

Understanding Spatial Abilities and Spatial Strategy under Extreme Visual and Gravitational Environments

Hannah Park¹; Manish Dixit²; Nafiseh Faghihi³; Ann McNamara⁴; and Jyotsna Vaid⁵

¹Dept. of Construction Science, Texas A&M Univ., College Station, TX. Email: hnpark@tamu.edu

²Dept. of Construction Science, Texas A&M Univ., College Station, TX. Email: mdixit@tamu.edu

³Dept. of Psychological and Brain Sciences, Texas A&M Univ., College Station, TX. Email: nafisehfaghihi@tamu.edu

⁴Dept. of Visualization, Texas A&M Univ., College Station, TX. Email: ann@viz.tamu.edu

⁵Dept. of Psychological and Brain Sciences, Texas A&M Univ., College Station, TX. Email: jvaid@tamu.edu

ABSTRACT

The purpose of this study is to understand how spatial ability differs under extreme environments and to provide implications on individually relevant training approaches by using VR technologies. Special jobs under extreme conditions (e.g., astronaut or scuba diver) demand higher spatial ability and effective spatial strategy. This paper examines how the conflicts between visual vertical and the body vertical may affect spatial ability. In addition, the study tested the relationship between an individual's tendency to adopt a certain spatial strategy (egocentric vs. allocentric) and their use of a particular spatial reference frame (body vs. visual) under the extreme condition.

INTRODUCTION

With emerging new technologies, the future of work is being transformed and will involve the exploration of desolate and hard to reach altered environments such as space, deep ocean, and polar regions (Clément et al., 2015; Stapleton et al., 2016; Kanas, 2015; Marin & Beluffi, 2018; Smith, 2014; Tiziani, 2013). Such environments pose extreme visual or gravitational conditions that may affect our ability to work safely and productively. Two commonly reported difficulties adversely influencing work performance and worker safety include: (1) misaligned body and visual axis due to weightlessness (e.g. visual reorientation illusion), and (2) absence of familiar visuospatial cues (NASA, 2015; Zhu et al., 2011). Failure to create a clear spatial representation of space could result in poor performance and even risk of injury under such conditions (Zhu et al., 2011). Therefore, reliable training technologies for workers to adapt to extreme environments must be developed in order to generate significant benefits in such work domains (London et al., 2017; Clément et al., 2015; Bertels, 2006; NASA, 2015). Although extreme environments have various environmental conditions that might affect work performance (e.g. temperature), this study addresses the following kinds of extreme settings: spaces with conflicting body and visual orientation.

The main knowledge gaps addressed in this paper are summarized as follows. First, this study empirically demonstrates how extreme conditions, particularly, with conflicting visual and body verticals affect a specific dimension of spatial ability. While some studies have

experimented with spatial abilities in conditions where a visual orientation is upright (e.g., Matsakis et al. 1993; Leone et al. 1995), in extreme environments, a visual reference frame may not always be upright and can constantly change with time (Harris et al., 2017; Kanas, 2015). Moreover, spatial ability consists of two major dimensions including object manipulation ability and spatial orientation ability (Hegarty & Waller, 2004; Gagnon, 1985; Ray et al, 1981; McGee, 1979). Most of the research on spatial ability under extreme environment, however, has been focused on object manipulation ability (e.g. mental rotation test), and less attention has been paid to spatial orientation ability (Matsakis et al., 1993; Leone et al, 1995).

Second, this study will investigate the relationship between individual's tendency to adopt a certain spatial strategy (egocentric vs. allocentric) and their use of spatial reference frame (body vs. visual) under such conditions. A recent study suggested that there might be an individual characteristic that favors a specific reference frame over another when acquiring spatial representation (Gramann, 2013; Gluck & Fitting, 2003). The spatial strategy indicates the process of encoding spatial information to construct an accurate spatial representation (O'Keefe & Nadel, 1978). Depending on the spatial reference frame that one relies on, a spatial strategy can be of two types: egocentric or allocentric. An egocentric strategy involves updating the position of objects in a spatial environment relative to one's body reference frame. An allocentric strategy, on the other hand, updates the position of objects with respect to the visual frame of reference including other objects in the environment (Kozhevnikov & Hegarty, 2001). Although some studies have proposed the existence of reliable individual differences in spatial strategy usage, they have not been empirically tested (Gramann, 2013; Gluck & Fitting, 2003).

