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The effect of the configuration and the interior design of a virtual weightless space station on human spatial orientation

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Abstract

In a virtual weightless environment, subjects' orientation skills were studied to examine what kind of cognitive errors people make when they moved through the interior space of virtual space stations and what kind of visual information effectively decreases those errors. Subjects wearing a head-mounted display moved from one end to the other end in space station-like routes constructed of rectangular and cubical modules, and did Pointing and Modeling tasks. In Experiment 1, configurations of the routes were changed with such variables as the number of bends, the number of embedding planes, and the number of planes with respect to the body posture. The results indicated that spatial orientation ability was relevant to the variables and that orientational errors were explained by two causes. One of these was that the place, the direction, and the sequence of turns were incorrect. The other was that subjects did not recognize the rotation of the frame of reference, especially when they turned in pitch direction rather than in yaw. In Experiment 2, the effect of the interior design was examined by testing three design settings. Wall colors that showed the allocentric frame of reference and the different interior design of vertical and horizontal modules were effective; however, there was a limit to the effectiveness in complicated configurations.

1. Introduction

As the interior volume of manned space systems becomes larger, astronauts can move around freely and may expect more disorientation and space motion sickness [1]. In space, it is difficult to orient yourself by proprioceptive cues like inner ear organ and muscles, and it is reported that people rely more on visual information [1–3]. In previous studies, the relationships between visual information of direction such as ceiling and floor and the body posture of astronauts in a room were mainly considered [3,4]. From these results and many experiences in space [5–8], design guidelines of lighting, wall color, and equipment were suggested [9]. However, little systematic study has been conducted on spatial orientation in the microgravity of large space stations like Mir and ISS [10,11]. They are constructed by several modules connected not only in a horizontal direction, but also in a vertical direction. Since astronauts have trained on the ground and

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experienced each module separately in an upright way before the launch, it is hard to know the relative position of the horizontal and vertical modules or recognize something from a different direction like upside down. Astronauts who stayed in Mir for 3 months reported they could not imagine the three-dimensional relationship between modules and felt potential danger not knowing their position relative to the emergency module [12]. Therefore, it is essential to study fundamental human spatial cognition in weightlessness for astronaut training and future large space station design.

Aoki et al. examined subject three-dimensional orientation skills using a virtual reality simulation [13]. The virtual reality simulation is a useful tool for spatial orientation study in weightlessness [11,14]. It also enables us to have the sequential experience that had not been dealt with in the previous space station studies but is very important for the better knowledge of spatial orientation. In their experiments, subjects followed virtual routes that were constructed of three or four rectangular modules that were connected by the cubical modules. Each subject moved from one end to the other end. and pointed to the start point and reproduced the experienced route using a scale model. The configurations (i.e. specific shapes) of the routes were changed systematically. Analyses of the results indicated that the ability of spatial cognition changes with such variables as the number of bends, the number of embedding planes and the number of planes with respect to the body posture. However, the causes of spatial cognition errors could not be specified because of the small number of subjects and rather simple configurations.

By using a virtual reality simulation, this research explored human spatial orientation in a space station. We examined what kinds of cognitive errors people make when they moved though the interior space of virtual space stations with more subjects and more complicated configurations in Experiment 1, and what kind of visual information is effective to decrease those errors in Experiment 2.

2. Experiment 1

2.1. Equipment

Experimental spaces were modeled and each surface was textured by a computer-graphics workstation. The subject, who sat down in a chair as an erect posture, wore a head-mounted display (Shimadzu STV-ES) to view the spaces (Fig. 1). The display was color stereoscopic VHS resolution (more than 350 scanning lines) at 25–60 Hz, and the field of view was 48° (horizontal) ×36° (vertical). Subjects used a hand controller to enter into the virtual space station and moved around. The controller was an input device with six degrees of freedom, and subjects could move to front and rear, right and left, and up and down, and rotated on each axis. In order to represent weightless motion more faithfully, inertial movement was programmed into the parallel translation. To maintain some ease of operation for the subject, rotational inertia was not included.

