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Three dimensional spatial memory and learning in real and virtual environments

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Abstract. Human orientation and spatial cognition partly depends on our ability to remember sets of visual landmarks and imagine their relationship to us from a different viewpoint. We normally make large body rotations only about a single axis which is aligned with gravity. However, astronauts who try to recognize environments rotated in 3 dimensions report that their terrestrial ability to imagine the relative orientation of remembered landmarks does not easily generalize. The ability of human subjects to learn to mentally rotate a simple array of six objects around them was studied in 1-G laboratory experiments. Subjects were tested in a cubic chamber (n = 73) and a equivalent virtual environment (n = 24), analogous to the interior of a space station node module. A picture of an object was presented at the center of each wall. Subjects had to memorize the spatial relationships among the six objects and learn to predict the direction to a specific object if their body were in a specified 3D orientation. Percent correct learning curves and response times were measured. Most subjects achieved high accuracy from a given viewpoint within 20 trials, regardless of roll orientation, and learned a second view direction with equal or greater ease. Performance of the subject group that used a head mounted display/head tracker was qualitatively similar to that of the second group tested in a physical node simulator. Body position with respect to gravity had a significant but minor effect on performance of each group, suggesting that results may also apply to weightless situations. A correlation was found between task performance measures and conventional paper-and-pencil tests of field independence and 2&3 dimensional figure rotation ability.

Key words: mental imagery, mental rotation, spatial memory, spatial orientation, vestibular, vision

1. Introduction

Humans keep track of their orientation and location by a normally effortless and reliable sensory integration process, even when visual cues are momentarily absent (Pick and Reiser 1982; Ivanenko et al. 1997; Loomis et al. 1992; Loomis et al. 1993; Mittelstaedt and Glasauer 1991; Rieser 1989; Rieser et al. 1986). Nonetheless, people occasionally need to reorient themselves when they view a familiar environment from a unfamiliar direction, or if their sense of direction or place is mistaken – for example when a person emerges from an underground subway station and discovers that familiar landmarks do not lie in the expected directions. In such situations, the ability to imagine the spatial structure of an environment from a different direction is presumably important. When learning a new environment, subjects may remember it from one or more "prototypic" views, and generally perform better when they imagine themselves moving within a stationary environment, rather than imagining the equivalent movement of the environmental objects about themselves (Huttenlocher and Presson 1979; Wraga et al. 1999). The prototypic spatial model of the environment is usually relative to a spatial framework defined by the observer's body and view direction (e.g. front/back, left/right, headward/footward referent directions), but it can also be from an environmentally fixed external perspective. There is evidence that mental models of environments are categorical, reflecting conceptions of space rather than direct "photographic" mental images of it. Imagining an environment from a novel perspective presumably involves applying a transformation to the prototypic spatial model. The headward/footward and front/back asymmetries in the human body, and the up/down asymmetry imposed by gravity on the environment apparently help people retrieve spatial information slightly ($<$0.8 sec) faster: Imaginary objects located gravitationally above or below are identified slightly more quickly; imaginary objects located on the subject's left or right are identified more slowly (Franklin and Tversky 1990; Franklin et al. 1992; Bryant and Tversky 1992).