The purpose of this study is to understand how extreme conditions with statically and dynamically conflicting visual and body orientation influences spatial ability. The study also investigated the relationship between a tendency to adopt a certain spatial strategy (egocentric vs allocentric) and the use of a certain spatial reference frame (body vs. visual) under such conditions. We contend that identifying individual differences in spatial strategy preference could help guide training methods for working under extreme conditions.

RESEARCH METHODS: STUDY DESCRIPTION

Participants. Thirty-two participants (20 males and 12 females) at Texas A&M University with normal or corrected-to-normal vision took part in the study. All participants were recruited through a notice sent in the university's email system. Participants were undergraduate students, graduate students, and doctoral researchers. Their ages ranged from 18 to 39 years old, with a mean age of 24.8 (SD=6.27). All the participants provided written consent prior to the study and research was carried out in agreement with the Institutional Review Board of Texas A&M University. Study participation was voluntary.

Study Environment. The study environments were created in the Unity game engine (<http://unity3d.com/>) which allows creating and running games in customized environments and writing codes for desired performance (Unity 3D, 2019). We created a cubical virtual room with a space shuttle-like interior (Figure 1. left). All four walls of the space were covered with the same texture and color. The ceiling contained a brighter shade in order to match the general "light-from-above" heuristic (Champion & Adams, 2007). The floor of the room was covered with darker metal textures. We intentionally used the distinct texture and color for the floor, walls, and ceiling to give a clear surface identity, which also helped replicate the real work environment such as Russian Mir Station which has modules with dark floors and light ceilings (NASA, 1995).

In order to test how misalignment of the visual axis and body axis affects the spatial ability, we created three environmental conditions. The first condition was a *Normal* condition in which the body axis of a subject was aligned with the visual axis. This condition served as the control for the other two conditions. The second condition was a *Static* condition in which the visual axis tilted at a randomly chosen fixed angles while the subject's body axis was upright. The tilting angles ranged from -90 degrees to 90 degrees in 15-degree intervals. The angle for x , y , and z axes were chosen within the range by using a random number generator. The third condition was a *Dynamic* condition in which the visual axis (the VR room) was programmed to continuously rotate randomly around x , y , and z axes while the subject was seated upright (see Figure 1. right).

During the experiments, the participants sat erect in a swerve chair and viewed the interior of a virtual module through a high-resolution (640 X 480 pixels per eye) color stereo head-mounted display (HTC Vive) that had a 60-degree diagonal field of view and 100% stereo overlap. Participants were free to look around the virtual environment while seated on the chair during the experiments.

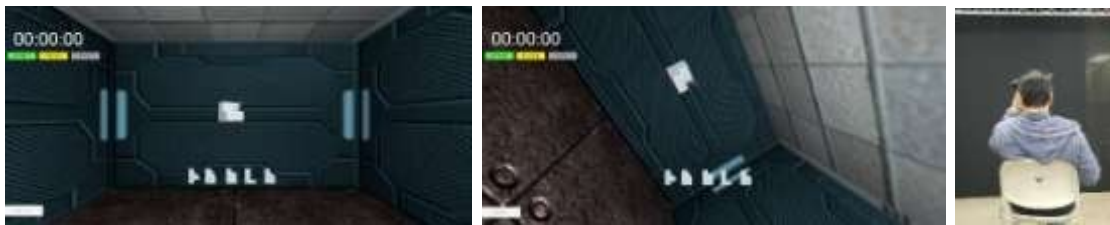


Figure 1. VR Study Environment: Aligned (left), Misaligned (middle) Condition.

