A Training Methodology for Spatial Orientation in Spacecraft

By

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ABSTRACT

This thesis investigates a way to use virtual reality techniques to teach space vehicle inhabitants about the configuration of their craft so that their performance in orientation and spatial memory tasks is improved. An "adjacency training" method was developed that taught connections between landmarks in two joined modules with inconsistent visual verticals by emphasizing functional relationships among adjacent surfaces within and between modules. An experiment was performed (n = 17) that compared this training with a control treatment that emphasized the rotational relationship between the two modules as a whole rather than connections between individual surfaces. On average, adjacency training was not effective in decreasing the total time to respond or increasing the accuracy in placement and orientation of module walls between the two modules. Adjacency trained subjects were significantly better in responding to a novel perspective. All subjects responded to an orienting cue surface more quickly when visually upright, suggesting their spatial knowledge of both groups remained orientation dependent. However, within each group, subjects who used a "consistent visualization" as determined by a post training questionnaire, performed 5 seconds faster ($F(1,9)=7.41$, $p= 0.02$) than the subjects who did not. Visualization consistency was determined by asking the subjects to describe which direction they considered one module to be when viewed from the other module and then the reverse. Consistent responses indicated that the subjects were able to combine/concatenate their cognitive mental maps of each of the modules and make correct, consistent judgments in a single allocentric coordinate frame. Subjects who reported consistent visualization were distributed evenly among both training groups, so the training manipulation had no clear effect on the consistency of visualization achieved. The adjacency training method did help subjects remember the relationship between objects on which they had been specifically trained, as determined by a subsequent post-training questionnaire

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1 Introduction

A spacecraft in orbit is a disorienting place to be. Astronauts report Visual Reorientation Illusions and Inversion Illusions (Oman 2006) and – ever since the Apollo missions of the 1960s – additional spatial memory and navigation problems created because the visual vertical of adjoining work areas are not always aligned (Figure 1) Spacecraft interior architecture created similar problems on Mir, and the problems may recur on future spacecraft, such as Mars transit spacecraft. This thesis investigates a way to use virtual reality techniques to train space vehicle inhabitants about the configuration of their craft so that disorientation is reduced.

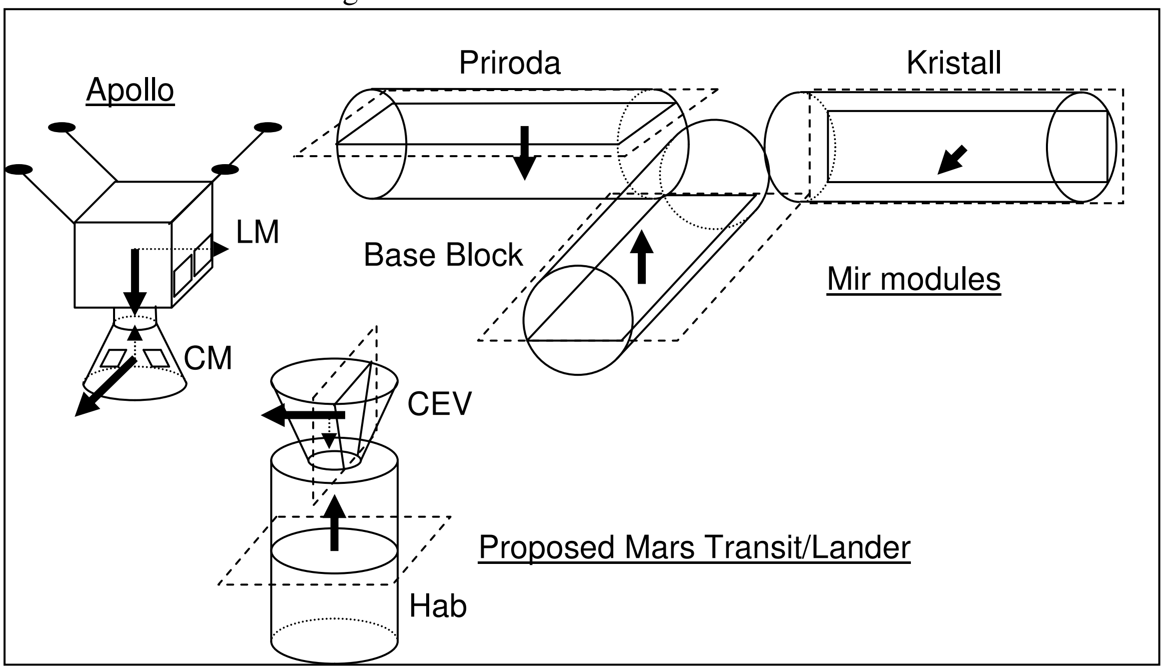


Figure 1. Visual verticals of multi-module spacecraft. Solid arrows are the visual vertical and thin arrows point forward relative to the crew's normal working position.

Today's astronauts and cosmonauts first encounter mockups of the vehicles they will be traveling in space laid out either on the floor in Building 9 at Johnson Space Center (Figure 2) or the Cosmonaut Training Facility in Star City. Because gravity is present, some of the individual module mockups cannot be arranged relative to the others in the same physical orientation as in flight. (If they were arranged as shown in the Figure 1 examples, some areas would be tilted 90 degrees or upside down relative to gravity. Crews like to train visually upright so they can read labels, and usually work in that orientation when in flight). Astronauts visually experience the correct relative orientation of the modules for the first time when they enter them in orbit. Crews presumably acquire mental representation (a cognitive map (O'Keefe and L 1978)) of individual modules, where "up" and "down" are defined by the gravity-constrained arrangement of the mockups they trained in.

Flight

Ground

Figure 2. Flight and ground configuration of International Space Station.

There is reason to think they may have trouble mentally assembling a correct complete cognitive map for the entire station from their cognitive maps of the individual modules. For example, several astronauts have reported being lost and disoriented when transiting or making spatial judgments between modules (Richards, Clark et al. 2001; Lu 2003). This could be dangerous, especially in the first days of the flight when disorientation may be strongest. If there is a fire or a power failure – and a consequent loss of visual cues – an astronaut with an inaccurate mental model of the complete spacecraft might not be able to navigate accurately through it. If not completely lost, at least they would have to regress to memorized landmark and route navigation strategies; which themselves might not be reliable. The cues in the ground mockups are often different from those in the orbiting modules because they are often lower fidelity; some flight equipment is not installed on the racks of ground mockup trainers, wires could be in different bundles, labels and marking could be in different locations, etc. Arguably an imperfect cognitive map may have contributed to the Mir collision of June 1997, as the inhabitants of the station, two of whom had been orbiting for at least 120 days, did not know which window to look out of to properly track the incoming Progress module. Other stories of the Mir crews reporting loss of orientation while traversing the central six-sided node between modules are documented by Richards(2001). Mir crewmembers fashioned Velcro arrows to help visiting Shuttle crews find their way home. On the International Space Station, some vehicles often dock with at 90 degrees with the main station axis (e.g. Shuttle, Soyuz, Progress, MPLM) and other modules have multiple interior visual verticals (e.g. US lab and nodes), or verticals that do not align with adjacent modules (e.g. Partner EVA Air Lock). When emergency exit signs were first posted inside an ISS node by a crewmember they were initially placed pointing in the wrong direction.

While disorientation and navigation problems have been noted in previous flights, so far ground training has not been modified to reduce its occurrence. Disorientation episodes have also been reported during EVA. Anecdotally, one reason astronauts train for EVA in neutral buoyancy tanks is to gain visual experience working inverted, though in fact many actually work gravitationally upright because being upside down in the suit underwater is uncomfortable. Over the past decade, virtual reality has been used extensively as an adjunct to EVA training, and it reportedly provides valuable additional experience (Walz 2002). However, currently training sessions for non-space suited activities inside mockups generally provide experience in only one relative orientation. When a trainee learns the position of a particular switch or dial, they implicitly learn that it is “below” or “to the right of” another position. Their training generally provides few opportunities to orient or practice procedures from other relative body orientations, and when they do utilize those opportunities they say the interiors seem like a whole different place (NASA Astronaut R. Satcher, personal communication).

Hopefully, the training methodology proposed in and partially validated by the research in this thesis will allow crews to arrive in orbit with a correct mental model of the vehicle already encoded. One way to gauge if the most efficient mental model of an environment is being utilized is by analyzing the time to respond to 3 dimensional spatial orientation and position questions and to measure how accurate the responses are. A person with the most efficient model would have a less orientation-dependent response (i.e. would not respond faster or more accurately when the environment is presented from one particular set of relative body orientations, e.g. visually upright).

2 Background

2.1 Previous work

Using immersive virtual reality techniques Oman (2002) and Richards (2000) showed that subjects wearing a head mounted display (HMD) and head tracker can be trained to recall the relative location of nameable objects (e.g. animal pictures) displayed on the interior walls of a 6-sided cube regardless of subject relative body orientation. Accuracy was dependent on mental rotation skills, but largely independent of physical orientation with respect to gravity (Oman, Shebilske et al. 2002). Subjects who were taught a specific learning strategy (e.g. memorizing opposite pairs or corners) performed better than those who were not (Richards, Oman et al. 2002).