Humans evolved as terrestrial creatures, and most large body rotations occur about the body's head/foot axis, which is usually aligned with gravity. What are the limits of human ability to imagine rotations and to reorient in environments when body rotations are not so constrained? Skylab and Shuttle astronauts have reported momentary disorientation when they float into an unfamiliar orientation inside their spacecraft. Since gravity is absent, there is a natural tendency to perceive whichever interior surface that is closest to being beneath their feet as a "floor". As a result, the floors, walls and ceilings exchange subjective identities. The sudden change in perceived orientation, termed a "visual reorientation illusion" (VRI) triggers attacks of space sickness (Oman et al. 1986), and makes crewmembers reach the wrong way for remembered objects and look the wrong way in search of visual landmarks. Astronaut disorientation problems have recently been compounded by the complex three dimensional interior architectures of the Russian Mir space station and the International Space Station (ISS). These large spacecraft consist of multiple research and logistics modules, connected together by one or more “nodes”. The Mir station had a single central node. The ISS may eventually have as many as six. Each node has six hatches, 90 degrees apart, each facing one of the principal spatial directions. When fully configured, each hatch leads to an adjacent research or logistic module. Unlike houses on Earth, where all floors are in parallel planes, the “floors” of some research and logistic modules on Mir and ISS are oriented 90 degrees or even 180 degrees apart. Many ISS modules have equipment racks on the ceiling and floor as well as the walls, creating dual visual verticals. As a result, crewmembers say they frequently experience VRIs and loose their sense of direction, particularly when traversing nodes. “Even though you knew the modules went in six different directions, it felt like the node was a vestibule in a single story house”. Crewmembers apparently rely on hatch labeling and use memorized landmarks and routes. However, the ability to transform a 3D mental model of the station is arguably essential in certain emergency situations, for example should visual landmarks be obscured due to smoke or darkness. Space station crewmembers currently have little opportunity to develop such a mental model of the entire station before they fly. It is impractical to physically connect multiple ground simulator modules and nodes together in the complete flight configuration. Instead, crews train inside individual module simulators, working in an upright gravitational orientation. They have no opportunity to view the module interiors from non-upright perspectives. Some astronauts tried practicing moving around inside a simulated Spacelab module interior (Parker et al. 1993) in order to reduce their susceptibility to space sickness. However, the effectiveness of this training on spatial orientation ability within the module was not measured, and the technique is not in routine use. The situation is different with respect to training for extravehicular activities: Astronauts have long recognized that it is important to train for spacewalks in ways that give them visual experience working in a variety of different body orientations relative to the spacecraft. Crews routinely rehearse spacewalks in neutral buoyancy facilities, and use immersive virtual reality simulators.

NASA’s National Space Biomedical Research Institute (NSBRI) recently began to develop 3D spatial orientation assessment methods appropriate for astronaut preflight visual orientation training. This experiment was part of that effort. We studied how well our subjects could learn to imagine rotations as if they were at the center of a simulated space station node. The node was approximated by a cubic chamber, with display monitors mounted at the center of each interior surface. A picture of a familiar object could be presented on each monitor. The pictures were analogous to hatches leading to adjacent space station research modules. Just as a disoriented astronaut might view the interior of the space station node from an arbitrary or unexpected viewing orientation, in our experiment a display computer could change which picture appeared on which monitor. The computer could rotate the entire array of six objects around the subject, preserving the spatial relationships between all the objects, but changing their relative orientation with respect to the subject. In our experiments, subjects were given the opportunity to learn the spatial arrangement of the objects from a prototypical orientation. Then their ability to imagine themselves in a variety of different orientations was tested in successive trials by specifying a different imaginary orientation relative to the prototypical orientation, and then measuring the accuracy and speed with which they pointed at a specific imaginary object. Before the end of each trial, the displays were turned on for a few seconds so subjects could actually see the object array in the transformed orientation, and verify the correctness of their previous answer. Our hypothesis was that subjects would learn from experience how to visualize this relatively simple, six object array from four different roll orientations, and that their accuracy would gradually improve and their response time would diminish somewhat. Based on prior research, we expected that most subjects would imagine themselves rotating, rather than rotating the object array around themselves. We expected that if the subject's viewing direction was changed, and the subject was asked to imagine roll orientations about a different axis, they would learn to do the task as well or better than from the first view axis orientation. We anticipated that response time might show some dependency on target direction relative to the body axis or whether the subject's body was in a gravitationally erect vs. supine position, but believed that the task error rate would not be strongly dependent on body posture. Because mental imagery could be used to perform the task, we hypothesized that measures of task difficulty and performance might correlate with results of traditional paper-and-pencil tests of visual field dependence and 2/3D figure mental rotation ability. Our experiments were initially conducted with a physical display. Since virtual reality techniques could be used for astronaut spatial memory training, we repeated the experiment with a different group of subjects in a "virtual" node using a head mounted display (HMD) in order to see whether the distortion, dynamic lag, and field of view limitation introduced by the HMD were significant impediments to spatial learning using our paradigm.

2. Materials and methods

Learning effects prevented use of a factorial crossover design. Experiments were blocked by display system/subject group: physical display tests used

Figure 1. Physical display apparatus. Subject supine. Four of the six display monitors mounted to the walls of the node are visible.