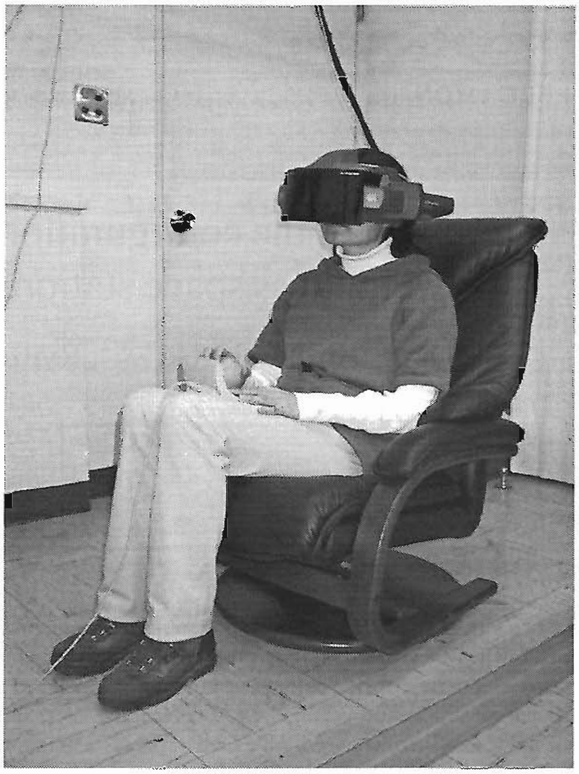


Fig. 1. Subject wearing a head-mounted display (HMD).

2.2. Method

The routes of the virtual space station used in this experiment were constructed of five rectangular parallel piped modules (3 × 3 × 15 m each) that were connected by 3-m cubical modules. There were walls between modules with a gray circle like a hatch at the center of each wall, so that subjects could not see through the adjacent module. The wall surfaces were held constant to off-white color with a random white-gray pattern and there was a uniform light with no brightness gradient in order to study the effects of configurations of route on orientation (Fig. 2).

Each subject moved from one end to the other end, then, pointed to the start point with their hands and words such as "right-forward-up", which means the start point was 45° clockwise in azimuth and 45° pitch-backward. There are 26 possible directions (8 directions in the horizontal plane (every 45°) × 3 directions in the perpendicular plane (horizontal, 45° pitch forward/backward) + 2 (right above/under) = 26). This was called the "Pointing task". Then, subjects reproduced the configuration of the experienced route using a scale model ("Modeling task"). The answers were considered to be correct only when subjects pointed the exact directions in the Pointing task and reproduced the exact configurations in the Modeling task. Subjects could stop at any time by pressing a button on the controller during their travel; however, they were asked not to go back to the previous module.

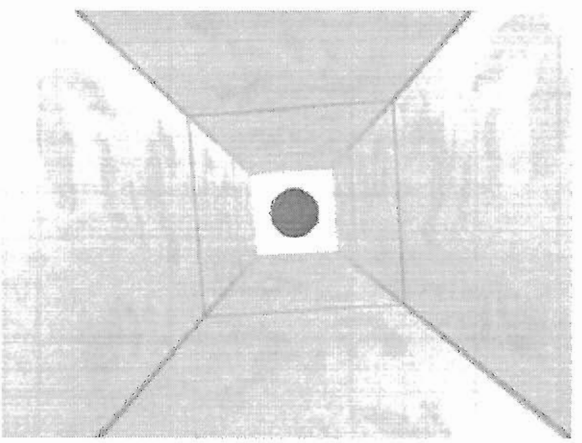


Fig. 2. An example of an image presented to subjects.

Table 1 shows the variables of routes affected the choice of configurations.

1. The number of bends in a route (#BEND); that is, the number of turns in a course. When the number of bends increases, it may become difficult to recognize the configuration.
2. The number of embedding planes defined by two connecting legs of the route (#EMB). For example, since (a) in Fig. 3 is contained in one horizontal plane and (b) is contained in one perpendicular plane, there is only one embedding plane in each case.
3. The number of planes with respect to the body posture (#BP). As compared to conditions of normal gravity, under conditions of weightlessness the plane might change when moving in the vertical direction. For example, when you move rightward in (a) of Fig. 3, the plane does not change with respect to the body posture so the number of planes remains only 1. In (b) of Fig. 3, the plane may change when you move upward, and then the number of planes becomes 2. It is assumed that it was more difficult to recognize the configuration as the number of planes increased.

Nine configurations (A–I) in Table 2 were used in the experiment. "Movement" in Table 2 shows the direction(s) of turn(s) at the node(s). "Right" means yaw right 90°, "left" means yaw left 90°, "up" means pitch backwards 90°, and "down" means pitch forward 90°. The circled S symbols in the table showed the starting

Table 1
The variables of configurations of routes

Number of bends	(#BEND)	Number of turns in a route
Number of embedding planes	(#EMB)	Number of planes defined by two connecting legs of a route
Number of planes with respect to body posture	(#BP)	Number of planes relative to the body's vertical axis. As compared to conditions of normal gravity, under conditions of weightlessness the plane might change when moving in the vertical direction

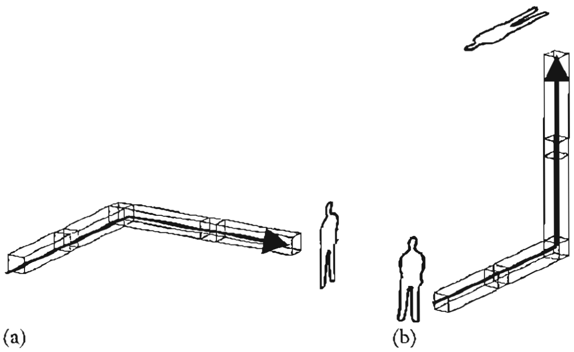


Fig. 3. Configurations with the same #EMB but different #BP.

positions in each configuration. The configurations of the routes were expected to influence a subject's orientation. Please note that these configurations do not exhaust all possibilities such as symmetrical configurations.