2.1.1 Benveniste 2004

Following up, Benveniste (2004) hypothesized that the cognitive map of the space station formed based on experience in incorrectly oriented replicas on the ground could be hard to unlearn. He studied the ability to learn the interiors of two realistic cubic modules. Seated subjects wearing a HMD viewed these virtual spacecraft module interiors. Each module had readily distinguishable floor, wall and ceiling textures defining a locally consistent visual vertical. As shown in Figure 3 ("Benveniste" row) subjects learned these modules first separately, then together, attached in two different configurations. The intrinsic visual verticals of both modules were co-aligned in the first configuration the subject learned but not the subsequent one (where the 2nd module was yawed and pitched relative to the 1st, the non-aligned configuration) and walls at the interface between the modules were different in the two configurations. Subjects initially listened to verbal guided tours of the modules. Then, during repeated computerized trials in which they were only shown the wall facing them (the "cue" wall), they had to determine their own relative orientation with respect to the interior, and then predict the relative location and orientation of a second wall (the "target" wall) in either the local or adjacent module. The virtual environment was pseudo-randomly rotated between each trial. After each trial the subject was allowed to see all walls so they could verify their answers. Trials were split into different phases, in which the configuration of the environment seen was changed, as shown schematically in Figure 3. Subjects were initially trained in first one module and then a second. Then in the final three phases, the two modules were viewed joined together In these final phases, subjects were located in the first module and had to place and orient the target wall in the second without feedback between trials. For each orient/place-target trial, the total time to respond and the percentage of correct responses were measured. Analysis showed that time to respond decreased continuously within each phase, but was significantly larger in the non-aligned configuration than the aligned one. Percent correct reached very high values early in the experiment and was significantly but slightly lower in the non-aligned configuration than the aligned one. The target position relative to the subject's body did not affect performance, but orientation with respect to the cue wall did: subjects responded significantly faster when they were visually upright in the local module than when upside-down. Although alternative explanations cannot be ruled out, data collected and subjects' comments suggested that unlearning the aligned cognitive map posed a challenge, and that subjects' knowledge of modules in the aligned configuration, acquired earlier in the experiment, impeded their subsequent learning in the non-aligned configuration, at least for the complex flight configuration used.

		Training			Testing	
Phase		1	2	3	4	5
Configuration	Benveniste	Ground	Ground	Ground	Ground	Flight
	Oman	Ground	Flight	Flight	Flight	Ground
Targets		Local	Local	Adjacent	Adjacent	Adjacent
Feedback		Yes	Yes	Yes	No	No

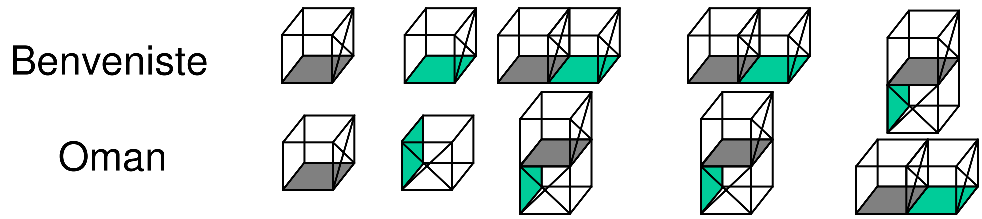


Figure 3. Procedure and configuration of the Benveniste and Oman experiments. Gray surface represents the floor of the first module, green the floor of the second. The X represents a specific wall

2.1.2 Oman 2006

In a subsequent effort, a second group of subjects was tested using the identical experimental paradigm, but this group learned the non-aligned configuration first and then were tested in the aligned configuration without feedback (Figure 3) (Oman 2006). Most subjects learned to perform the orientation/placing task with >90% accuracy in both groups. Response time for both groups in the flight configuration was significantly (F(1,32)=58) longer (4- 6 sec.) when locally visually upright, and greater still when tilted or upside down. Response time correlated significantly (R^2>.3, p<0.001) with standard 3D Cube Comparison (Ekstrom, French et al. 1979) and Perspective Taking Ability (after (Kozhevnikov and Hegarty 2001)) test scores. It was concluded that both groups remembered each local module in a visually upright orientation. In the flight configuration, apparently they needed over 5 seconds to interrelate their local cognitive maps in order to form a unified cognitive map of the entire spacecraft in a single, unified, “allocentric” (spacecraft fixed) coordinate frame.

2.1.3 Lessons from previous work

Considering the experiment results together, it was concluded that spacecraft designers should ideally keep module visual verticals aligned. However, it may be practically difficult due to other engineering considerations. If so, then what is the best way to train a subject so they have a unified cognitive map of the interior of the entire spacecraft, in which cognitive maps of individual models are combined or concatenated together efficiently, and inter-module spatial judgments can be easily made?

When subjects in the Benveniste and Oman experiments were debriefed, we consistently noted that some of the better performing subjects remembered pairs of surfaces that were adjacent to each other between the two modules. They would use these “bridge” surfaces to remember how the two modules were aligned and therefore could respond particularly quickly and accurately whenever a bridge surface was shown. It then logically followed that they would do better if they were taught several bridge pairs that more completely defined the relationship between the two modules, giving the subject a better mental representation of the environment, rather than using the strategy we generally verbally suggested, which was to memorize the relationship between the modules in terms of a sequence of rotations. The difference between the absolute level performance of Richards' subjects (who had to memorize abstract relationships like "the pizza is opposite the light bulb") and Benveniste's subjects who saw realistic environments and could invoke functional relationships ("this bar is next to the window so I can hold it to observe what is outside") led us to conclude that explicitly teaching subjects functional relationships between landmarks would increase their performance as well.

2.1.4 Other previous work

Some prior research shows that multiple views of the environment can reduce orientation specificity of the cognitive map a local environment (McNamara 1986). If the orientation dependency of an astronaut's 3D map could be reduced, it would assist astronauts in the performing tasks in orbit (Stroud, Harm et al. 2005). When multiple views are presented, random ordering of orientations during training should enhance 3D spatial skill transfer and retention (Bjork 1994; Shebilske, Tubre et al. 2006).

People learn quickly when they know what errors they make each time they practice (Salmoni, Schmidt et al. 1984). Effective training philosophy emphasizes the value of repeatedly trying something over and over again, continuously receiving feedback throughout the process so the trainee can know what to change right away and see the benefits of the change. In spatial relationship training, this concept can be applied by asking subjects about spatial relationships in many different orientations, showing them after each question what the correct relationship is, so that they can learn rules that help them visualize and orient in the environment that work despite changes in relative body orientation with respect to the environment,. Other experiments (Bjork 1994) have shown that when teaching subjects to perform complex difficult tasks, sometimes it is useful to simplify the task at the start of the training so subjects are not totally confused. However, thereafter the training should revert to the full, more difficult task as early in training as possible.

2.2 Experimental design

From the previous results and training philosophy, a possible training strategy emerged based on the notion of teaching functional relationships between pairs of landmark objects located on adjacent surfaces within and between modules. Functional relationships were emphasized, so it would be easier to remember specific pairs of objects. We decided it would also be useful to formally teach the subjects pairs of such objects, and then verbally quiz them on the object pairs before beginning immersive VR training. During the beginning of immersive training in the combined modules, the first several trials would consist exclusively of these functionally related surfaces and objects.

In order to experimentally evaluate the effectiveness of such an "adjacency" based cognitive map training strategy, a second training strategy was needed as a control. For this purpose, a second training technique was used that did not stress adjacency of specific, functionally related landmark objects. The instructions instead encouraged subjects to learn the two modules as independently and think of them as rotated relative to one another, joined by a common surface. This "rotation" training strategy approximated the technique used by Benveniste to train his subjects.

None of the previous experiments explicitly tested two-dimensional spatial memory, per se, as a predictor of the subject's inherent ability to do the 3D orientation and positioning task. Such a spatial memory test would help us separate the effects of inter-subject differences in intrinsic ability to remember spatial relationships from the effect of adjacency/rotation training. A new spatial memory test, developed for this purpose, was developed for this experiment and is detailed in the methods section.

Pilot experiments comparing prototype adjacency and rotation methods demonstrated that a "within subjects" experiment design would not work; if subjects were trained using two different strategies and then tested on them, they tended to use whichever strategy they believed was better in the second half of the experiment, regardless of instruction. In these pilot experiments, many subjects chose – or invented- the adjacency method. Therefore, for the final experiment, a "between subjects" design was adopted, where two groups of subjects – balanced in terms of spatial ability – were trained, one using adjacency and the other using rotation, and all subjects were naïve at the start.