73 subjects, aged 18–22, from Texas A&M University; virtual display tests used 24 subjects (ages 19–45), from Massachusetts Institute of Technology. As shown in the Figure 1 photograph and Figure 2 schematic, the physical display apparatus consisted of a cubic (4 ft. × 4 ft.) plywood chamber, with a black interior. Objects were presented on computer display monitors mounted at the center of each of the walls. Subjects head and torso were positioned into the chamber through an aperture. Subjects' were tested while both lying supine on a small cot (Figure 1) or while sitting erect in a chair (Figure 2). Subjects were free to move their heads to look around at the objects.

The virtual display system shown in Figure 3 consisted of a head mounted display (Kaiser Proview 80 , 68 deg. × 48 deg. field of view per eye, 640 × 480 × 3 resolution, 100% binocular overlap) and an electromagnetic head tracker (Ascension Flock-of-Birds). A visual scene resembling the six walled interior of the physical node was rendered in color stereo by a graphics accel-

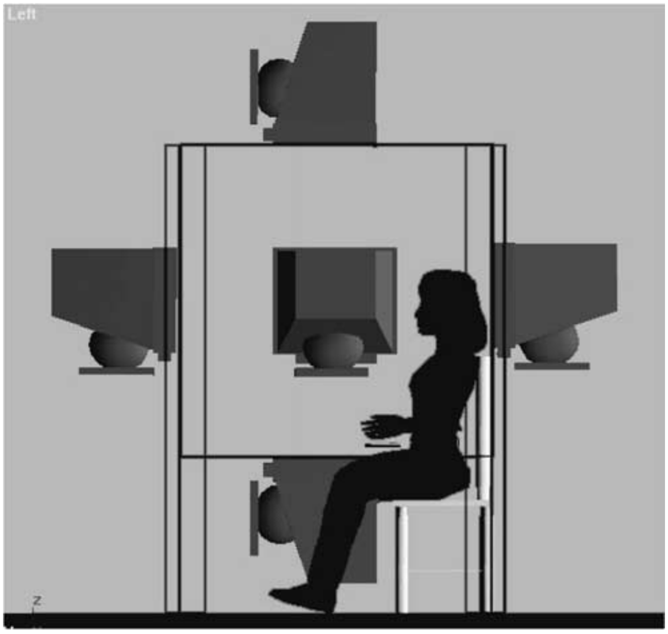

Figure 2. Physical display schematic. Subject seated.

erator equipped PC workstation (25 Hz. average scene update rate, 65 msec. lag from head movement to scene motion). As with the physical display, the virtual display subjects sat erect in a chair or lay supine on a cot. Since the HMD could not be worn supine with the head resting on a pad, the supine subjects' heads were supported by a system of pulleys and counterweights, as shown in Figure 3. The HMD restricted the instantaneous field of view of the virtual display group compared to that of the physical display group, but the pulley/counterweight system allowed the HMD users to make the head movements necessary to see all the objects.

For both the physical and virtual display, the object array consisted of small color 2D pictures of familiar, easily recognizable and nameable items. During the first five trials, the orientation of the array was not changed, so that the subjects could learn the objects' locations from a prototypical viewpoint. In this prototypical orientation, the objects and their locations were: a broom (above), a light bulb (right), a pair of scissors (below), a saw (left), spark plug (ahead), and a pizza (behind). Each object subtended approximately five degrees of visual angle. The entire array of objects could be rotated as an ensemble by the display computer, so that any object could be presented on any wall, but the spatial relationships between the objects in the array always remained constant relative to one another.

