamic visual cues increased the vision effectiveness to identify the perceptual vertical. They further discussed why dynamic cues may enhance visual cues to a greater degree as compared to static cues. Dynamic conditions may improve visual effectiveness through enhanced depth information. Moreover, motion is preferred by the visual inputs represented by the ventral intraparietal (VIP) substructure of the brain to create a mental representation of an allocentric spatial environment

(Jenkin et al. 2011; Schlack et al. 2005; Zaehle et al. 2007). In other words, motion may moderate the process of identifying the direction of perceptual vertical. This might indicate why this study found no statically significant difference between the control group and experiment group I, but a significant difference between the results of the control group and experiment group II. The only difference in experiment group II is the motion of the visual frame of reference. However, we need to explain and understand why there was no difference in spatial test results between experiment groups I and II in the PTA test. One possible explanation is that both experiment groups experienced misaligned visual and idiotropic axes, and since motion may improve visual effectiveness, it may have compensated for the challenges associated with dynamically misaligned visual and idiotropic axes. Even though no significant differences in certain dimensions of spatial ability existed among the control and experiment groups, there may be more mental allocation needed in certain conditions, which must be measured in future research. In addition, examining and understanding participants' spatial strategies on the three tests under the three conditions through techniques such as eye-tracking may yield important insights into why participants' performance is more impacted by the rotation of the visual FOR.

5 Conclusions

The findings of this study demonstrate that spatial relations performance in terms of both accuracy and response time measured through the object-based MCT test may not be impacted by either a static or dynamic misalignment of visual and body axes. However, this dynamic misalignment of the axes may influence human spatial orientation and spatial visualization performance in terms of accuracy. The key difference here is the random movement of the visual FOR, which may moderate spatial cognitive processing. In all three tests, neither static nor dynamic misalignment of visual and body axes affected participants' response times. There was no gender difference found in the accuracy and response time of participants on the MCT and PSVT: R tests. This was not the case in the PTA test results, which showed males performing better than female participants. Participants' age made no difference in the spatial test performance on all three tests. There were no correlations between accuracy and participants' response times on all three tests. These results are significant for the safety and productivity of workers who may work in altered visuospatial conditions of future settings, such as those existing on other planets and the International Space Station (ISS) and in deep sea, polar, and military operations.

6 Future research direction

While the sample size of 100 participants is relatively large, future research could benefit from a broader and more diverse group of participants to enhance the generalizability of the results. Moreover, the use of specific spatial tests might not fully capture the complexity of real-world spatial tasks, suggesting the need for a wider range of spatial assessments in future studies to gain more comprehensive insights. Additionally, future studies could explore how this knowledge can be turned into action, developing tools to train broad populations to work safely and productively in such altered conditions.

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Data availability As a result of the study's nature, ethical approvals, and the sensitivity of the data, raw data cannot be shared.

Declarations

Conflict of interest The authors declare no conflict of interest (financial or otherwise) related to the work submitted for publication.

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