2.3 Scientific questions

Overall, this study attempted to answer the following scientific questions:

1) Was the training successful? Did the adjacency-training method increase the percent of correct responses and lower the time to respond, relative to the rotation method subjects? A comparison of response times and percent-correct between groups should, after being corrected for subject differences, provide a measure of the relative efficacy of the two training types. If not, then:
2) Did the subjects in the two groups actually use the strategy we trained them in? We decided that by analyzing the answers they gave to a questionnaire we administered after the experiment, and by analyzing their responses during VR training. We expected each subject's performance might depend on how successfully they were able to concatenate their knowledge of each of the modules into a single coordinate frame, and visualize each module reciprocally in a consistent way.
3) Did the adjacency training reduce the orientation dependency of the subject's cognitive map of the local module? Specifically, were the subjects in the rotation-training group more dependent on the relative orientation of the cue surface than those in the adjacency-training group? If the subjects in the rotation-training group show significantly larger effects of orientation on the time to respond to the cue, i.e. if the cross effect, Group*Orientation is statistically significant, it suggests that adjacency-trained subjects are using a less orientation-dependent mental model.
4) Did the adjacency training allow subjects to adopt an allocentric reference frame for the entire spacecraft based on the visual vertical of one of the modules, rather than using two independent reference frames interrelated by a mental coordinate frame rotation between them? It was anticipated that not all subjects would exhibit completely orientation independent responses, and much can be learned from them. For those subjects who had a significant within-subject effect of orientation in each module, if the relative body orientations that produce the shortest response time in each module are spatially co-aligned with one another, it may be inferred that the subject is likely using a consistent allocentric reference frame anchored to one or

another of the modules. The fraction of subjects in each group who have a consistent reference frame can then be compared.

5) Are adjacency-trained subjects better able to respond to novel perspectives than rotation-trained subjects? We can test that by comparing the groups' average time to respond (and percent correct) in looking from one (Command) into a second (EVA) module with the same quantities as measured when the subject is looking from the EVA to the Command module.
6) Are the subjects in the adjacency-trained group better able to remember spatial relationships taught in their computerized training, as measured by an independent method? We test that by comparing the groups' ability to recall and verbally describe the modules' configurations when their immersive testing is over.

3 Methods

3.1 Subjects and pre-tests:

All subjects (n=21) were MIT students or visiting students in MIT summer programs aged 19 to 29. They were recruited from emails to various technical student groups at MIT. Four did not complete the experiment due to symptoms of motion sickness. The remaining 17 subjects were divided between "Adjacency" training (n=8) or the "Rotation" training (n=9); approximately balanced by gender (4 females and 5 males in rotation-training group, 3 females and 5 males in adjacency-training group) and by Cube Comparisons Test score (Figure 4) as a general indication of spatial ability. The protocol for the experiment was reviewed and approved by the MIT Committee for the Use of Humans as Experimental Subjects. Subjects were paid for their participation, and received a bonus for good performance, as detailed an Appendix B.

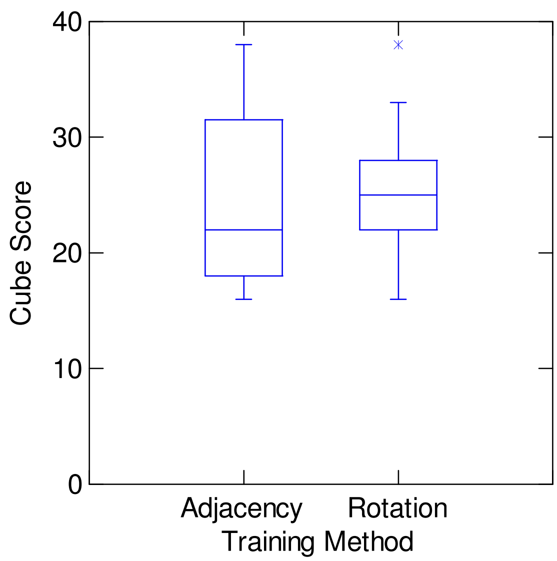


Figure 4. Distribution of Cube Comparison score by training group, boxes indicated first quartile above and below median while stems indicate second quartile.

Subjects took three types of pre-tests (Cube Comparisons, Perspective Taking Ability, and Spatial Memory) before doing the Virtual Reality training; their pre-test scores were later correlated with their performance.

The Cube Comparison (Ekstrom, French et al. 1979) test measured the subject's ability to mentally rotate a six-sided cube in three dimensions. An isometric view of two sided cubes was shown; three sides of each cube were visible. Subjects had to decide if the two images could be different perspective of the same cube.

Perspective Taking Ability (adapted by Kozhevnikov based on (Kozhevnikov and Hegarty 2001)) measures the ability to visualize a two-dimensional scene, seen from overhead, from a different perspective in the plane of the image. Subjects view a computer screen that shows an icon representing the view they must take and other icons representing landmarks. They must then indicate the direction of a certain landmark as seen from the perspective of the viewpoint icon.

The Spatial Memory test was a simple paper-and-pencil task developed specifically for the experiment. Test materials are presented in Appendix A. Subjects were shown a 2-D black and white photograph of a desk surface with 20 objects on it. They were read a list of 10 of the objects to ensure familiarity with their specific names and then had 60 seconds to memorize the location of objects in the photograph after being told they would be asked the locations of the objects and the objects relations to each other. Subjects then were asked to recall where those objects were located by indicating which section of the photograph the object was in (while answering these questions they were shown a blank outline of the photograph split into 11 uneven sections). They were also asked several true/false questions dealing with the spatial relation of those objects to other objects in the picture. No time limit was given to answer the questions, but subjects were encouraged to answer as quickly as possible. The same questions were asked twice, first right after looking at the photograph, and then at the end of the experiment (typically about 2.5 hrs later, and without showing them the photograph again). We called the latter the Spatial Memory post-test.

3.2 Equipment:

Virtual environments were generated using Vizard 2.5, a software program (WorldViz LLC, Santa Barbara, CA) run on a Dell PC (Xeon 2.4 GHz processor, NVIDIA Quadro4 Graphics Card) PC. Color stereo scenes were displayed on an NVIS nVisor SX Head Mounted Display (HMD) (50 deg. diagonal field-of-view, 1280x1040 pixels per eye) and tracked by an Intersense IS-600 Mark II 6-DOF or IS-300 head tracking system. When IS-600 Mark II was used only rotational data were used for the head tracking. The scene was refreshed at a rate consistently above 40 fps and the head tracker had a lag of less than 10ms. Subjects sat erect in a swivel chair, and responded sitting up using 2 buttons of a 10 button game pad (Figure 5). SYSTAT V11 (SPSS, Inc., Chicago, IL) and Excel 2003 (Microsoft Corp.) were used for data analysis.

3.3 Virtual Environments

Two different virtual spacecraft interiors – a “Command Module” and an “EVA module” were created using 3D Studio Max V4 (Autodesk, Inc.). Each had a cubic interior, 3 meters on a side.

Each of the six surfaces forming the interior of each module was detailed (“textured”) using images shown in Figure 6. The texture images were prepared using Photoshop Elements Ver. 2.0 (Adobe Systems, Inc.) from photographs of actual ISS and Shuttle work stations and also computer generated images from a space station simulation. The visual complexity (e.g. the number of color changes per unit area) of the two modules was similar. The interior of each module had a consistent “visual vertical”, as defined by the orientation of the labeling on racks, the placement of racks only in “walls”, the relative placement of control knobs, the placement of lighting units and stowage bins on the overhead, images of upper torso and head of space suited astronauts, and darker floor surfaces with foot restraints.

The two modules were attached after undergoing two rotations (a pitch and then a roll) as can be seen in Figure 7, with the EVA module “beneath” the Command Module (as seen from the perspective of a visually upright observer within the Command Module). Benveniste's pilot study (2004) suggested this configuration to be one of the most difficult to learn. The textures on the common wall between the two modules depicted an open circular hatch.