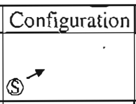
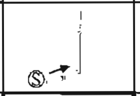
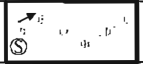
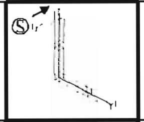
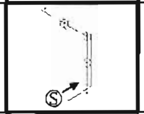
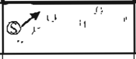
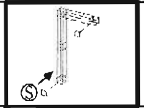
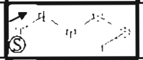
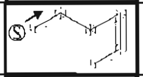
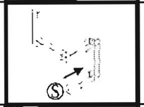
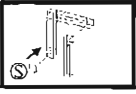
2.3. Procedure

The subjects consisted of 20 naïve people (the range of ages was 22–27), of whom 12 were male and eight were female. Before the experiment, they were instructed how to use the controller, how to answer the direction, and how to reproduce the scale model. Then, they experienced one or two training configurations with three turns. After the training, they started the experiment and moved through the first configuration and did Pointing and Modeling tasks. Each subject made two trials successively for each route. Half of the subjects (six male and four female) experienced the configurations in the order of C-E-I-F-D-H-G-A-B, whereas the other half went through the configurations in the reverse order.

2.4. Results and discussion

Fig. 4 showed the percentage of incorrect answer of each subject from 1 to 20 in Pointing and Modeling tasks. There were wide variations between subjects. Also the percentage of incorrect answers in Pointing and Modeling tasks were not fully correlated. That meant the causes of errors might be different between subjects and each answer should be examined carefully.

Table 2
The configurations of routes used in Experiment 1

#BEND	#EMB	#BP	Movement	Configuration	
0		1	(Straight)		-
1	1	1	Left		-
		2	Up		-
2	1	1	Right-left		A
		3	Up-down		-
	2	2	Down-right		B
			Up-left		C
3	1	1	Right-left-right		-
		4	Up-down-up		-
	2	2	Left-up-right		-
		3	Up-right-up		D
4	1	1	Right-left-right-right		E
		4	Down-up-down-up		-
	2	2	Right-right-up-left		F
		3	Right-left-down-down		G
		4	Up-up-left-down		H
	3	3	Up-right-up-right		I

Ⓢ ; Start point

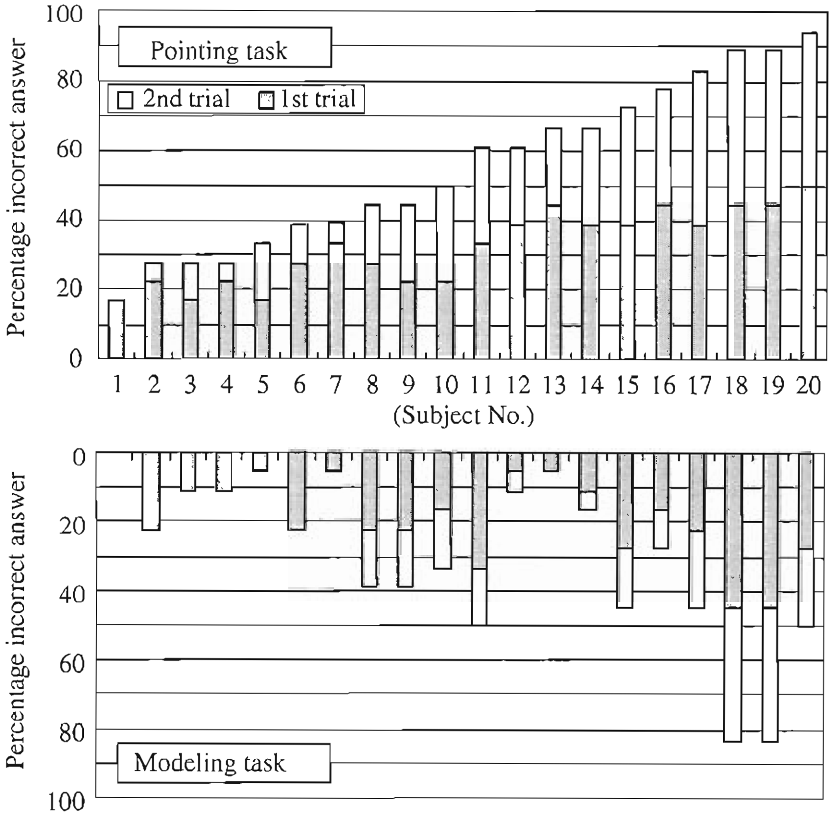


Fig. 4. Percentage incorrect answer of each subject in Pointing and Modeling tasks.