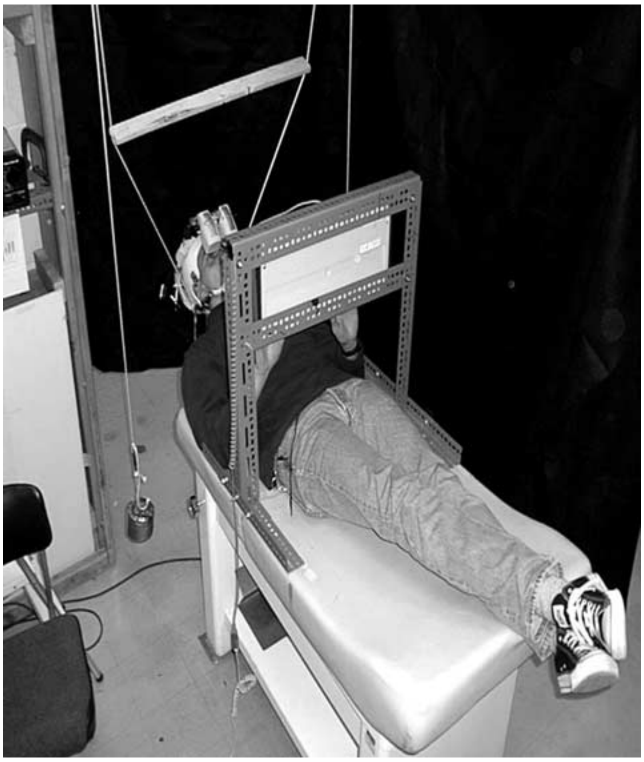

Figure 3. Virtual display apparatus. Subject wearing HMD, lying supine. Head support counterweight system, and waist level bracket support for response keyboard.

Before beginning the experiment, subjects were provided with scripted instructions, and were allowed 10 practice trials using a different environment to become familiar with procedures. (The practice environment had 1-6 black spots on each wall, in the familiar arrangement of a gambler's die. A small handheld clear plastic model of the practice environment was used to explain the experiment concept).

As shown schematically in Figure 4, during each 18 second experimental trial, subjects were first shown a clock hand on the opposite wall. This indicated the desired imaginary body roll orientation for the trial relative to the prototypical orientation, with upright as 12 o'clock. Next they were shown a picture of the object which would be located immediately behind them when they were in the imaginary orientation, thus specifying the direction they were facing. A picture of a target object was concurrently shown. Next, all displays were turned off, and the subjects were told to imagine the object array from the previously specified perspective, and to indicate the relative direction to the target in body coordinates. To make the indication, subjects

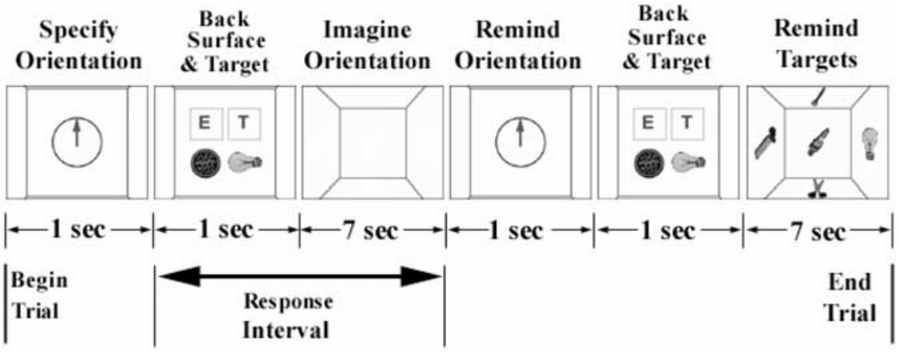

Figure 4. Timeline for each trial, schematically illustrating the sequence of display configurations.

pushed one of five buttons on a keyboard mounted at waist height. The buttons were arranged in a cross, with the center button denoting “ahead”, and the four adjacent buttons denoting “left”, “right”, “above head”, and “below feet” target directions in body axes. (The object behind the subject was never used as a target.) Though the keyboard was in the subjects’ transverse plane, none reported any difficulty remembering and using the button mapping. Finally, the imaginary orientation and target information was presented again, and the complete target array was displayed, rotated into the orientation called for in the trial. This allowed subjects to verify the correctness of their imaginary directional judgement based on direct visual observation of the array in it’s rotated orientation. To encourage the subjects to verify their answer, they were asked to indicate the target direction using the button. Subjects could use the remaining seconds to review the relative arrangement of the objects in preparation for the next trial. Inevitably, subjects were completely naïve about the arrangement of the objects in the array during the very first trial, but over subsequent trials they usually were able to memorize the relative location of the objects to one another. Subjects were free to use whatever strategy they desired to remember the array configuration. To allow subjects time to learn at least a few of the target relationships in a prototypical configuration without imaginary mental rotations, as earlier noted, the clock hand was kept at 12 for the first 5 trials. Thereafter, imaginary orientations and relative target directions were randomized and balanced across groups of 12 trials. Four successive trials were referred to as a “set”, since all four possible imaginary roll orientations were presented once every four trials. The entire experiment thus consisted of the five upright trials followed by 60 trials (i.e. 15 sets) in various orientations.