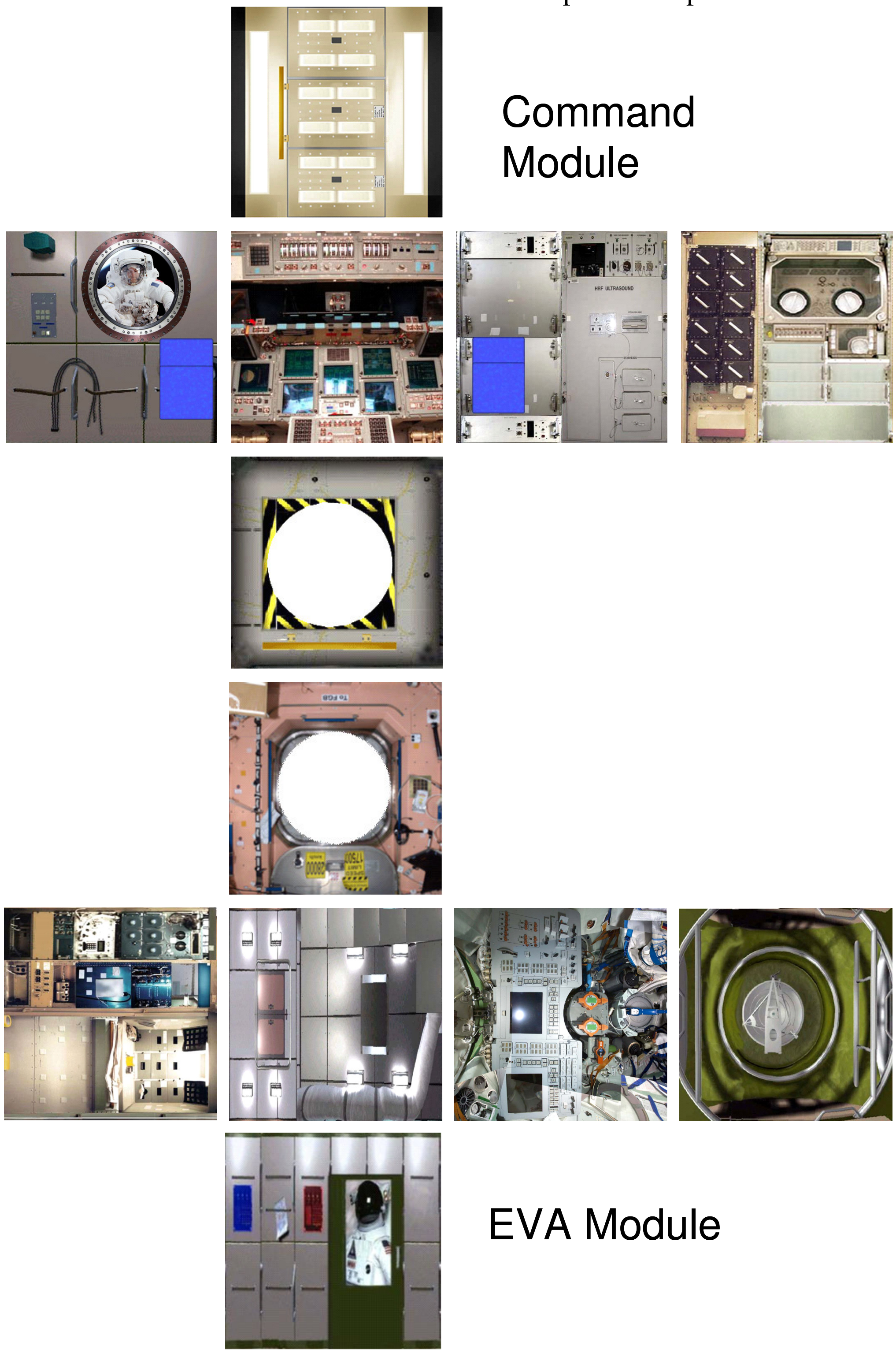


Figure 6. Layout of Command and EVA module surface textures relative to each other.

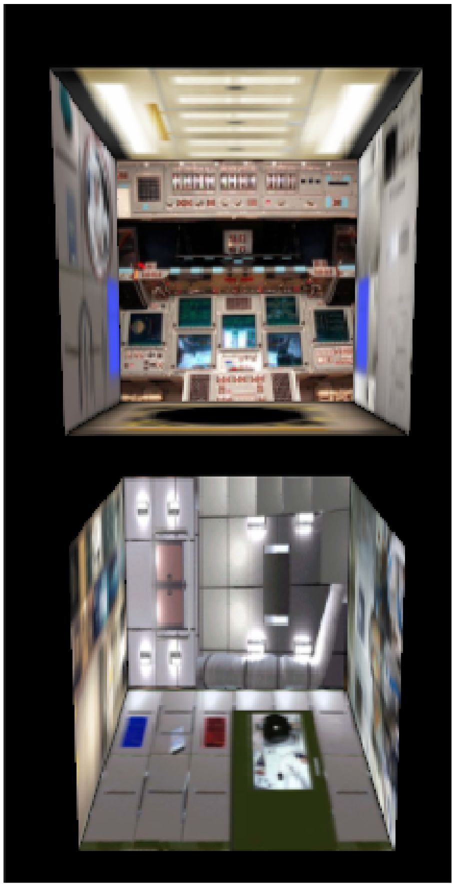


Figure 7. Perspective view of the combined modules.

3.4 Experiment Design and Procedure:

A repeated measures experiment design was used, with training type ("adjacency" vs. "rotation") as the between-subject-group independent variable; As shown in Figure 8, after pre-testing was complete, the subject went through 5 successive phases of training followed by testing. All subjects went through all phases in the same order. Basically, each subject was trained first in the Command Module, then in the EVA module, and then in the combined configuration. Hence, the viewpoint of the subjects in the first 2 phases was floating in the center of the module; in the last 3 phases the subject was floating in the center of one of the modules (the "local" module) with the other module (the "adjacent" module) visible through the hatch between them. Each training phase consisted of a verbal tour and training sub-phase (detailed below), followed by a computerized training sub-phase

1a. Command module verbal tour and training

1b. Command module computerized training

2a. EVA module verbal tour and training

2b. EVA module computerized training

3a. Combined modules verbal tour

3b. Combined modules computerized training

4. Combined modules forward computerized testing

5. Combined modules backward computerized testing

	Training			Testing	
Phase	1	2	3	4	5
Viewpoint	Command	EVA	Command	Command	EVA
Targets	Command	EVA	EVA	EVA	Command
Feedback	Yes	Yes	Yes	No	No

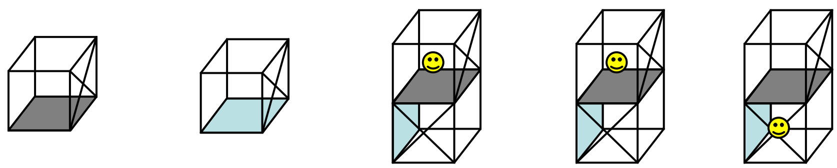


Figure 8. Sequence and Configuration of experiment. Gray surface represents the floor of the first module, green the floor of the second. The X represents a specific wall.

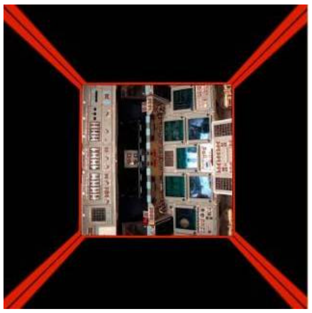
The difference in the training procedure between the two groups was the training procedure manipulation and the order of the trials in the combined modules computerized training (Phase 3b). (The trial order manipulation – see below - was done to ensure the adjacency-trained groups familiarity with the pairs of adjacent walls).

3.4.1 Single module

The single module verbal tour and training phases (1a, 2a) consisted of reading a script to the subject as they looked around the module, pointing out the names of specific landmarks on each of the six walls. The scripts for this verbal tour are provided in Appendix B. To more fully understand this complex experiment, the reader is strongly encouraged to review these scripts. The subject was asked to verbally confirm that they saw each landmark as it was pointed out. For the adjacency-trained group, in addition to the landmark name and description, the functional relationship of that landmark to several other landmarks near it on the same and/or adjacent walls in the same module was provided. Conversely, the rotation group was only told the names positions of the landmarks and their relationship to other landmarks on the same wall, and functional relationships were not emphasized. The differing tours were made simply by removing the sentences detailing the relationships from the adjacency training group's script (see Appendix B). After the verbal tour the subjects removed the HMD and then were asked to recall for the experimenter the landmarks and relationships between them that they remembered. The experimenter recorded their responses using a post-tour checklist (Appendix C). Finally, the experimenter reminded the subjects of the landmarks they had failed to mention and, in addition, reminded the adjacency trained group of relationships they had forgotten.

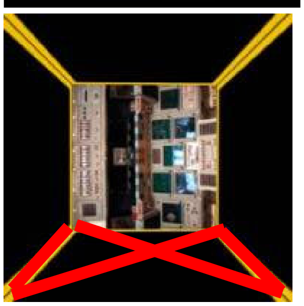
After the tour and training sub-phases, subjects began computerized training (phases 1b and 2b). The procedure is shown in Figure 9 from the subject's perspective. As in Benveniste's experiment, the procedure required the subject to first determine their orientation based on a view of a "cue" wall, and then place a second "target" texture on the appropriate wall and in the correct orientation. Unlike Benveniste's experiment, the "cue" wall remained visible while placing and orienting the target wall. Also only 30 trials rather than 36 were used for local module training, (36 rather than 40 trials were later used for combined module training) a different sequence of cue orientations was used, and a simpler response button syntax was utilized (Appendix B). The first few trials were presented upright, after that they were pseudo-randomized. Fewer numbers of trials were used because it was noticed in the previous experiments that subjects began to get bored and possibly perform worse the longer the experiment went. An attempt was made to use the fewest amount of trials necessary to see all the cue and orientation permutations.