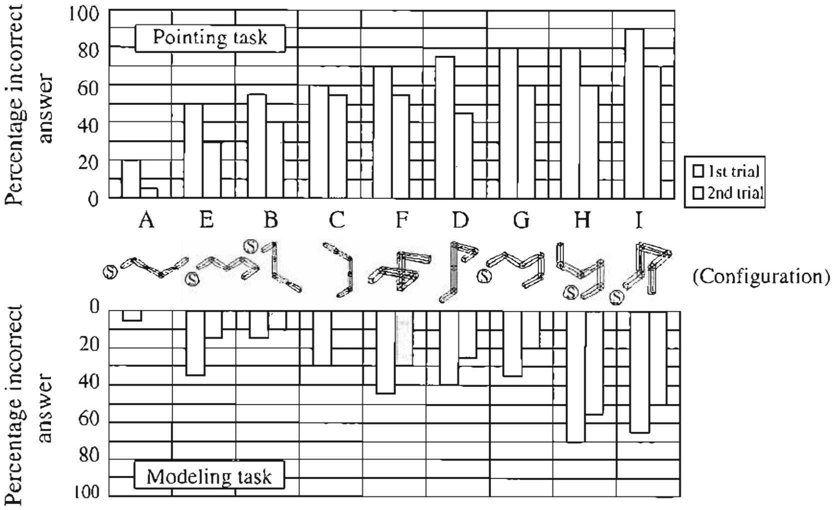
Fig. 5 showed the percentage of incorrect answers for each configuration in Pointing and Modeling tasks. The tendency to make mistakes increased along with the numbers we hypothesized. In Pointing task, the percentages of B and C, which had more #EMB and #BP but less #BEND, was higher than that of E; that is, #EMB and #BP had more influence on errors in Pointing task. In Modeling task, however, the percentage of E was higher than that of B and C; therefore #BENDS influenced errors in Modeling task. The percentage of H and I in Modeling task were statistically higher than other configurations except F by ANOVA because they have large number of the variables. In comparison with G and H, the percentage of incorrect answers for H in Modeling is much higher than that of G even though the percentages of incorrect answer in Pointing task were the same. This will be discussed later.

The detailed analyses of the results of both tasks indicated that spatial orientation errors were explained by two causes.

1. The place, the direction, and the sequence of turns were incorrect.
2. Subjects did not recognize the rotation of the frame of reference.

The former kind of errors are typical in navigation tasks. The latter kind of errors seem specific to the weightless state, so they are explained in detail below.

In the previous experiment [13], a simple configuration similar to Fig. 6 was used. For example, when subjects turned up, some of them believed their posture was like Fig. 6(b) and answered that the start point was diagonally below, even though their actual postures were like Fig. 6(a) and the start point was



#BEND	2	4	2		4	3	4		
#EMB	1		2						3
#BP	1		2			3		4	3

Fig. 5. Percentage incorrect answer of each configuration in Pointing and Modeling tasks.

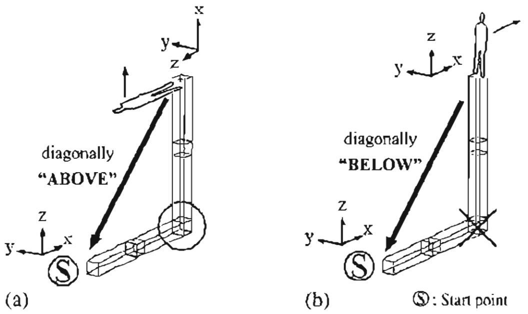


Fig. 6. Subjects' actual (a) and believed (b) posture.

diagonally above. When subjects made two turns, there were four possible orientations, through recognition of the subject's frame of reference in each corner correctly or not. Most of the correct and incorrect answers in Pointing task were explained thusly.

When subjects reproduced routes on scale models, some subjects made such incorrect configurations as Fig. 7(b) and (c); nevertheless they actually experienced Fig. 7(a), because they did not take their posture at the each corner into account. Therefore, it was reasonable to think that some people did not recognize their reference frame correctly when they moved around in a virtual weightless environment.

Table 3 shows the percentage of spatial orientation errors in each configuration. "Inexplicable" showed the percentage of the answers of which the causes of errors could not be explained. "No answer" showed the percentage of the trials subjects could not answer the direction. "Quit task" showed the percentage of the trials in which subjects could not reproduce the experienced route by the scale model. "Unintentional rotation" showed the percentage of the trials in which subjects rotated unintentionally, and did not reorient themselves or were not aware of their rotation.