Average response time (RT) and percent correct (%C) were calculated from the imaginary target button push data for each four trial set to provide good time resolution. Data were omitted if the subject failed to respond. RT in each trial was measured from the moment of presentation of the imaginary target object. Subjects were instructed to respond accurately, but as quickly as possible. We considered %C as a direct measure of the accuracy of spatial memory, and RT as an indirect measure of spatial task difficulty. Since subjects usually took more time to respond when they were uncertain of their answer, we expected the two measures to be approximately inversely correlated.

Statistical analysis was performed using conventional repeated measures ANOVA packages (Systat v9.0, SPSS, Inc.; StatXact-4, Cytel, Inc.). For purposes of analysis results were compared over multiple sets: Learning during the first part of the experiment was assessed by comparing the RT and%C from sets 1–3 with those from sets 4–6. To test our hypotheses we manipulated the subjects body posture and view axis direction: Half the subjects in each group began training in an erect initial body posture (denoted "IBP-E" in the figures) and the remainder began supine ("IBP-S"). After five upright practice trials and 24 randomized trials (i.e. sets 0–6), each group then changed body posture. Testing continued for another 12 trials (i.e. sets 7–9). The effect of changing gravitational posture was assessed by comparing RT and %C data from sets 4–6 with those from sets 7–9. To see whether the subjects' knowledge of the environment from the first viewpoint helped them learn to do the task from a second viewpoint more easily, the view axis direction was shifted by 90 degrees beginning with set 10: The back surface was shifted from the "pizza" to the "saw". The immediate effect of this change on performance was assessed by comparing the change in RT and %C data between sets 9 and 10.

At the beginning of each session, subjects completed the Group Embedded Figures Test (GEFT, Witkin et al. 1971), and the Card Rotations and Cube Comparisons Tests (Eckstrom et al. 1976). At the end of the session, subjects completed a strategy questionnaire, which included both multiple choice and open ended questions about the strategies they employed in learning the environment. Finally, their configurational knowledge was tested using a second written questionnaire. Subjects were provided with a list of alternative back surface/orientation/relative direction combinations, and asked to choose the correct response from among 6 target pictures. The entire experiment took approximately 2 hours to complete.

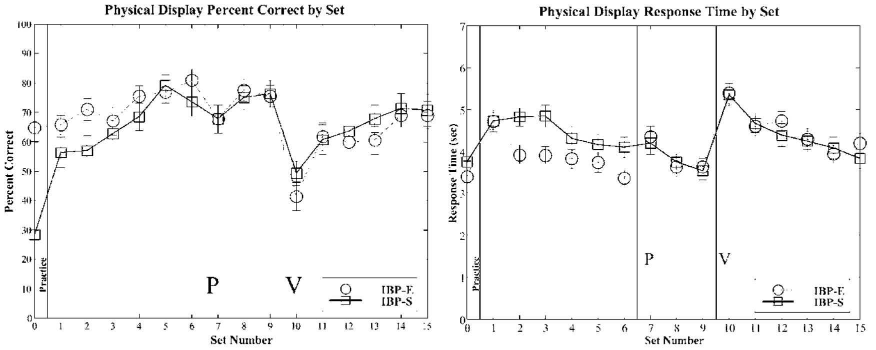

Figure 5. **Physical display group**: Left panel: Mean % C vs. set for erect(IBP-E, dotted) and supine(IPB-S solid) initial body posture. Error bars: +/– SEM. Right panel panel: Corresponding RT data. Four trials per set. IBP-E subjects started erect. P denotes body posture mainpulation after set 6. V denotes view axis manipulation after set 9

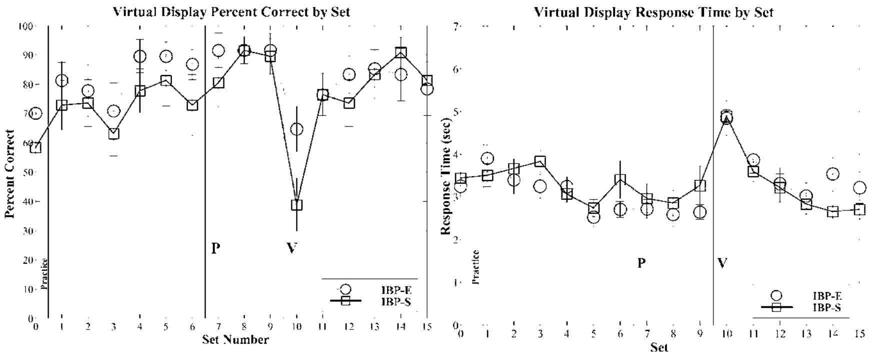

Figure 6. **Virtual dispaly group**: Left pannel: % correct; Right panel: RT. Other details as in Figure 4.