Begin Trial

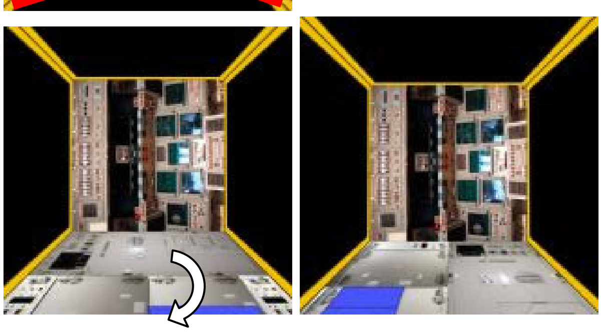


Orientation cue:
The wall ahead is displayed. It may be tilted relative to subject. Subject must imagine how the other walls are oriented

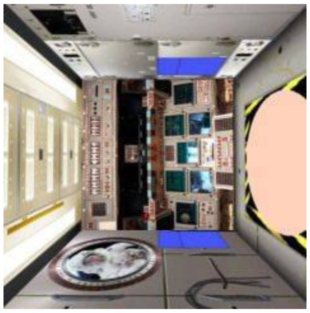
Target:
This is the wall the subject must put in its place



Placement of target:
Subject turns head to moves a red cross to move target to proper surface and presses a game pad “proceed” button when done.



Orientation of target:
Subject rotates the target on into correct orientation, using game pad “proceed” button, and pushes “select” button when done



Feedback:
All walls reappear in the correct orientation so that the subject can check his answer. When done, he presses "proceed"

END TRIAL

Figure 9. Schematic of a computerized trial in a single module. Subject was shown first the cue texture ahead in a randomized orientation then a target ahead in a visually upright orientation. Then the subject had to turn toward the correct wall till a red X appeared on it, and push a button . Finally he could check his answer using the feedback. Additional procedural details in Appendix B. Figure adapted from Benveniste (2004).

For local module training, 30 trials were run in which subjects had to correctly position and rotate one of the six walls of the module, based on the position of another wall in the module (which could be any of the six walls rotated either 0,1, or 2 times 90 deg clockwise). After each trial the correct answer was shown so that the subject could make corrections to any mental models or rules they were utilizing.

3.4.2 Combined module

The combined module verbal tour (phase 3a) was similar in procedure to the local module tour and training (1a and 2a), except that the subject's viewpoint was in the center of the Command Module, and the hatch between the modules was removed so the subject could look into the adjacent EVA module. The combined module verbal tour (Appendix B) differed between the two training groups. The training scripts were designed so that the rotation-training group was encouraged to remember the two modules as independent modules, joined through the two hatches and rotated with respect to each other by a pitch and a roll. ("It might be easiest to think of the relationships between the modules as a pitch and a roll. To remain upright in both modules you would have to move down from this module and then rotate forward and roll over.") The adjacency-trained group script encouraged the subjects to remember the two modules as 4 pairs of connected walls and to remember adjacency relationships between the surfaces of the adjacent modules that would help them remember how the walls were oriented relative to one another. ("Remember that the instrument panel is adjacent to the EVA ceiling, the ultrasound wall is adjacent to the EVA control panel, the animal racks are adjacent to the airlock hatch, and the astronaut window is adjacent to the EVA tools.") After the tour the subject again removed the HMD and was asked to recall the configuration of the environments from memory. The experimenter used a checklist of landmarks (Appendix C). The adjacency-trained group was asked about landmark relationships between modules, whereas the rotation-trained group was asked about the rotational relationship between the modules.

Combined modules computerized training (phase 3b) was similar to the single module training, and a similar "orient to cue/place the target" task was used. However, instead of positioning and rotating a target wall within the local module, in this phase subjects had to position and rotate a target wall correctly in the adjacent EVA module based on the position and orientation of the "cue" wall in the local command module (Figure 10). Subjects were given 36 trials to learn the combined modules, after each trial the correct configuration was shown. The adjacent group's first 6 trials had an adjacent relationship, meaning the pair of walls used was one of the four pairs of wall the subjects had been taught to associate with one another, to reinforce their training strategy, and randomized thereafter.

Phase 4b and 5b testing trials (2 phases of 36) were the same type as the training trials of the phase before, except that the first wall (the "cue") shown, which defined the subject's relative orientation, was not visible when placing and rotating the target texture, and the correct answer was not shown to the subject after each trial. As with the Benveniste and Oman experiments, we used this inter-module version of an orient-to-cue/place-the-target task because the inter-module spatial knowledge it required would be the similar to kind needed to respond to emergencies. For example, in a sudden complete power failure, an astronaut only has the last visual image seen before blackout to form a navigation plan to emergency response equipment located in the next module. In phase 4, the "look forward" phase, the subject had to position and orient walls in the EVA module based on the position and orientation of walls in the Command module (the same as the previous phases training). In phase 5, the "look back" phase, walls in the Command module were positioned and oriented based on the position and orientation of EVA module wall in order to determine the knowledge transfer between perspectives. The 36 trials in each phase were randomized.

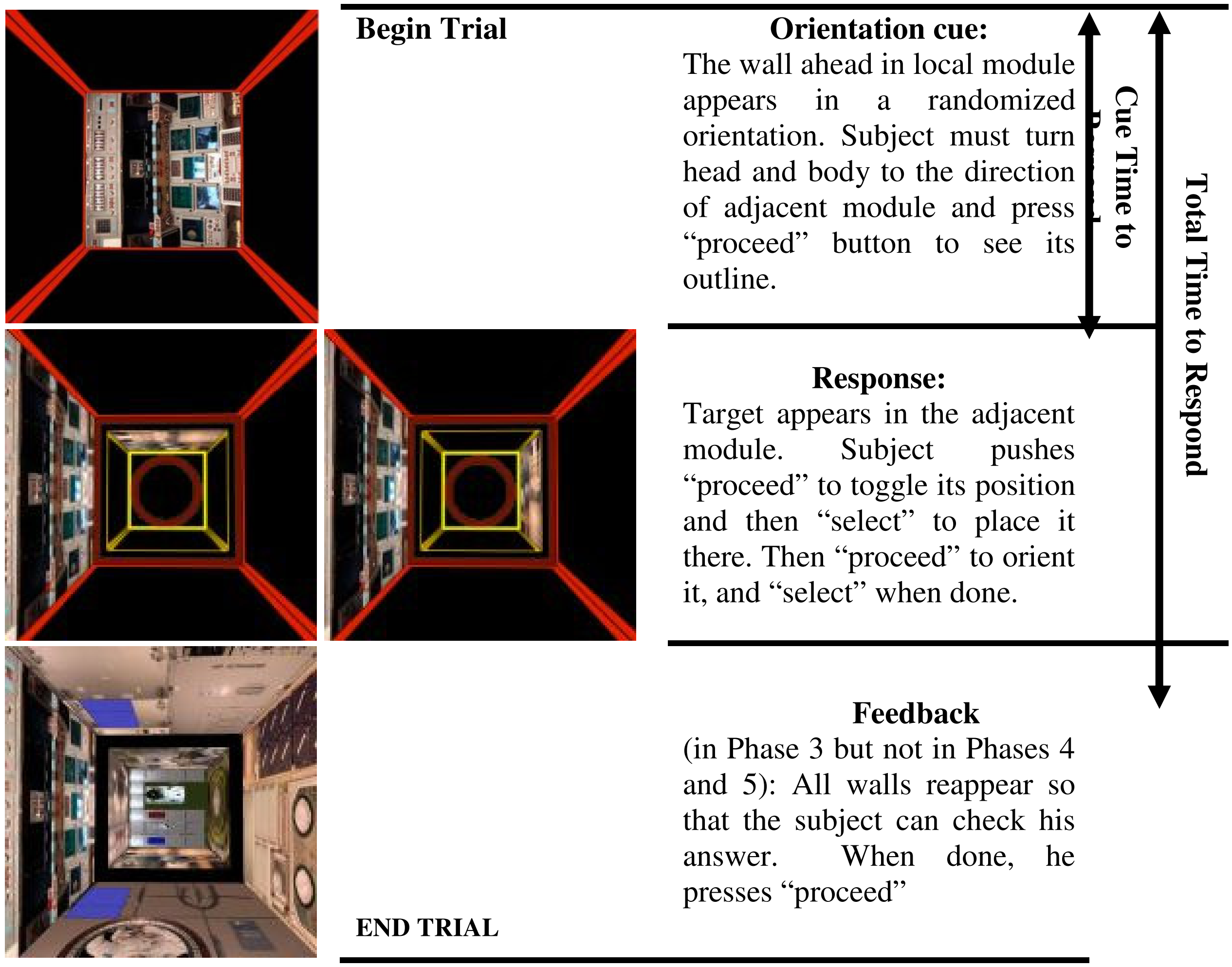


Figure 10. Schematic of combined module computerized trial (Phases 3 to 5). Subject was shown the local module surface ahead then had to face the direction of the second module and press a button to see a wire frame outline with the target displayed inside. The subject toggled the position and orientation of that target using the game pad indicating that he believed correct. Figure adapted from Benveniste (2004).

3.4.3 Post-testing questions

After the final testing the subjects removed the HMD and were again asked to recall which landmarks and relationships they remembered, using the same checklist used earlier post-tour, Subjects were asked about landmarks and relationships in the individual modules and then how they remembered the two modules as being connected. Finally, they were then given a multiple choice questionnaire which asked more explicit visualization and reference frame questions (Appendix D).