Tasks. Participants completed the following individual tasks:

The *Navigation Strategy Questionnaire* (NSQ: Zhong, 2013; Zhong & Kozhevnikov, 2016) measures individual everyday spatial strategy. The NSQ was designed to assess the strategies that different individuals engage in when they encode environmental information. There were 44 items assessing the individual preferred spatial updating strategies including 12 survey strategy items, 17 egocentric survey strategy items and 15 route strategy items. **Survey strategy** refers to the use of Euclidean information of space such as cardinal/compass direction and exact distances (e.g. “*I tend to judge my orientation in the environment in terms of cardinal directions (north, south, east, and west)*”). **Egocentric-survey strategy** also refers to the use of Euclidean information of space. The difference between survey strategy and egocentric survey strategy is “field perspective” (Zhong, 2013). **Egocentric spatial strategy** relies on the first-person perspective, whereas survey strategy relies on a top-down perspective (e.g. “*I can point to the exit after several turns in a building without relying on salient landmarks/objects as points of reference.*”) **Route strategy** refers to a reliance on environmental information such as visible signs, landmarks or direction of turn (e.g. “*When I navigate, I pay attention to the landmarks at the turning points and try to remember their sequence*”).

The *Mental Cutting Test* (MCT: Vandenberg & Kuse, 1978) and *Purdue Spatial Visualization Tests: Visualization of Rotation* (PSVT: R) measure object manipulation abilities. The MCT requires participants to view different 3D stimuli being cut with

slanting planes at different angles along with five 2D answer choices. In this test, participants were asked to imagine the cut sectional profile and select a matching 2D view. In PSVT: R, participants were asked to imagine rotated versions of three-dimensional objects in the same direction as visually indicated in the instructions. The participants then selected the right answer from the given five choices.

The *Perspective Taking Ability* (PTA: Kozhevnikov & Hegarty, 2001) is a measure of spatial orientation ability. In this test, a set of seven objects is presented and participants are asked to imagine themselves standing at one object facing another object and indicate the angle to a third object by drawing a line on the answer sheet (e.g. *Imagine you are standing at the Yellow facing Red, point to the Blue.*). The original test has seven objects such as a house, traffic lights, tree, etc. We used seven different colored spheres (with no top and bottom) in order to avoid implying to the participants the direction of the top and bottom of the space. The participants were prevented from physically rotating their answer sheets.

The *Subjective Vertical* test was conducted as an informal interview to identify whether participants rely on the visual axis or body axis for the spatial reference frame. In this test participants were asked to point to the floor of the space at the end of the *Dynamic* and *Static* condition. More specifically, the participants were told: "Please point to the floor of this room and explain why."

For all three psychometric spatial ability tests (MCT, PSVT: R and PTA), the traditional paper-based items were digitized and integrated into the developed environments in VR. Since the discomfort is often experienced within 10 minutes of the tests, we limited testing to only 5 items, which took no more than 10 minutes. This was done to minimize simulation sickness. In an earlier pilot study with 25 participants involving traditional paper-based spatial tests, we found that the error rate of participants was 30% for some task items and 60% for others, and we designated these items as easy and difficult, respectively. Accordingly, we included 2 easy and 3 difficult tasks in the 5 test items. Although there was no time limit for all three spatial ability tests, no subject took more than 10 minutes to finish each test.

Procedure. All participants were tested individually, and the total study duration was approximately one hour. At the beginning of the study, participants completed a demographic questionnaire followed by the NSQ on the computer. Next, the investigator briefly introduced the VR study tasks.

Design of VR Study. All participants were randomly assigned to one of three test groups. Each group participated in all environmental conditions (*Normal*, *Static* and *Dynamic*) but performed only one spatial task (MCT, PSVT: R and PTA). We took this approach because of two reasons. First, we wanted to avoid the participants repeating the same spatial test to minimize a practice effect. Second, we wanted to minimize the simulation sickness that might be caused by long exposure in VR environments, especially under the *Dynamic* condition. Thus, with this study design each participant did only one spatial test at each environmental condition.