The configurations of A, B, C had the same #BEND (2). There was no misrecognition of the frame of reference in A; however the percentages of that in B and C were about 30%. A reasonable explanation for these differences was that B and C had a turn in pitch direction and the #BPs were two, compared to A that had no turn in pitch and the #BP was only one.

Multiple regression analyses were performed for the percentages of each configuration and each type of error in Table 3 by stepwise regression of #BEND, #EMB, and #BP as predictors in order to determine the influence of each variable on the errors. In Point-

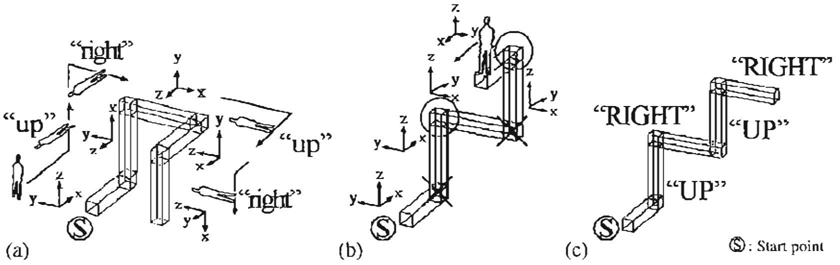
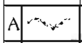
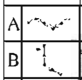
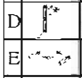
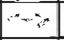
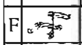
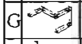


Fig. 7. Correct configuration (a) and misrecognized configurations (b), (c).

Table 3
Percentage of the spatial orientation errors in each configuration

Configuration		Pointing task				Modeling Task			Unintentional rotation
		Misrecognition of the frame of reference	Misrecognition of the configuration	Inexplicable	No answer	Misrecognition of the frame of reference	Incorrect of place, direction, and sequence of turns	Quit task	
A			3	10			3		
B		28	3	15			10		3
C		38	10	5			10		5
D		10	15	30		10	18		5
E		8	20	8			20		5
F		25	8	13	5	3	20	3	13
G		25	8	25			15		13
H		15	18	18	3	10	33	3	18
I		23	23	20	3	8	43	3	5

☐ $0<x<10$; ☐ $10\leqq x<20$; ☐ $20\leqq x<30$; ▨ $30\leqq x$ (%).

ing task, #EMB tended to have an influence on the misrecognition of the frame of reference (coefficient $=12$) and #BEND on the misrecognition of the configuration (coefficient $=4.9$), even though the coefficients were not statistically significant ($p=0.086$ and 0.058, respectively). In Modeling task, the percentages of incorrect place, direction, and sequence of turns were statistically significant ($R^2=0.77$, $p<0.05$) using #BEND and #EMB as predictors (coefficients=7.6 and 10, respectively).

In Modeling task, the percentage of incorrect answer of H was statistically higher than that of G in spite of the same percentage in Pointing task. That would be caused by reference frame misrecognition. When subjects firstly go upward two times in H, the frame of reference of the subjects was inverted to the reference frame of the configuration and some subjects assembled the following module in the opposite direction. In G, however, the two upwards were the last in the series of movements and there was no module connected after them; thus the models made in the task were the same even if some subjects misrecognized their frame of reference.

Based on these results, we conclude that people misrecognized the rotation of the frame of reference when they turned in pitch direction rather than in yaw.

3. Experiment 2

3.1. Objective

In order to reduce the errors of place, direction, and sequence of turns drawn from the results by

Experiment 1, labels would be effective. In case of the ISS, labels that indicate the name and the direction of the adjacent modules are defined [15]. But it will be difficult to read when astronauts are away from labels and approach from a slanted angle or upside down [16], and labeling would not be helpful for understanding of the configuration.

Concerning the misrecognition of the reference frame (the second type of errors in Experiment 1), the use of interior color for effective spatial orientation is recommended [16]. The interior design scheme of ISS is also defined [17]; however, there is not a clear definition of color for the all modules for easy navigation and spatial orientation. In order to clarify what kind of interior design of a virtual space station is effective for human spatial orientation, three orientation cues were examined by conducting Pointing and Modeling tasks similar to Experiment 1.

3.2. Method

Three orientation cue settings of the interior design in Fig. 8 were tested.

Setting I: Each module had a distinction between ceiling and floor by color; however, all modules were the same and there was no discrimination between them. People could understand which wall was up or down in a module, but might have difficulty knowing where they were.

Setting II: The colors of walls showed the allocentric frame of reference of the virtual space station, namely, red wall showed port side, green showed starboard, gray showed aft, and beige showed deck. These colors of walls probably gave a clue to people which direction they were facing.

Setting III: As well as Setting I and II, the walls of the horizontal modules of this setting were the racks of equipments. However the interior design of the vertical modules was different and the walls were filled with shelves. People would recognize the movement (moving up or down) in the vertical modules.