Questions 1-4 were asked to determine what reference frame the subjects used in the first two phases where the modules were presented by themselves. Question 5 asked if the subjects ended up thinking of the two modules as a single large module during the combined module phases. It was hoped that subjects in the adjacency-trained group would think of the modules as a single module due to their training. The sixth question asked what strategy the subject used to recall the configuration of the combined modules. In order of increasing integration of the two environments, subjects could say they remembered the environments as rotated relative to each other, as recalling how a single pair of walls was connected between the modules, and as recalling how two or more pairs of walls were connected between the modules. Again, it was hoped that subjects in the adjacency-trained group would remember and use the strategy they were instructed to use. Questions 7 and 8 asked which direction the subject considered the adjacent module from both the Command and EVA modules. This question was used to determine if the subjects had a consistent visualization and is discussed in detail in the results. 9 and 10 also asked this and were used as a verification of 7 and 8. There was no time limit on response.

3.5 Dependent variables measured

The time to respond to the orientation cue and the total time to respond were recorded for each of the 72 testing trials (36 in each phase) (Figure 10). If a subject answered both the orientation and position components of the trial question correctly the trial was scored as correct. Subjects could not skip a question, so times and correctness were observed for all trials for each subject. All values were averaged over six-trial increments (subphase). Percent correct is the fraction of trials scored correct over these six trials. If the subject randomly guessed at a trial, they would have a 1 out of 20 (5%) chance (5 positions and 4 orientations) of getting it correct. Number of landmarks and number of relationships between landmarks were determined from the experimenter's Recall Checklists (Appendix C) for each of the three training phases (1-3) after the verbal tour and after the final testing phase (5). Using subject's answers from post-training Strategy and Visualization Questionnaire (Appendix D) the textures the subjects believed they used to define "forward" and "up" in each module, number of pairs of walls remembered, and the location of the one module as seen from another were determined.

4 Results

4.1 Spatial Memory Test norms:

The results of the spatial memory test are seen in Figure 11. All subjects, including pilot subjects and motion sickness dropouts, who were given the test are included (n=21) in this figure, so as to provide the largest normative data set. The mean score was 21.4 with a variance of 6.8. This preliminary normative data will be useful for further development or utilization of this test.

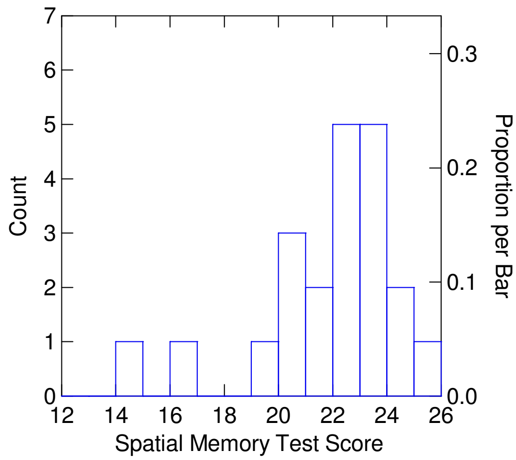


Figure 11. Distribution of Spatial Memory Test scores (n = 21).

4.2 Total Time to Respond and Percent Correct

The Total Time to Respond and Percent Correct (here, plotted as fraction correct) of each group are shown in Figure 12 and Figure 13 by phase and subphase. Unlike the experiments of Oman (2001) and Richards (2000) using abstract environments, but as in Benveniste (2004) and Oman et al's (2006) experiments using realistic environments, both the adjacency trained and rotation trained subjects learned quickly, and performed well, perhaps because the relationships between landmarks in the realistic environments were easier than in the abstract ones. The realistic environments led to a high accuracy and a consequent ceiling effect (in several subphases (6 trials) subjects achieved greater than 95% mean accuracy) making it difficult to separate group responses. Though of general interest, the percent correct data were not further analyzed.

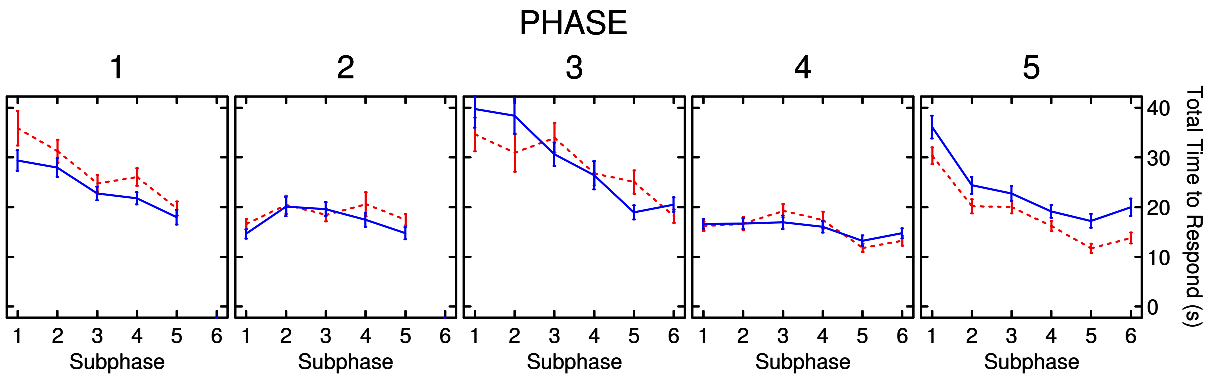


Figure 12. Total time to respond among all 5 phases divided by group. Blue solid lines are the rotation-trained group; red dotted lines are adjacency-trained group. Error bars are standard error of the mean.

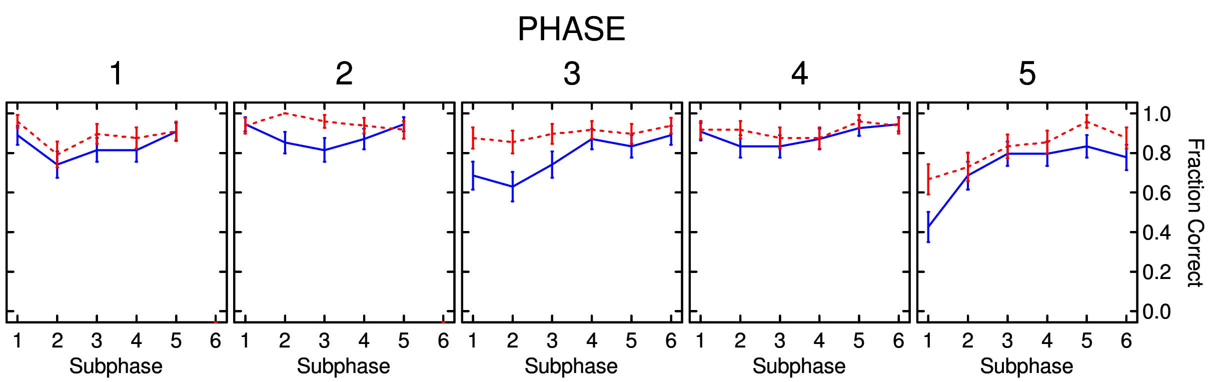


Figure 13. Fraction correct of subphase (6 trials) among all 5 phases divided by group. Blue solid lines are the rotation-trained group; red dotted lines are adjacency-trained group. Error bars are standard error of the mean.

4.3 Data Transformation and GLM Analysis of Variance

The observed cue response time and total time to respond data were not normally distributed. The times were logarithmically transformed to improve the normality of their distribution and satisfy the Fisher assumptions for the General Linear Model (GLM) that was used for analysis. Residuals for all GLMs were normally distributed. A primary repeated-measures GLM ANOVA of the log transformed total time to respond data in the testing phases 4 and 5 (look forward and lookback) is shown in Table 1 including all subjects; including eight different effects and two cross effects, as discussed in more detail below. All independent variables were assumed fixed effects. Additional GLM ANOVAs were performed to address the scientific questions discussed in other sections below. The GLM used for Question 4 used the log of Time to Respond to the Cue as the dependent variable and each subject was modeled individually.

Table 1. General Linear Model ANOVA for Total Time To Respond in testing phases 4 and 5 (look forward and lookback) across all subjects. ** denotes significant effects and cross effects where p<0.05.

Factor	df	F	p-value
Training	1,9	0.00	0.98
Gender	1,9	2.30	0.16
Visualization**	1,9	7.41	0.02
Cube Comparison Score	1,9	0.00	0.98
Spatial Memory Test	1,9	0.01	0.94
PTA Score	1,9	0.00	0.97
VisualizationxTraining	1,9	0.08	0.78
Phase	1,9	0.35	0.57
PhasexTraining**	1,9	6.27	0.03
Subphase	5,45	1.12	0.36

4.4 Performance Prediction

As shown in the GLM analysis above, and confirmed by calculation of Pearson correlation coefficient, no significant relationship could be demonstrated with predictive factors such as gender, Cube Comparison score, and PTA score. Richards (2000) and Oman (2002) had found performance in single module spatial memory tasks correlated with Cube scores and with gender. Benveniste (2004) had noted a combined module performance correlation with PTA and a transient effect of gender. In the present tests, the number of landmarks recalled when the post-tour checklist was administered also did not correlate with performance for either group. As expected from prior studies, orientation did not correlate significantly with total response time, but it did reliably predict response time to the cue, as detailed below.

