The Influence of Visual Cues and Human Spatial Ability on Intra-vehicular Orientation Performance

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Abstract. Astronauts often experience disorientation when floating inside their spacecraft due to the lack of gravity. Previous research showed that the intra-vehicular orientation performance correlated with human spatial ability, but paid less attention to the visual cues in the environment. In this study, an experiment was conducted to explore the role of visual cues on spatial orientation performance inside a virtual space station module. Results implicated that visual cues might help in three-dimensional space orientation, but its effect varied between different spatial ability groups. People with low spatial ability might depend more on visual cues for orientation whereas people with high spatial ability could be independent of visual cues in spatial orientation. This finding reveals the effect of visual cues for orientation inside the spacecraft and provides useful guide for prefight orientation training.

Keywords: Spatial orientation · Virtual reality · Visual cues · Spatial ability · Weightlessness

1 Introduction

Humans have the ability to locomote through their immediate environment and keep track of their orientation and location without much cognitive effort [1–3]. This mainly relies on the effortless and reliable sensory integration process, such as the integration of visual, vestibular and proprioceptive cues [4–6]. Among these senses, visual cues play an important role. Firstly, visual information is the most direct information humans can perceive in daily life and it tells people the spatial relationship of different objects in an intuitional way [3, 7]. Secondly, in many cases, landmarks presented in vision are crucial for choosing turning direction at decision points and updating the egocentric or allocentric spatial relationship during locomotion [8, 9]. Furthermore, in the gravitational environment on earth, visual polarity cues usually appear in a congruent way with the gravity vector, so people can always easily retrieve spatial information about objects located gravitationally above or below [10].

But in the weightless world, such as astronauts in the space station, spatial orientation becomes a troublesome problem and humans need special efforts to fulfill the

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orientation tasks in many situations [10, 11]. These troubles are mainly caused by the lack of gravity. On earth, people are restricted to move on a two dimensional plane and most large body rotations occur about the body's head/foot axis, which is usually in alignment with gravity. But when gravity is absent, these restrictions are removed, and astronauts can rotate their bodies around arbitrary axes, which makes both locomotion and visual experience appear in an very unfamiliar way. In the spacecraft, visual verticals are usually established to help astronauts build a reference for orientation inside the module and reduce the adaptation time needed in the spatial orientation by making interior surfaces of space module look different [12], e.g. putting the lights overhead, the racks on bilateral walls and little equipment beneath the feet. But only the visual verticals are still insufficient for spatial orientation in weightless space as astronauts cannot always have the opportunity to view the module interiors from upright perspectives inside the space station. In weightlessness, they can float freely in various body orientations which having not experienced before entering into space and view the interior of the module from arbitrary or unexpected perspectives. Previous study showed that spatial orientation ability in a simulated weightless environment correlated significantly with human spatial ability factors such as mental rotation ability and visual field dependence as these spatial ability factors can indicate the ability to transform the imagery of spatial relationship between different perspectives [13–15], however, the role of visual cues was not discussed in detail. In practice, sometimes it is possible that the visual cues inside the module are obscured by smoke or fog in emergency [16], so it is also necessary to make it clear what the visual cues affect in the intra-vehicular spatial orientation tasks.

On the earth, it is impractical to provide all the possible body orientations using physical simulators that astronauts may float into in space for prefight training due to gravity. But with the help of computer science, virtual reality simulation has provided an alternative method for spatial orientation training and research under conditions similar to the weightlessness on the earth. In this study, we developed a training system for the intra-vehicular spatial orientation based on virtual reality technology, and set up an interior visual environment with/without abundant visual cues. Participants in the experiment were first tested for their spatial ability in 2&3D mental rotation and perspective-taking ability tests, and then participated in the task for intra-vehicular spatial orientation which was similar to the paradigm used in previous studies [13, 17], but with some adjustments. We anticipated that visual cues could help in the intra-vehicular spatial orientation task as it could help participants establish a reference for orientation in the module and identify targets' location. As demonstrated by previous studies, mental imagery could be used to perform the task, so we also expected that this result could be repeated in our experiment.

2 Materials and Methods

2.1 Participants

Forty adults (20 men and 20 women, mean age = 23.53, SD = 3.45, ranging from 20 to 27) with college-level education participated the experiment. None of these participants had conducted the intra-vehicular spatial orientation task or the same spatial ability tests before the experiment. The study was approved by the IRB and all participants signed the informed consent prior to the experiment.