Subjects did Pointing and Modeling tasks in the same condition of Experiment 1. The configurations of routes used in Experiment 2 were shown in Tables 4 and 5. In this experiment, people could reorient themselves even though they rotated unintentionally because there were polarity cues in each module. Different from Experiment 1, #BP was not defined in one way according to the configuration in this case. In order to define #BP of each configuration, it was assumed that people reorient with the polarity cue in each module by rolling on x-axis (forward-aft) (because "roll" is the easiest way to reorient to the vertical) when they moved to the next module in which local vertical was not same as the former one. For example, subjects' assumed movement was "up (90° pitch backward)" - "right (90° right in yaw)" - "90° counterclockwise roll" in Setting I in Fig. 8. When the configurations were chosen, all possibilities of the directions of turns and rolls were examined and three configurations were selected to include most variations of turns and rolls. Moreover, the same configurations or the symmetrical configurations were chosen in each setting, so that the influence of the difference between configurations was lessened as much as possible.

3.3. Procedure

Thirty subjects in their 20–30's were used, of whom 18 were male and 12 were female. All subjects were divided into three groups of 10 people and each group experienced the setting order I-II-III, II-III-I, III-I-II, respectively, so as to reduce differences between setting order.

After they were instructed how to use the controller, answer the direction, and reproduce the experienced route by a scale model, subjects learnt the first orientation cue setting by one of the perspective drawings shown in Fig. 8 and by moving in a training configuration. The meaning of color scheme in each orientation cue settings was instructed at the same time. They experienced the first configuration, and did Pointing and Modeling tasks. They underwent three configurations in one setting. Then, they changed the setting and did both the tasks in three configurations. They did the experiment in all three settings, nine configurations. They did one trial in each configuration.

3.4. Results and discussion

Because any significant statistical difference between groups by the setting order was not seen in the data, all subjects' results will be analyzed after this.

The results of Pointing and Modeling tasks in each setting are shown in Fig. 9. The vertical axis showed the sum total of the percentages of the correct and in-

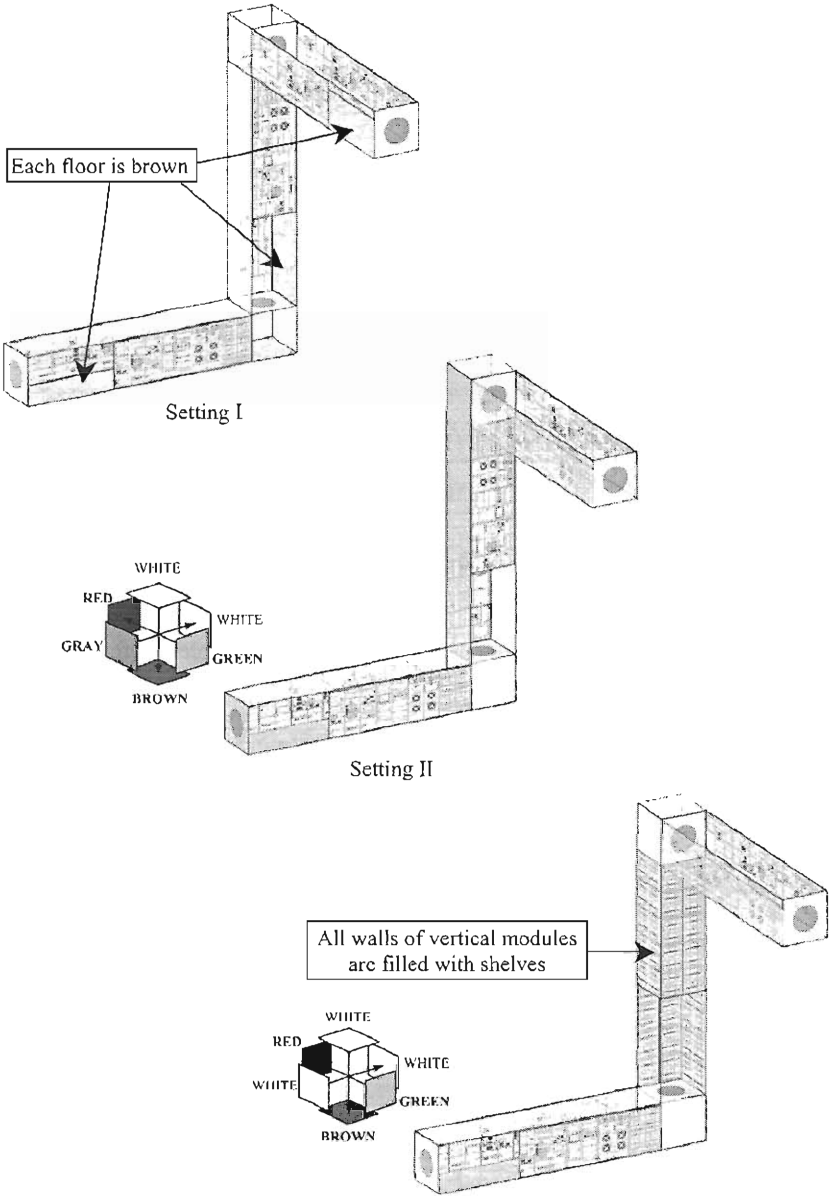
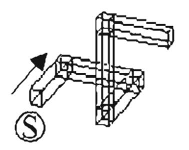
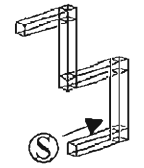
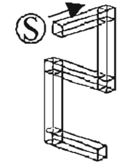