4.5 Answers to scientific questions:

4.5.1 Question 1

How effective was the training manipulation? Did the adjacency-training method increase the percent of correct responses and lower the time to respond, relative to the rotation method subjects?

As is evident from the data in Figures 11 and 12, and the GLM analysis of Table 1, if there was any average effect of the adjacency training manipulation, it was not statistically significant, averaging all subjects. Neither did the training change the variability of the group responses in a consistent way. We could not demonstrate that the variance of the two training groups were significantly different (Levene test for Equality of Variances). Conceivably this could have been because of the large variability in the performance of the different subjects. We therefore also wondered:

4.5.2 Question 2

Did the subjects in the two groups actually use the strategy we trained them in?

One measure of success in training was the performance achieved by the subjects in their post-testing responses to the recall checklist questions. However, both groups' subjects performed well, so apparently both groups learned the objects they were taught. Another possibility – discussed further in section 5 - is that despite our attempts to manipulate the rules they used and visualization strategies via our verbal tour, subjects in both groups discovered successful strategies to perform the task, and in approximately equal numbers. Some subjects did well, and others did not. One measure of their success in learning how to concatenate their mental models of the two environments into a single allocentric coordinate frame was provided by their responses to answers to the post test Strategy and Visualization Questionnaire (Appendix D) Analysis showed that the consistency of their answers to several of these questions strongly predicted their performance:

Questions 7 and 8 asked in which direction the adjacent module was located. All but one subject who answered Question 7 reported that the EVA module was "below" the Command module. If the subject also gave a consistent response to Question 8, namely that the Command module was "above" the EVA module it suggested that the subject had successfully concatenated his mental models of the two modules into a single allocentric coordinate frame. Note that the absolute direction of "down" is not essential; one subject consistently described the EVA module as on the left, and the Command Module as on the right. By contrast, if the subject had said that the EVA module was below, but the Command module was "right" or "in front" of the EVA module, we would have concluded that he had two different, inconsistent reference frames. That is, the subject's forward and reverse visualization of the two modules were inconsistent. Checking the consistency of visualization relative to an unseen allocentric reference frame in terms of up or down, left or right provides the important insight.

Questions 9 and 10 were visual analogs to Questions 7 and 8. Ideally the answers to all questions should be congruent. Ten subjects answered all four questions. Seven subjects' answers on 7 and 8 agreed with their answers to Questions 9 and 10, while 3 did not. Though the subjects' answers to Questions 7 and 8 may not be a perfect tool for assessing the consistency of their visualizations, it appeared a valid measure, and answers were available for all 17 subjects.

Based on their answers to Questions 7 and 8, 5 out of 8 adjacency-trained subjects reported a consistent visualization. One of those said consistently that the two modules were aligned next to each other, left and right. Of the 9 rotation-trained subjects, only 3 reported consistent visualization. The difference between training groups is not large enough to be statistically significant (using Yates-corrected χ^2 test) because there are so few subjects, however the trend is consistent with the notion that adjacency training improves visualization consistency. It was interesting that all 3 of the females in the adjacency-trained group reported a consistent visualization, but only 2 of the 5 males did so. In the rotation-trained group 1 of 4 females and 2 of 5 males reported consistent visualization (Figure 14).

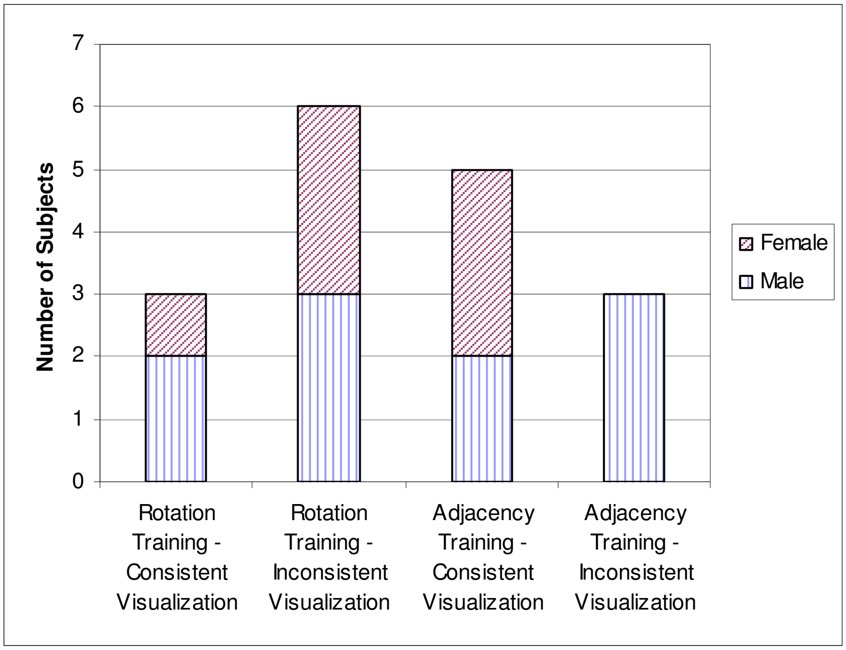


Figure 14. Distributions of Subjects among training groups.

Question 5 asked whether subjects considered the combined modules to be one large module or two connected independent module. Their answers did not correlate with the consistency of their visualization as determined by Question 7/8. This could be because subjects could concatenate their visualizations consistently without necessarily seeing the spacecraft as a single entity. For example one can picture a house as several connected rooms with consistent vertical without seeing all the rooms as a single large room.

Question 6 asked whether the subject remembered the modules as connected by pairs of walls, and how many, or whether they remembered the connection as a series of rotations or by some other strategy. Responses did not correlate with visualization consistency either. Nor did they correlate with training group. Possibly this could be because subjects remembered the spatial relationships using objects, not walls or whole module rotations.

The consistency of module visualization report, as defined above, did significantly correlate with total time to respond, as shown by repeated measures GLM ANOVA (Table 1) ($F(1,9)=7.41$, $p= 0.02$). However, the subgroup of subjects within each training group who reported a consistent visualization were on average about 5 seconds faster to respond than those who did not (Figure 15). There was no corresponding effect on percent correct (Figure 16). Gender had no significant effect: The predictive-tests (Cube Comparison, PTA, and Spatial Memory) were not correlated with visualization method using Pearson's correlation.

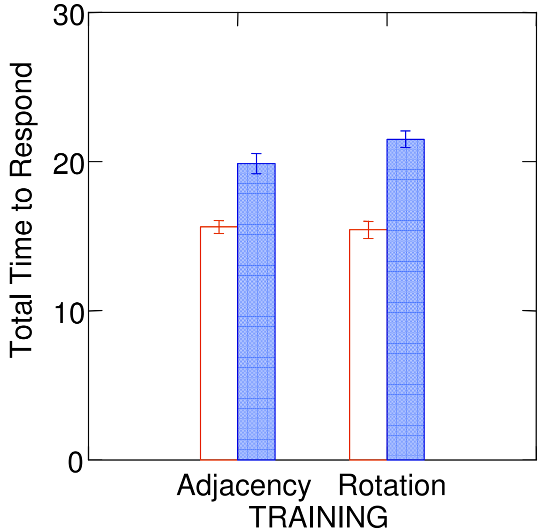


Figure 15. Average time to respond by training method and visualization. Empty is the consistent visualization and filled is the inconsistent visualization. Error bars are standard error of the mean of the untransformed values.

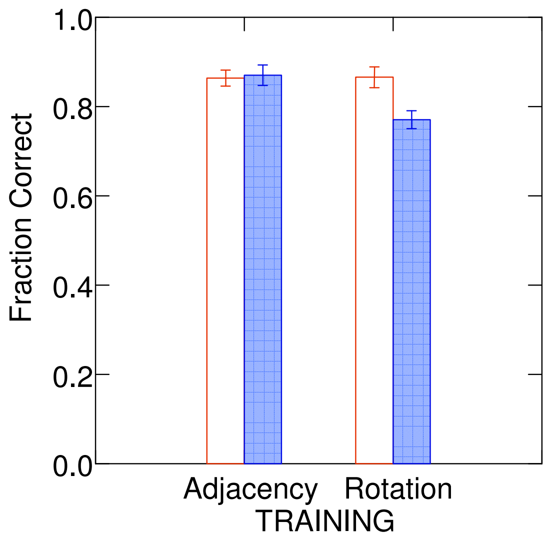


Figure 16. Fraction Correct by training method and visualization. Empty is the consistent visualization and filled is the inconsistent visualization. Error bars are standard error of the mean of the untransformed values.

Overall, when the subjects are split by visualization the untransformed data is presented in Figure 17 and Figure 18, clearly a significant split in performance in time, but not in accuracy.