2.2 Measurement of Spatial Ability

Two spatial ability factors, mental rotation and perspective-taking, were measured both in their 2D and 3D versions. The 3D Mental Rotation Ability (MRA) was measured by Cube Comparison Test (CCT) using paper-and-pencils, and the 2D MRA was also measured by Card Rotation Test (CRT) through paper-and-pencils. The 3D Perspective-taking Ability (PTA) was measured by the paradigm developed by Guay [18] on computer, and the 2D PTA was also measured by the paradigm developed by Kozhevnikov and Hegarty [19] using specially developed software. The specific parameters used in the spatial ability tests were shown in Table 1.

Table 1. Parameters setting in the four spatial ability tests

Parameters	Trial Numbers	Time Limitation	Test Platform	Performance Indicator
2D Perspective-Taking	24	25 s	Computer Software	Percent Correct
3D Perspective-Taking	24	40 s	Computer Software	Percent Correct
2D Mental Rotation	Maximum is 20	6 min in total	Paper-and-pencil	Right answers minus wrong ones
3D Mental Rotation	Maximum is 42	6 min in total	Paper-and-pencil	Right answers minus wrong ones

2.3 Intra-vehicular Spatial Orientation Task Appartus

The intra-vehicular spatial orientation task was conducted in the virtual environment developed by 3ds MAX and OGRE (Open Graphic Rendering Engine). Two kinds of the virtual environment were provided, as shown in Fig. 1. In Fig. 1 (a) there were distinct visual vertical cues visible, e.g. the ceiling and lights overhead, the floor beneath the feet and the different textures on bilateral walls. Whereas in Fig. 1 (b), there were only similar brown interior surfaces could be seen in the module. To provide an immersive environment for participants, the virtual interiors of the module were presented by Sony HMZ-T3 W HMD. Participants fulfilled the task sitting on a chair with a computer.

(a) (b)

Fig. 1. Two kinds of the virtual interior environment used in the intra-vehicular spatial orientation task. (a) The interior environment with visual cues, e.g. the ceiling and lights overhead, the floor beneath the feet and the different textures on bilateral walls. (b) The interior enviroment without visual cues, only similar brown interior surfaces were presented.

2.4 Experiment Procedure

The whole experiment was conducted in two periods. In the first period, we measured the spatial ability of all the participants and calculated the participants' scores in the spatial ability tests; and then in the second period, according to the spatial ability scores in the first period the participants were divided into two groups for fulfilling the intra-vehicular spatial orientation tasks.

To be specific, during the first period, participants' spatial ability in 2D & 3D MRA and PTA were tested. Their scores in each test were obtained using the performance indicators as shown in Table 1. Then to give a comprehensive description of spatial ability for each participant, the scores in the four spatial ability tests were normalized at first and summed up afterwards to form a final number representing each participant's overall spatial ability score. Then in the second period, with the overall spatial ability test scores balanced, all the participants were assigned to two groups (visual cue group and no-visual-cue group) for the intra-vehicular spatial orientation task with an equal number of males and females in each group. In the visual cue group, the participants were presented virtual environments with visual vertical cues as shown in Fig. 1 (a). And in the no-visual-cue group, the participants were presented virtual environments with the similar brown interior surfaces as shown in Fig. 1 (b). Except for the visual cues, the two groups completed the orientation task through the same procedure. Averaged response time (RT) and percent correct (%C) in the intra-vehicular spatial orientation task were recorded for evaluating participants' performance.

To fulfill the intra-vehicular spatial orientation task, participants needed to image themselves floating in various places inside a simulated cubic space module, and view the intra-vehicular environment from the corresponding specific viewpoint, just as the floating astronauts might view the interior of the module from arbitrary or unexpected viewpoint. There was one recognizable object at the center of each interior surface, which made up an object array containing six items. The location of each object remained unchanged during the experiment. Participants could learn the spatial relationship of the six objects from a prototypical viewpoint in the first five trials as a practice. This could help them form a basic understanding of the spatial relationship among the six objects. In this prototypical orientation, the objects and their locations were: a camera (above), a spacesuit (right), a treadmill (below), a Chinese knot (left), and a hatch (behind). After the initial learning trials, their ability to image the spatial arrangement of the six objects from a rotated viewpoint was tested in successive formal trials.