3. Results

Figures 5 and 6 show the mean %C (upper panel) and RT (lower panel) for the physical display and VR display groups, respectively. In the figures, the set numbers where posture and viewpoint were changed are denoted with “P” and “V”, respectively.

If subjects were simply guessing, on average they had one chance in five (i.e. %C = 20%) of making a correct indication. By the end of set 6 (29 trials, including the practice trials), %C had risen to the 70–90% range. Subjects were instructed to respond quickly, but they knew we were measuring their accuracy. RT consistently fell in the 3–5 second range, and as expected was inversely correlated with %C.

To examine learning during the first stage of the experiment, prior to manipulation of subject posture, we divided the %C and RT data into early (sets 1–3) and late (sets 4–6) epochs and then analyzed it using a repeated measures ANOVA with IBP and epoch as factors. The improvement in %C and RT performance between early and late epochs was significant for both the physical display group [%C F(1,71) = 31.19, $p < 0.01$ and RT F(1,71) = 34.44, $p < 0.01$] and the virtual display group [%C F(1,22) = 12.02, $p < 0.01$ and RT F(1,22) = 12.02, $p < 0.01$]. We found some evidence that initial learning may be slightly easier in the erect posture: During sets 1–6, those subjects who trained first in the erect posture had significantly higher %C scores (sign test, $p < 0.05$) than those whose first training was in the supine posture. For virtual display subjects the effect was significant over all 6 sets. For physical display subjects, the effect was significant only over the first 3 sets. However no corresponding significant effect of IBP on RT was found. We concluded there was an effect of body posture on acquisition of spatial memory, at least in the early stages of the experiment, but that the effect was quantitatively not a major one.

Using a similar approach, we also tested for effects on %C and RT resulting from the manipulation of body posture at set 7. Comparing data from sets 6 and 7 we found a small decrease in %C for the physical display group [F(1,71) = 6.37, p = 0.05]. The change was reliable, but quantitatively small. For the virtual display group, we could not demonstrate a significant change in %C, and the IBP interaction was not significant. RT increased for the physical display IBP-E group [F(1,370 = 17.14, p = 0.001)] but other RT changes were not significant. By set 9, the %C of both groups had improved to levels similar to or greater than the asymptotic performance level achieved prior to the posture manipulation.

Changing the direction the subject's view axis after set 9 – so the subject now faced the object that had previously been on the right in the baseline orientation – produced a larger and longer lasting effect on %C and RT as compared to body posture manipulation. Comparing the set 9 and 10 data, %C decreased 30–40%, and RT increased by about 2 seconds for both the physical and VR display groups. All four effects were statistically significant: Physical display %C [F(1,71) = 44.33, $p < 0.01$] and RT [F(1,71) = 64.03, $p < 0.01$]; Virtual display %C [F(1, 22) = 23.50, $p < 0.001$] and RT [F(1, 22) = 22.72, $p < 0.001$]. Comparing sets 10–12 with sets 13–15 significant improvements in both %C and RT were seen for both display groups: Physical display%C [F(1,71) = 31.52, $p < 0.01$] and RT [F(1,71) = 58.51, $p < 0.01$]. Virtual display %C [F(1, 22) = 16.30, $p < 0.01$] and RT [F(1,22) = 37.98, $p < 0.01$].

For both display groups, the trajectory of improvement in %C and RT after the view axis change to a new viewpoint was similar to or slightly faster to that in sets 1–6. For the virtual display group, the asymptotic level of %C and RT for sets 13–15 could not be distinguished from that for sets 4–6. However, for the physical display group, asymptotic %C and RT were slightly (but significantly) poorer for IBP-E subjects. The physical display IBP-E subgroup had significantly lower %C [F(1,37) = 11.25, $p < 0.01$] and longer RT[F(1,37) = 11.92, $p < 0.01$] for sets 13–15 than they did for sets 4–6.

Based on the previously cited research of Bryant and Tversky, we had expected that our RT data might show small effects of relative target direction. We were unable to demonstrate this, possibly because the learning process caused more variation in our RT data. Bryant and Tversky's subjects were allowed as much time to learn the environment as they wanted prior to performance measurement.