FINDINGS AND DISCUSSION

Spatial Ability in Altered Environments The dependent variable used in MCT and PSVT analyses was accuracy, coded as correct or incorrect. In PTA analysis, the dependent variable was calculated based on the number of degrees of deviation from the correct response. As smaller deviations showed better performance, we reversed this relationship by subtracting each response deviation from 360°. After this operation, larger numbers would show better performance. Each row in the data set belonged to a single response from a participant for each item of a spatial ability task.

The coded data were then submitted to Generalized Linear Mixed-effects Model (GLMM) for MCT and PSVT, and Linear Mixed-effects Model (LMM) for PTA to examine the effect of Normal versus Static or Dynamic condition on each spatial ability performance. The analyses were conducted in R (R version 3.5.2; R Development Core Team, 2018) using the lme4 package (version 1.1.20; Bates, Maechler, Bolker, & Walker, 2015). We included test items as a random effect to account for the variance coming from different levels of difficulty of the test items. In addition, participants were added as another random effect due to the different levels of spatial abilities among them. For instance, some participants may have had experiences in jobs that improved their spatial abilities. Moreover, some participants may come from educational backgrounds that required taking courses that were focused on sharpening some aspects of spatial abilities.

In all following reports of mixed-effects analyses for each spatial ability task, the base model consisted of the random intercepts of test items and participants as well as the fixed effect of condition (*Normal*, *Static*, or *Dynamic*), which is the main predictive variable of interest in this study. Other variables were tested in comparison models against the base model and improvement to the model fit was assessed using a chi-square analysis on the -2LogLikelihood (ΔLL) change in model fit.

Table 1. Summary of the GLMM for Random Effect of MCT Items and Fixed Effect of Environment Condition.

Predictors	Accuracy	SE	z-value	p
	Odds Ratios			
Intercept	0.26 (0.12 – 0.55)	0.38	-3.54	< .001*
Normal vs. Dynamic	0.51 (0.21 – 1.27)	0.46	-1.44	0.15
Normal vs. Static	2.29 (0.97 – 5.39)	0.44	-1.90	0.058 ⁺
Dynamic vs. Static	1.18 (0.46 – 2.98)	0.47	0.34	0.73
N Test items	5			
Test items	SD = 0.44, SD ² = 0.2			
Marginal R ² / Conditional R ²	0.036 / 0.091			

Note: The numbers in parentheses represent confidence intervals for *Odds Ratios*

+ approached significance, * $p < .05$

MCT. As the base model did not converge, the random effects of items and participants were removed in separate efforts to see which change would help the model to converge. Removing the random effect of participants resulted in model convergence. So, the analysis was continued by a beginning model consisted of the random intercept of stimuli items and the fixed effect of condition.

Taking a forward selection approach, each of the random slopes of test items and participants were added in a comparison model but none of them converged. The beginning model was then compared to comparison models by adding gender and subjective vertical of participants in separate steps. Neither gender nor subjective vertical could improve the model. In the final model, which was the same as the beginning model- only the difference between performance in Normal (38% correct) versus static (21.7% correct) conditions approached significance. See Table 1 and Figure 2 (Left) for a summary of the results.

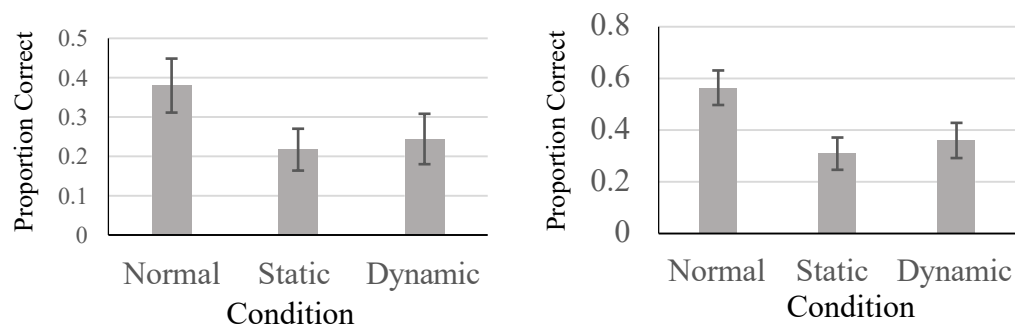


Figure 2. (Left) Proportion of correct answers in MCT per environmental condition. (Right) Proportion of correct answers in PSVT per environmental condition. Error bars represent SE