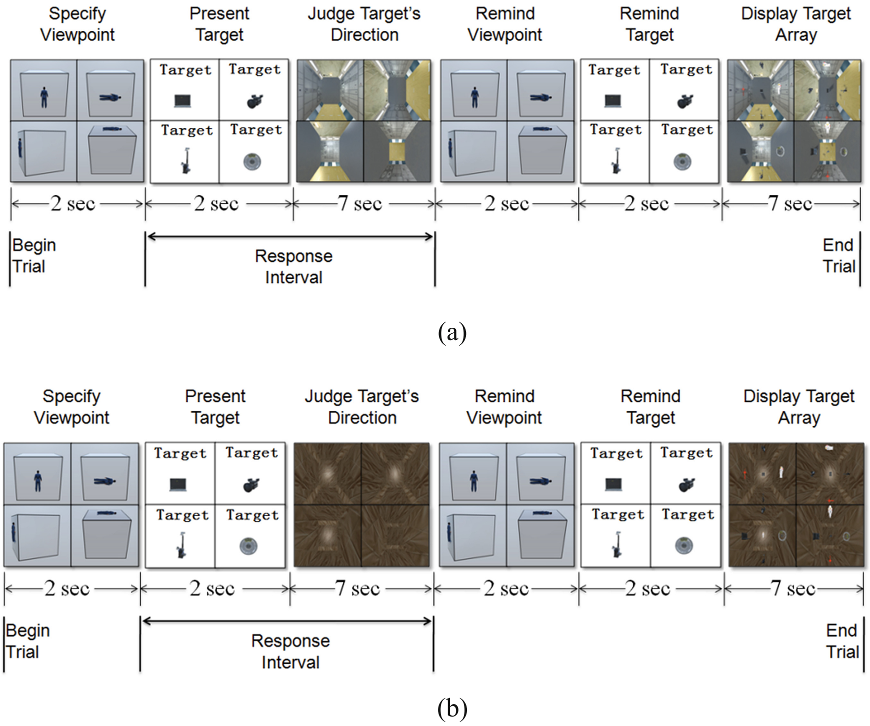

Fig. 2. Procedure for each trial. To illustrate four successive trials concurrently, the picture in each step was divided into four parts. The parts locating at the same position of the quads in every step composed an integral trial. (a) The procedure in visual cue group. (b) The procedure in no-visual-cue group

There were 12 different viewpoints in the entire task, distributing on three square surfaces that were perpendicular to each other. On each surface, there were four different orientations that in alignment with the two symmetrical axes of the surface, and each orientation represented a specific viewpoint. The task consisted of 72 trials. During each trial, the participants were first shown a picture that indicated the desired imaginary viewpoint. Next the target object whose direction needed to be indicated by the participants later was shown, and then the interior surface with/without visual cues was shown to the participants, but no object array appeared. The participants needed to indicate the relative direction to the target in body coordinates on this step. To make this indication, participants pushed one of five buttons on a numeric keyboard. After this, the imaginary viewpoint and target object was presented again, and the complete object array was displayed, rotated into the viewpoint called for in the trial. This allowed the participants to verify the correctness of their judgments based on the direct visual observation of the array in its rotated viewpoint. Participants could review the spatial arrangement of the object array in preparation for the next trial. The imaginary viewpoints distributed randomly during the entire task but same to all the participants. The procedure for each trial was shown schematically in Fig. 2. At the end of the intra-vehicular spatial orientation task, participants completed a strategy questionnaire, which included both multiple choice and open ended questions about the strategies they employed in fulfilling the task. The entire experiment of the two periods took approximately 2 h to complete.

3 Result

Since no significant difference was found in terms of gender, data from male and female participants were not distinguished in later analysis. Statistical analysis was conducted using SPSS. We first compared the participants' performance under different visual cue conditions. The percent correct performance in the intra-vehicular spatial orientation task for all the participants in both visual cues conditions was shown in Fig. 3. Generally, the participants in visual cue group performed better than no-visual-cue group, although the advantage was not significant. But further analysis showed that spatial ability moderated the relation between visual cues and intra-vehicular spatial orientation performance. Both in visual cue group and no-visual-cue group, parting the spatial orientation task results into two subgroups according to the participants' spatial ability: one subgroup contained the results of the better half participants in spatial ability and the other subgroup contained the remaining. Then the t test was conducted to compare the spatial orientation performance under different visual cue conditions both in higher spatial ability subgroups and lower spatial ability subgroups. And the moderate effects manifested as follows: on one hand, participants with higher spatial ability showed no significant differences in percent correct under visual cue/no-visual-cue conditions ($t(18) = 1.225$, $p = 0.128$); on the other hand, participants with lower spatial ability in the visual cue group performed better significantly in percent correct than those in the no-visual-cue group ($t(18) = 2.674$, $p = 0.008$). In terms of the response time, participants with higher spatial ability in the no-visual-cue group had significantly longer response time than the participants with higher spatial ability in the visual cue group ($t(18) = 3.002$, $p = 0.006$). No significant difference was found in the response time of participants with lower spatial ability under different visual cue conditions($t(18) = 1.292$, $p = 0.105$).