Fig. 8. Three orientation cues of the interior design.

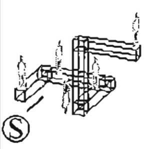
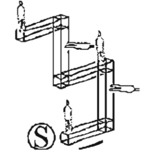
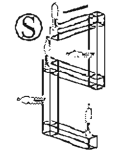
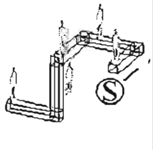
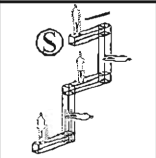
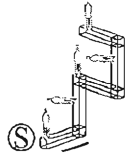
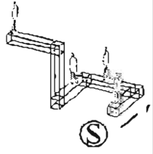
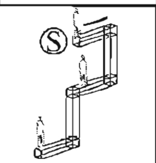
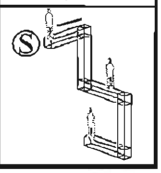
correct answers. Two-way ANOVA of Setting (I, II, III) × Configuration (1, 2, 3) was performed with regard to the percentages of the correct answers, and the significant difference ($p < 0.05$) was seen in Setting in both tasks. As a result of Fisher's LSD, the difference between the mean of the percentage of correct answer in Setting I and that in Setting III was significant in Pointing task. In Modeling task, the significant differences were seen between Settings I and II, and between Settings I and III.

Table 4
The number of the variables of the configurations

#BEND	#EMB	#BP	Configuration
4	2	3	1 
	1	5	2 
	2	5	3 

Ⓢ ; Start point

Table 5
The configurations used in Experiment 2

		Configuration		
		1	2	3
Setting	I			
	II			
	III			

Ⓢ ; Start point

As compared to the percentage of the correct answers of F in Experiment 1, there was no significant difference in that of the configuration 1 of Setting I in this experiment. Therefore just adding ceiling and floor distinction in each module is not enough to recognize the configuration correctly.

Fig. 10 showed the result of both tasks in each shape. Chi-square test was performed in each setting of the three shapes. It was revealed that in complicated configurations of routes such as 3, which had a large number of embedding planes and the planes with respect to the body posture, the percentages of correct answers of both tasks were lower than those in 1 and 2. Therefore there was a limit of the effectiveness of the visual information on spatial orientation.

4. Conclusions

In a virtual weightless environment, subjects' orientational skills were tested with Pointing and Modeling tasks. The configurations of routes, which were constructed of modules, were changed systematically with such variables as the number of bends, the number of embedding planes and the number of planes with respect to the body posture. The results showed that the number of errors of the tasks varied with those variables, and that the variables were relevant to the difficulty of spatial orientation in a virtual space station. The detailed analyses indicated that those errors were explained by two causes. One cause was that the place, the direction, and the sequence of turns were incorrect. The other cause was that subjects did not recognize the rotation of the frame of reference, especially more often when they turned in pitch direction rather than in yaw.

In Experiment 2, Pointing and Modeling tasks were conducted in order to clarify the effect of interior design of virtual weightless space station on human spatial orientation. Three settings of the interior design were tested. In Setting I, each module had a distinction between ceiling and floor by color. In Setting II, the colors of wall showed the allocentric frame of reference of the virtual space station. In Setting III, the interior design of the vertical modules was different from that of the horizontal modules. By analyzing the results, it was found that people had most difficulty in recognizing the configuration of the routes they had experienced and the orientation in Setting I, and that such visual clues as the wall colors in Setting II and the different interior design of vertical and