PSVT. Taking a forward selection approach, each of the random slopes of stimuli items and participants were added to the base model in a comparison model but none of them converged. The base model was then compared to comparison models by adding gender and subjective vertical of participants in separate steps. Neither of gender or subjective vertical models converged. Thus, the base model remained as the final model. This model revealed significant differences in performance under Normal (56.4% correct) versus Static (30.9% correct) as well as Normal versus Dynamic (36% correct) conditions but no significant difference between Static and Dynamic conditions. See Table 2 and Figure 2 (Right) for a summary of the results.

PTA. Taking a forward selection approach, each of the random slopes of stimuli items and participants were added to the base model in a comparison model but none of them converged. The base model was then compared to a comparison model including gender. Adding gender improved the base model ($\Delta LL=2.53$, $p < .02$) and motivated adding the interaction term between condition and gender. However, the interaction term did not improve the fit of the previous model and was removed. Then, subjective vertical of participants was added in a comparison model but did not improve the model fit. The final model consisted of the random intercepts of stimuli items and participants as well as the fixed effects of condition and gender. This model did not show any significant differences in performance under different conditions, but the significant effect of gender showed that male participants ($M_{\text{accuracy}} = 348.64^\circ$, $SD =$

11.65) outperformed female participants ($M_{\text{accuracy}} = 340.93^\circ$, $SD = 26.82$). See Table 3 and Figure 3 for a summary of the results.

Table 2. Summary of the GLMM for Random Effect of Participants and PSVT Stimuli Items and Fixed Effect of Rotation Condition

Predictors	Accuracy Odds Ratios	SE	z-value	p
Intercept	0.40 (0.16 – 1.00)	0.47	-1.96	0.05*
Normal vs. Dynamic	0.39 (0.16 – 0.92)	0.44	-2.14	0.032*
Normal vs. Static	0.30 (0.13 – 0.72)	0.44	-2.72	0.007*
Dynamic vs. Static	1.29 (0.54 – 3.09)	0.45	0.57	0.57
N Test items	5			
Participants	$SD = 0.19$, $SD^2 = 0.04$			
Test items	$SD = 0.76$, $SD^2 = 0.58$			
Marginal R^2 / Conditional R^2	0.065 / 0.213			

Note: The numbers in parentheses represent confidence intervals for *Odds Ratios*

+ approached significance, * $p < .05$

In summary, the experimental results generally supported our hypothesis: misalignment of the visual axis and body axis creates difficulties in spatial abilities as indicated by a consistently lower score in Static and Dynamic conditions than in Normal condition. This phenomenon significantly appears in object manipulation ability (MCT and PSVT: R) versus spatial orientation ability (PTA).

Table 3. Summary of the LMM for Random Effects of Participants and PTA Stimuli Items and Fixed Effects of Rotation Condition and Gender

(360 – degrees of error)				
Predictors	Estimates	SE	t-value	p
Intercept	341.68 (334.91 – 348.46)	3.46	98.83	<0.001*
Normal vs. Dynamic	-2.27 (-9.32 – 4.79)	3.60	-0.63	0.53
Normal vs. Static	1.14 (-6.72 – 9.00)	4.01	0.28	0.78
Dynamic vs. Static	-3.41 (-10.71-3.90)	3.73	-0.91	0.37
Gender (M vs. F)	-7.46 (1.22– 13.71)	3.19	2.34	0.02*
N Test items	6			
Participants	$SD = 5.681$, $SD^2 = 32.28$			
Test items	$SD = 3.65$, $SD^2 = 13.33$			
Marginal R^2 / Conditional R^2	0.044 / 0.134			

Note: The numbers in parentheses represent confidence intervals.