The correlation between participants' spatial ability and intra-vehicular spatial orientation performance under different visual cue conditions was also analyzed. For the participants in the no-visual-cue group, their scores in all the four spatial ability tests correlated significantly with their performance in the intra-vehicular spatial

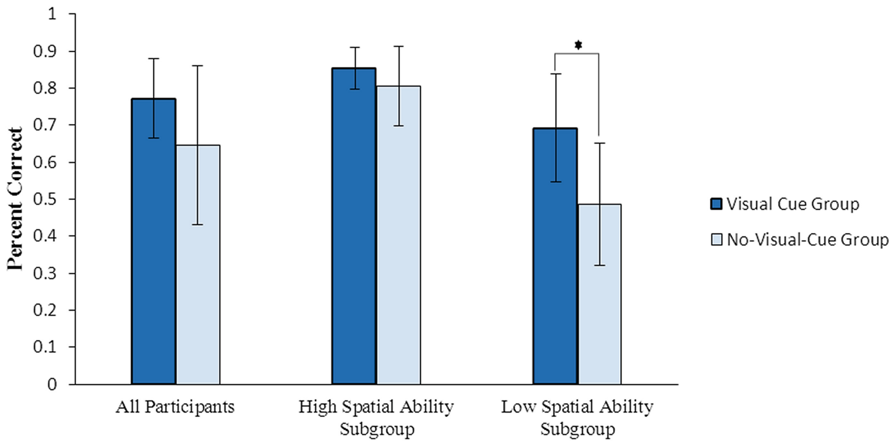

Fig. 3. Percent correct performance for both visual cue group and no-visual-cue group. In each group, parting the results into two subgroups according to the participants' spatial ability. The results of all participants (*left*), high spatial ability subgroup (*middle*), and low spatial ability subgroup (*right*) were shown with ± 1 standard error bars. The asterisk indicated significance at p level 0.01.

Table 2. Pearson correlation coefficients for spatial ability test scores and intra-vehicular orientation task performance (%C and RT) both in visual cue and no visual cue group

Test Type	2D Perspective-Taking	2D Mental Rotation	3D Perspective-Taking	3D Mental Rotation
%C in Visual Cue Group	0.128	0.286	0.273	0.378
RT in Visual Cue Group	−0.186	−0.152	−0.190	−0.291
%C in No-Visual-Cue Group	0.356^{*}	0.423^{**}	0.467^{**}	0.684^{**}
RT in No-Visual-Cue Group	-0.382^{*}	-0.680^{**}	-0.400^{*}	-0.577^{**}

$^{**}p < 0.01$; $^{*}p < 0.05$.

orientation task (both in response time and percent correct). But for the participants in the visual cue group, there was no significant correlation between the performance in the spatial orientation task and the scores in the spatial ability tests. The correlation coefficients were shown in Table 2.

Tabulation of the post-experiment strategy questionnaire results (Table 3) showed that for the participants in the no-visual-cue group, most of them learned the configuration of the object array by remembering paired opposite objects, whereas most of the participants in the visual cue group did this by relating the location of the objects with the visual cues on the interior surfaces of the modules. And when determining the target location, participants in the no-visual-cue group usually needed to image rotating their perspective to the viewpoint indicated in the trial, but majority of the participants in the visual cue group made their decisions by observing the location of the corresponding visual cues on the judgment step. And when asked in which imaged body orientation they found the spatial orientation task most difficult, most of the participants in both groups thought that the orientation deviated more from the prototypical orientation in initial learning trails, the more difficult they felt.