The overall differences in performance between the two display groups through the entire experiment was not large, but the virtual display group performed slightly but significantly better than those trained with the physical display (median test exact statistic = 8.3, $p < 0.01$ for % correct; = 17.5, $p < 0.001$ for RT). The virtual group also outperformed the physical group on the written exit questionnaire test of configurational knowledge (89% vs. 73%).

As shown in Table 1, the %C results for both display groups correlated significantly (t test, $p < 0.05$) with the results of the Group Embedded Figures Test (GEFT), and the Cube and Card rotation tests. RT also correlated significantly with all three of the pencil-and-paper test scores for the physical display group. The exit questionnaire configurational knowledge scores of the physical display group correlated with their own mean % correct score (rho = 0.69, $p < 0.01$), mean RT (rho = –0.28, $p < 0.05$) and GEFT (rho = 0.38, $p < 0.01$) results.

Tabulation of the post-experiment strategy questionnaire results (Table 2) showed that most subjects claimed to visualize the node from an internal rather than external perspective, to imagine the node as stationary, and to mentally rotate themselves within it. (In retrospect, our use of a handheld model gambler's die in the training procedure may have led a few subjects to imagine themselves outside the node, or to imagine themselves as stationary, while mentally rotating the node.) Typically subjects began by memorizing opposite pairs of objects. When their viewpoint was shifted, almost everyone used the same strategy they had used initially, though some chose to relearn the node from the new prototypical viewpoint, while some said they kept

Table 1. Pearson correlation coefficients for paper and pencil tests

Test Type	GEFT		Card rotation		Cube compare		%C		RT	
	Physical	Virtual	Physical	Virtual	Physical	Virtual	Physical	Virtual	Physical	Virtual
	1		1	1	1	1	1	1	1	
GEFT	1	1								
Card Rotation	0.18	0.61**	1	1						
Cube Compare	0.35**	0.68**	0.35**	0.72**	1	1				
%C	0.40**	0.49*	0.24*	0.54**	0.35**	0.35	11			
RT	–0.22*	–0.19	–0.25*	–0.30	–0.24*	–0.16	–0.47**	–0.57**	1	1

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

the original prototypical viewpoint and did an additional mental rotation. We were unable to demonstrate a consistent difference between the physical and virtual group questionnaire responses using a chi square analysis, nor did we find any clear relationship between answer category and mean %C and RT. As to whether the learning task seemed different when lying down vs. sitting upright, classification of their written answers (90 responses) showed: 51% felt there was no substantial difference, 26% believed erect was easier, 16% said supine was easier, and 7% made other comments.

4. Discussion

Subjects were interviewed informally by the experimenters at the conclusion of the session. Most said they found the early trials frustrating, but eventually discovered ways to do the task. Many subjects named the objects, memorized opposite pairs (e.g. “the light bulb is opposite the saw”) , and constructed mnemonic rules to help them remember where each object was when seen from the prototypical upright orientation (e.g. “the scissors are lying on the floor”). The prototypical arrangement of objects was often described using terms (“floor”, “ceiling”) that implied a gravitationally upright orientation of the imaginary prototypical viewpoint. Many claimed that by the end of the experiment they could mentally visualize the environment on most trials, falling back on their rules on some trials where they had difficulty. Their occasional use of rules to interrelate landmarks may be analogous to occasional reversion to use of landmark and route strategies by subjects who have

Table 2. Tabulation of post experiment strategy questionaire responses

Questions:	Answer category (n = 97)			
How did you go about learning the configuration of the node?	Paired opposite objects	Attached meaning to objects	Other	N/A
	74	9	13	
How did you go about determining the target location?	Imagined self stationary, mentally rotated the node	Imagined node stationary, mentally rotated myself	No mental rotation, just memorized each situation	Other
	23	66	2	4
How did you mentally visualize the situation?	Imagined self inside node	Imagined self outside node looking in	No visualization, just memorized each situation	Other
	68	10	16	2
When the back surface was changed, what is the strategy you used to determine the target location?	Learned all over again using same strategy	Learned all over again using different strategy	Mentally rotated from old to new viewpoint, then used same strategy	Other
	38	1	53	4

configurational knowledge of an environment, as described in the navigation literature (e.g. McDonald and Pellegrino 1993). For most subjects, the task became something “done in your head”, and the gravitational body posture and display characteristics did not seem to be of major importance. This encourages us to believe that if it were possible to repeat experiment aboard a spacecraft in true weightlessness, using either the physical or virtual display technique, substantially the same results would be obtained.