+ approached significance, * $p < .05$

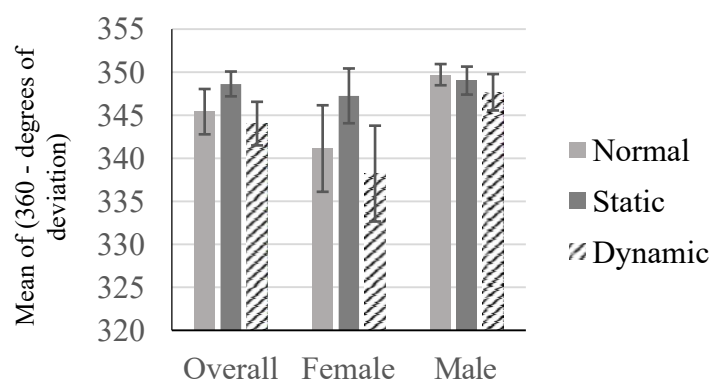


Figure 3. Accuracy of performance in PTA per environmental condition and per gender. Higher bars show better performance. Error bars represent SE

Relationship between the Subjective Vertical Groups and Navigation Strategies. To analyze individual navigation strategy, we summed participants' ratings on statements constituting the three types of strategies (i.e., survey strategy vs. egocentric-survey strategy vs. route strategy). The average ratings for each of the strategies were used for purposes of comparing the three types of strategies. Table 4 presents the descriptive statistics of the three strategy scales separated by subjective vertical groups. Overall, participants reported using route strategies more often than both survey and egocentric survey strategies.

Table 4. Individual Navigation Strategy per Subjective Vertical and Gender Group

Navigation Strategy	Body (n=10)		Visual (n=22)		Male (n=20)		Female (n=12)		Overall (n=32)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Survey *	3.37	0.76	2.98	0.76	3.37	0.76	2.98	0.76	3.22	0.77
Ego Survey *	3.44	0.48	3.00	0.41	3.44	0.48	3.00	0.41	3.27	0.50
Route *	3.65	0.56	3.84	0.58	3.65	0.56	3.84	0.58	3.72	0.47

* Scale ranges from 1 (low) to 5 (high)

To examine the relationship between navigation strategies and subjective vertical, a 3 (ego-survey vs. survey vs. route) x 2 (visual vs. body) mixed-model ANOVA was performed on NSQ scores. The subjective vertical category was the between-subject factor and Navigation Strategy was the within-subject factor. The ANOVA showed a significant interaction between Navigation Strategy and Subjective Vertical, $F(1.86, 55.79) = 6.37, p < 0.004, \eta^2 = 0.18$ (Greenhouse-Geisser corrected). As shown in Figure 4 (the mean NSQ scores were converted to z scores in this figure), this interaction revealed different distributions of NSQ scores across the two subjective vertical groups for each navigation strategy. The consistent use of a certain type of spatial reference frame in both everyday navigation (identified by NSQ) and under extreme conditions (identified by the subjective vertical test) may indicate that an individual would prefer a certain type of spatial strategy. Gramann (2013) proposed that an individual has a certain spatial strategy preference attributed to experience with an environment, biological factors, language and/or geographical region the one lives in.