Table 3. Tabulation of post experiment strategy questionaire responses

Questions	Answer Category					
	Visual Cue Group (n = 20)			No-Visual-Cue Group (n = 20)		
How did you build up the knowledge of the object array configuration?	Relate objects with visual cues	Paired opposite objects	Other	Paired opposite objects	Attached meaning to objects	Other
	17	3		18	1	1
How did you make decisions about target location?	Observe the interiors location	Imaged self rotating	Imaged the module rotating	Imaged self rotating	Imaged the module rotating	Other
	18	2		16	4	
Which body orientation made the task most difficult?	90° deviated from the prototypical	180° deviated from the prototypical	270° deviated from the prototypical	90° deviated from the prototypical	180° deviated from the prototypical	270° deviated from the prototypical
	2	3	15	1	3	16

4 Discussion

We interviewed each participant informally at the conclusion of the entire experiment. Most participants said that although the initial learning trials had gave them some basic knowledge about the configurations of the object array, they still felt confused to make orientation decisions in the first several formal trials. But with the help of the opportunity to learn the spatial arrangement of objects on the last step in each trial, they could build up the complete and stable spatial knowledge soon. And the data of percent correct also showed that participants under both visual cue conditions usually could achieve rather high (above 80 %) percent correct after about 25 trials. This testified that the paradigm used in our study was effective in building up three-dimensional spatial knowledge for novices. As shown in the strategy questionnaire results, most of the participants in the visual cue group said that they remembered the objects on the interior surfaces simply by the relating the objects with the visual cues, e.g. they remembered clearly that the camera was hung on the ceiling, and the spacesuit was put on the wall with more apparatuses. And on the judgment step, they would first observe the location of the interior surfaces and then made the decision according to the interior surface's location. It could be seen that in this process, the participants did not need to utilize the imagery of the spatial relationship or even image rotating their perspectives. They just needed to observe the visual environment all the time and then they could get their judgments. This strategy that mainly adopted by these participants could also explain the no findings in significant correlation between the individual spatial ability and the intra-vehicular spatial orientation task in the visual cue group.

For the participants in the no-visual-cue group, they had no visual cues in helping them remember the location of the objects, so they had to think out other methods to build up the spatial configuration of the object array. Most of the participants did that by remembering paired opposite objects and imaging the rotation of themselves when needed to indicate target's location in the specific body orientation. This strategy they claimed was verified by the significant correlation between their scores in the spatial ability test and the intra-vehicular spatial orientation task.

It was reasonable to conclude that visual cues could be helpful in the intra-vehicular spatial orientation, especially for those with lower spatial ability. As mentioned above, visual cues could help participants in identifying the location of objects and made them clearer about their body orientation relative to the prototypical orientation during the task. Although for those participants with higher spatial ability there was no significant difference in percent correct of the intra-vehicular spatial orientation task, the significant differences in response time indicated that participants in the no-visual-cue group needed more cognitive efforts to fulfill the orientation task. This meant that the visual cues could make the intra-vehicular orientation task easier. For the participants with lower spatial ability, it might be more difficult for them to transform the imagery of various spatial relationships, which was not an easy job indeed, but the visual cues could help them avoid the strategy related with spatial ability and gave them the alternative way to complete the task by observing and remembering those visual cues, so the participants with lower spatial ability in the visual cue group could outperform those participants with lower spatial ability in the no-visual-cue group significantly.

5 Conclusions

Spatial orientation under terrestrial conditions needs not much effort in most situations, but it is a troublesome problem for astronauts living in the space station as there is no gravity providing some helpful restrictions. This study explored the role of visual cues inside the space module in spatial orientation tasks by means of establishing a virtual reality environment. Through the experiment, we found that, like the terrestrial situations, visual cues can also provide a lot of help in fulfilling the orientation tasks in weightlessness. The direct visual impression of the spatial relationship between the targets and visual cues can reduce the cognitive efforts needed in location judgments. Especially for population with lower spatial ability, it could be more difficult for them to undertake mental rotation or perspective-taking tasks to identify target location, but the visual cues could simplify the complex process to remembering the combination of targets and the corresponding visual cues. This could be thought as the good side of the visual cues. But in another aspect, astronauts should not rely too much on the visual cues for intra-vehicular spatial orientation. Because in some emergencies, it is possible that these visual cues might be partly or mostly obscured by fog and smoke caused by loss of pressure or even fire. But spatial orientation is vital in these emergencies because astronauts need to react as quickly as possible to reach the destination module for some further actions. So astronauts still need to acquire the essential skills for orientation in three-dimensional space so that they can obtain a good sense of direction under any conditions in the space station. These essential skills are similar to the skills adopted in solving the problems in the spatial ability tests, because they both need to image the perspectives change or body rotation when the external environment keeps stationary. And it also indicates that the prefight training should not only be done in the environments with abundant visual cues, but also done specially in the environments without visual cues.

Except for the visual cues that indicate vertical vectors and make interior surfaces have different appearances, the effects of the visual directional landmarks that directly indicate the different modules or some specific orientations and its interactional effects with individual spatial abilities are still needed to be explored in further studies.

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