Although the averages responses of the virtual and physical display groups was qualitatively similar, the %C and RT performance of the virtual group was slightly better. The bottom quartile of physical display group did not achieve as high a performance level as the rest of the subjects. Though this could be due to the different displays the two groups used, it could also be due differences in the abilities of the two groups, who were from different universities. We could not find any difference between the groups performance on the Card Rotation Test or GEFT, but the virtual group outscored the physical group on the Cube Rotation test (median test exact statistic = 5.3; $p < 0.05$).

The observed correlation between our measures of spatial task accuracy (%C) and difficulty (RT) and the paper-and-pencil test scores of both groups is interesting. The task was designed to require an imaginary rotation of the self relative to an imaginary object array. The Cube and Card rotation tests measure the ability to mentally rotate pictures of 2D and 3D objects. The Group Embedded Figures Test measures field dependence/independence, and has been related to the influence of a visual frame on the subjective vertical (Asch and Witkin 1948). However, it is also a measure of general cognitive ability and problem solving style (Arthur and Day 1991). Performance on our experimental task probably correlates with many measures of cognitive and analytic ability, and not just mental rotation capability.

5. Conclusions

Astronauts who become disoriented inside a space station node arguably regain their sense of direction via a cognitive process that involves imagining their three dimensional orientation relative to the hierarchical spatial framework (coordinate system) defined by the station's architecture . Within a space station node, the local spatial framework is defined by six hatches, 90 degrees apart, leading to adjacent modules. Previous research on spatial learning has addressed terrestrial situations. The ability of human subjects to rapidly learn a three dimensional spatial array, to imagine their bodies in arbitrary three dimensional orientations within it, and to accurately predict the relative direction of target objects has not been previously quantified. Results are therefore also of general interest.

Experiment results confirmed that the majority of our subjects were able to learn the environment and achieve relatively high target direction accuracy (70–90%, where 20% was the chance criterion) within 20 trials from a given viewpoint, regardless of roll orientation. Changing the imaginary viewing direction within the environment produced a transient decrease in performance, but subjects' subsequently learned to perform from the second viewpoint with equal or greater ease. As expected, most subjects said they memorized the environment from a prototypical orientation, and imagined themselves rotating within it, rather than rotating the objects around themselves. When imagining their orientation, subjects apparently used a combination of declarative mnemonic rules and mental visualization techniques. A correlation between task performance and individual subject's scores on paper-and-pencil tests of 2D and 3D figure rotation ability and field independence was found. However, we were unable to demonstrate an effect of target direction relative to the body on response time, as has been observed in other studies. Manipulation of the subjects' body posture with respect to gravity during our experiment produced a statistically significant but quantitatively small effect on accuracy and response time. This finding encourages us to think that the results of our experiments – necessarily conducted in 1-G – probably apply in 0-G as well. Since NASA uses immersive virtual reality techniques for preflight training, we repeated our experiments using a group of subjects who wore a head mounted display. Although the virtual reality display imposed limitations in field of view, resolution, and head tracking delays, performance of this group was qualitatively similar – or better – than the group which used a physical display. Taken together, these findings indicate that head mounted displays can be employed for this type of spatial memory training, and that subjects may remain in the physically more comfortable and practical gravitationally erect position.

Spatial memory proceeds effortlessly in our normal terrestrial lives, but our experiments demonstrate the difficulty of spatial visualization tasks when the viewpoint requires reorientation in three dimensions, as is the case for astronauts or aerobatic aircraft pilots. Many important research questions remain: we tested learning while facing in only two different directions. Does each viewpoint have to be learned independently, so that at least 120 trials are required to learn all six viewpoints, or does the spatial framework established from training from one or two viewpoints help in learning the remainder? Can subjects perform the task if roll orientation and view axis direction are chosen completely at random? To optimize learning, should viewpoints be blocked or randomized? How frequently must subjects practice to retain their abilities? Our experiments used a relatively simple six object spatial framework. How well do subjects perform if the spatial framework is more complex, and involves hierarchical relationships between objects? Can subjects "learn how to learn" a 3D spatial framework by developing generic strategies which accelerate learning in other environments? What strategies are most successful? Does it help to formally teach them? Another series of experiments (Richards, et al. in preparation) has found answers to some of these questions.

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