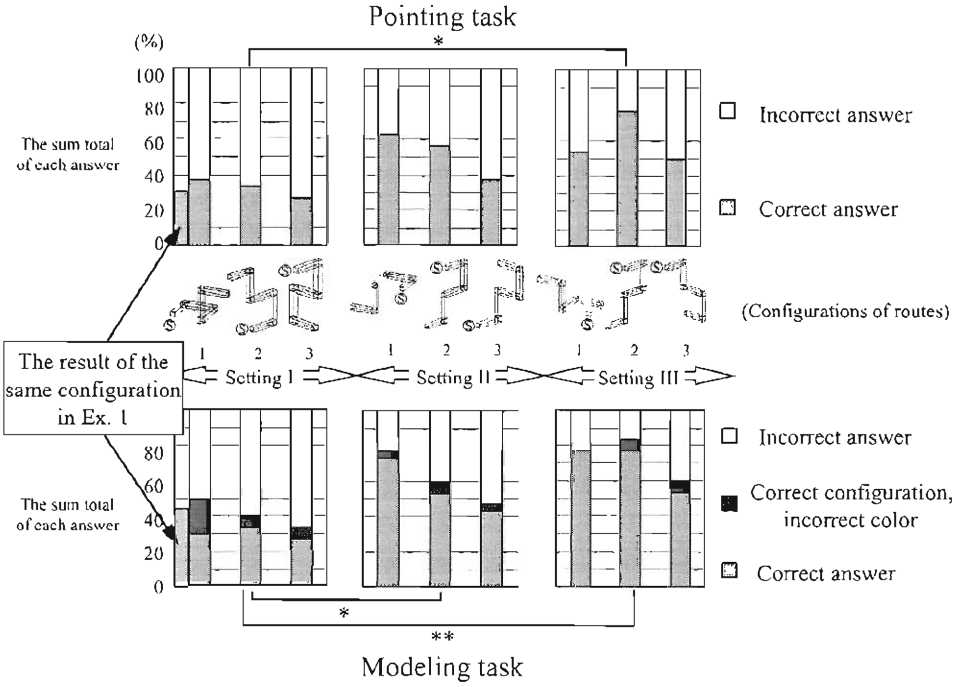


Fig. 9. The result of Pointing and Modeling tasks in each setting.

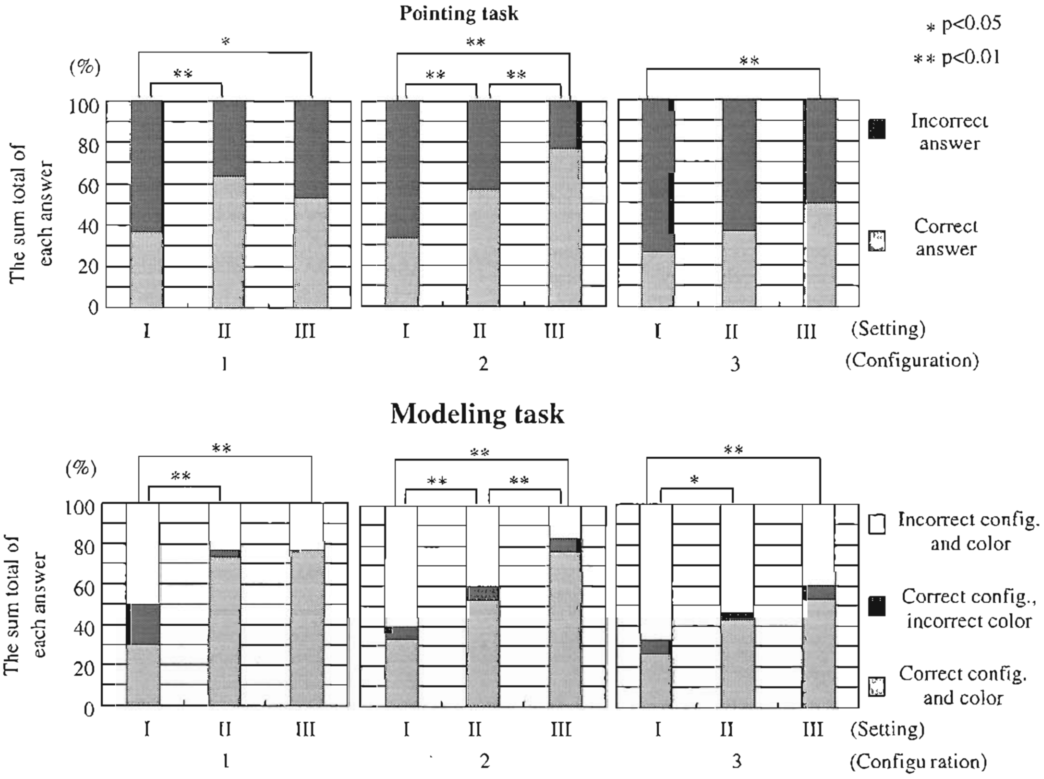


Fig. 10. The result of Pointing and Modeling tasks in each configuration.

horizontal modules in Setting III were effective measures in spatial orientation in a virtual weightless environment. However, in complicated configurations of routes that had a large number of embedding planes and the planes with respect to the body posture, there was a limit to the effectiveness of the visual information on spatial orientation.

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