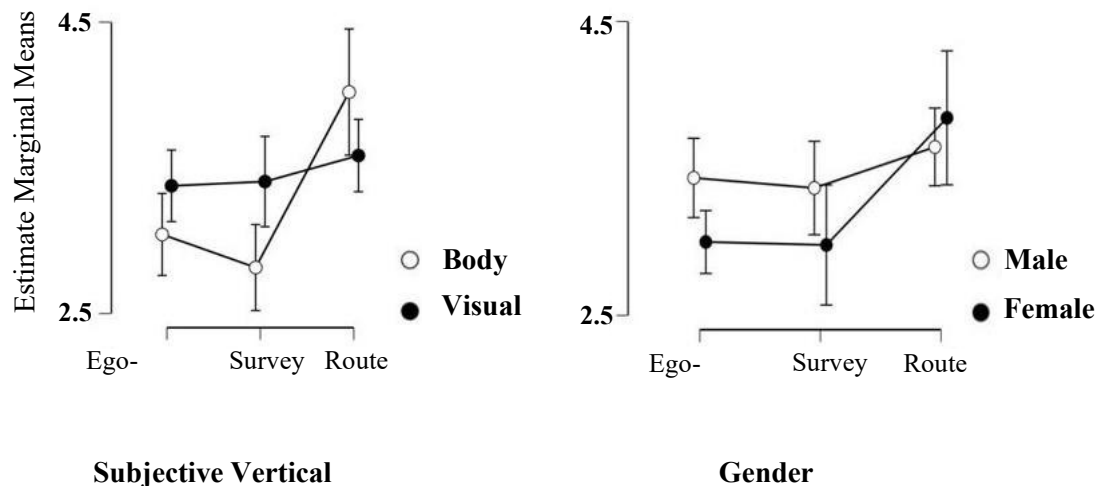


Figure 4. (Left) Relationship between NSQ and Subjective Vertical; (Right) Relationship between NSQ and Gender.

Relationship between Gender and Navigation Strategies. To examine the relationship between navigation strategies and gender, a 3 (Survey vs. Ego-Survey vs. Route) x 2 (male vs. female) mixed-model ANOVA was performed on NSQ scores. The interaction between the two variables approached significance (Greenhouse-Geisser corrected: $F(1.79, 53.5) = 3.12, p = 0.06$). However, at a descriptive level, males use both egocentric-survey strategy and survey strategy more than females. However, females used route strategy more than males (see Table 4 and Figure 4). The fact that males rely more on survey representation whereas females rely more on route representation is consistent with previous findings. Many studies found males significantly perform better on survey representation tasks in comparison to females, whereas females perform better on landmark recognition tasks (Galea & Kimura, 1993; Dabbs et al, 1998; Malinowski & Gillespie, 2001; Hegarty et al., 2006; Castelli et al. 2008; Lawton, 1994). Thus, our results add to previous work in showing that the use of a certain type of spatial strategy may differ by gender.

CONCLUSION

The present study aimed to investigate how the extreme condition where the visual vertical conflicts with the body vertical may affect spatial abilities. We also examined individual tendency to adopt a certain spatial strategy (egocentric vs allocentric). We observed that misaligned visual and body axes can adversely affect human spatial ability. Results of the statistical analysis show that object manipulation ability is affected more than spatial orientation ability. The significant effect of condition on the PSVT-R test in our study does not support the previous null effect of microgravity on mental rotation test reported by Matsakis et al., 1993 and Leone et al, 1995. One explanation could be the study environment. That is, in the present study, participants experienced microgravity through visual cues but in the mentioned previous studies, participants were physically present in the Russian MIR station but were seated in a body restraint and were prevented from seeing any visual cues by curbing their sights to only the computer screen during the experiment. Therefore, tasks requiring object manipulation ability such as a robotic operation

for installation and repair of external systems under extreme environment might need extra support.

Our results also confirm the previous assertions of Gramann (2013) that individuals favored one spatial strategy over the other. Most importantly, gender differences were observed in the use of spatial strategy. Males significantly rely on an egocentric-survey strategy which requires the use of Euclidean information of space. Although the results for women were not statistically supported the trend was for women to use a route strategy more for their everyday navigation which relies upon visible signs, landmarks or direction of the turn. This finding is in line with the previous finding that men prefer strategies rely on Euclidean features such as distances and directions versus women prefer strategies that rely on landmarks (Galea and Kimura 1993; Castelli et al. 2008; Dabbs et al. 1998).

The present study has some limitations that should be acknowledged. The measure of spatial ability was a simplified version due to the limitation of study duration. Also, the measure of everyday navigation strategy use was an indirect measure based on self-report. Thus, our findings would need to be replicated with additional measures of spatial ability including performance measures.

In conclusion, what is perhaps the most striking finding of this study is that individual proclivity for the use of a particular spatial strategy (egocentric vs. allocentric) persists in an extreme environment. As such, our results strengthen the hypothesis that individuals favor using a certain type of spatial reference frame.

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