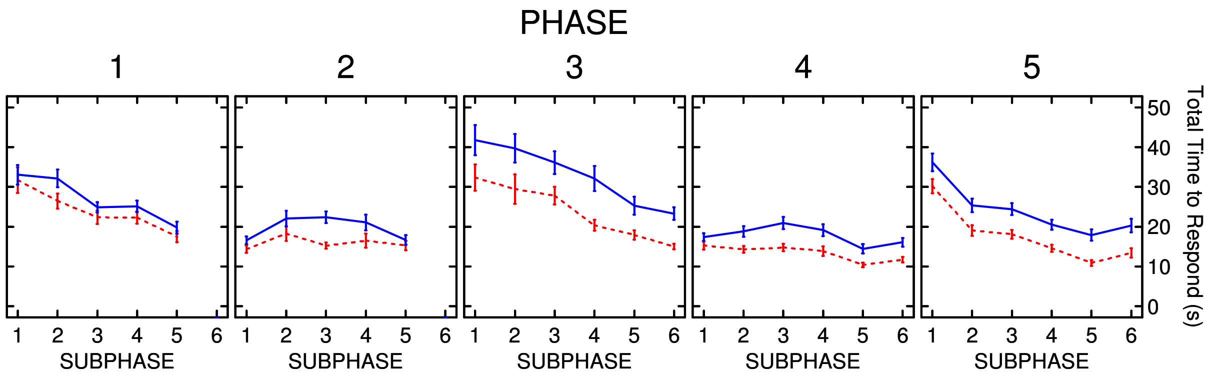


Figure 17. Total time to respond among all 5 phases divided by visualization. Blue solid lines are the inconsistent visualization; red dotted lines are consistent visualization. Error bars are standard error of the mean.

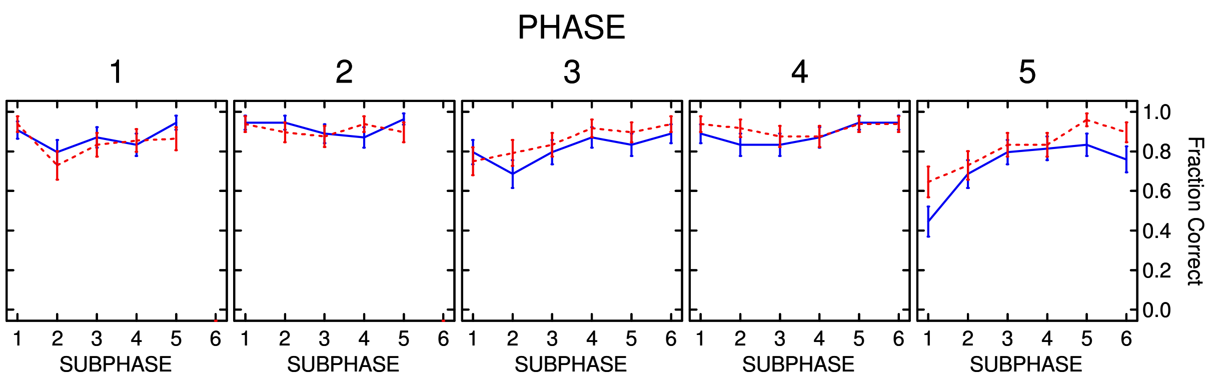


Figure 18. Fraction correct of subphase (6 trials) among all 5 phases divided by visualization. Blue solid lines are the inconsistent visualization; red dotted lines are consistent visualization. Error bars are standard error of the mean.

4.5.3 Question 3

Were the subjects in the rotation-training group more dependent on the orientation of the cue surface than those in the adjacency-training group?

Another GLM (Table 1) was run on the last four subphases of the look forward and lookback phases because those subphases had the same sequence of orientations. There is a significant effect of relative orientation of the cue on the time to respond to the cue ($F(2,26)=5.30$, $p = 0.01$) which suggests that both groups had an orientation-specific model for the local environment. Contrasts show the upright trials were about 2 seconds faster than the sideways trials ($p = 0.02$) and 1 second faster than upside down trials ($p = 0.03$) when the two phases are looked at together (Figure 19). Sideways trials were not significantly different than upside down trials. Phase*Orientation is a significant cross effect ($F(2,26)=6.41$, $p=0.01$), implying that subjects responded differently to the relative orientations in the two phases. There were no significant Group*Orientation or Visualization*Orientation cross effects. Therefore, there is no reason to decide that the adjacency-trained group or consistent visualization group has a less orientation-specific mental model than their counterparts. Again, possibly due to the ceiling effect, there is no significant effect of orientation on percent correct.

Table 2. General Linear Model ANOVA for Time To Respond to the Cue in the last 4 subphases of testing phases 4 and 5 (look forward and lookback) across all subjects. ** denotes significant effects and cross effects where p<0.05.

Factor	df	F	p-value
Training	1,13	1.39	0.26
Gender	1,13	0.31	0.59
Visualization**	1,13	6.67	0.02
Phase	1,13	3.90	0.07
Phase x Training	1,13	4.06	0.07
Subphase**	3,39	32.09	0.00
Orientation**	2,26	5.30	0.01
Phase x Orientation**	2,26	6.41	0.01
Orientation x Training	2,26	0.78	0.47
Orientation x Visualization	2,26	0.03	0.97

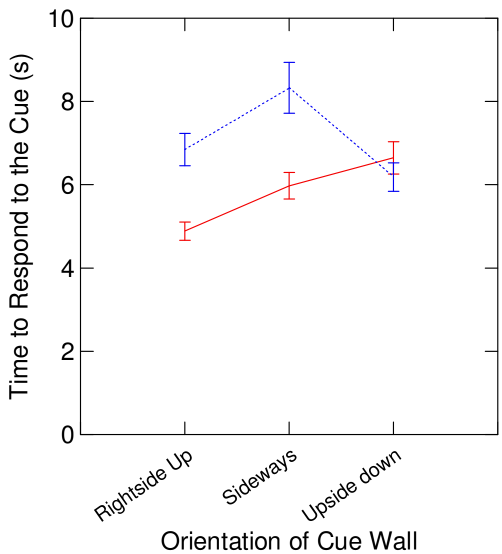


Figure 19. Time to Respond to the Cue Wall by phase and orientation. Solid red line is the look forward phase (phase 4) and dotted blue line is the lookback phase (phase 5). Orientation is in terms of the Command module reference frame. Error bars are standard error of the mean of the untransformed values.

4.5.4 Question 4

Did the subjects have an allocentric reference frame based on the visual vertical of one of the modules for the combined modules, rather than two independent reference frames navigated by a rotation between them? Does this integration of the reference frames correlate with training-group?

To some extent, this question has been addressed earlier. Some, but not all subjects responded differently to the orientation of the cue when they were in the reference (Command) module looking at the EVA module than the other way around. It would be expected that a subject using an inconsistent visualization (i.e. he reported inconsistent answers on Questions 7 and 8) would respond differently to the same allocentric orientation presented in the look forward phase (phase 4) and the lookback phase (phase 5) because he saw them as two different orientations. A GLM model for time to respond to the cue performed for each subject individually showed that the cross effect Orientation*Phase, was significant ($p< 0.05$) for 4 of the subjects analyzed individually; 2 of 9 in the rotation-trained group versus 2 of 8 in the adjacency trained group, not a significant difference in proportions. All 4 of the subjects who had a significant effect were among the 9 who reported that they used the inconsistent visualization. None of the 8 subjects who reported using the consistent visualization, however, had a significant cross effect. This difference is not significant, but no subject's results conflicted with his report on the questionnaire of which visualization he used.

4.5.5 Question 5

Are subjects in the adjacency-training group better able than rotation-trained subjects to respond to novel perspectives?

To some extent, yes. As shown in Figure 14, the adjacency trained group showed only a 3 second increase in total time to respond when in the EVA module vs. the Command module, whereas the rotation trained group responded 6 seconds slower The corresponding difference between reference modules for the adjacency-trained group was about 3 seconds (Figure 20). This cross effect, Group*Phase, taken from a repeated measures GLM looking at just the look forward and look back phases was significant ($F(1,9) =6.27$, $p = 0.03$). The histograms of the data in Figure 21 show the nature of the effect.

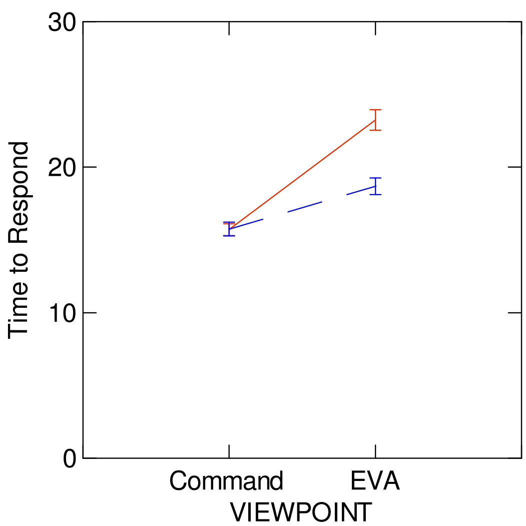


Figure 20. Time to Respond by module viewpoint and training method. The red solid line is the rotation-trained group and the blue dashed line is the adjacency-trained group. Error bars are standard error of the mean of the untransformed values.

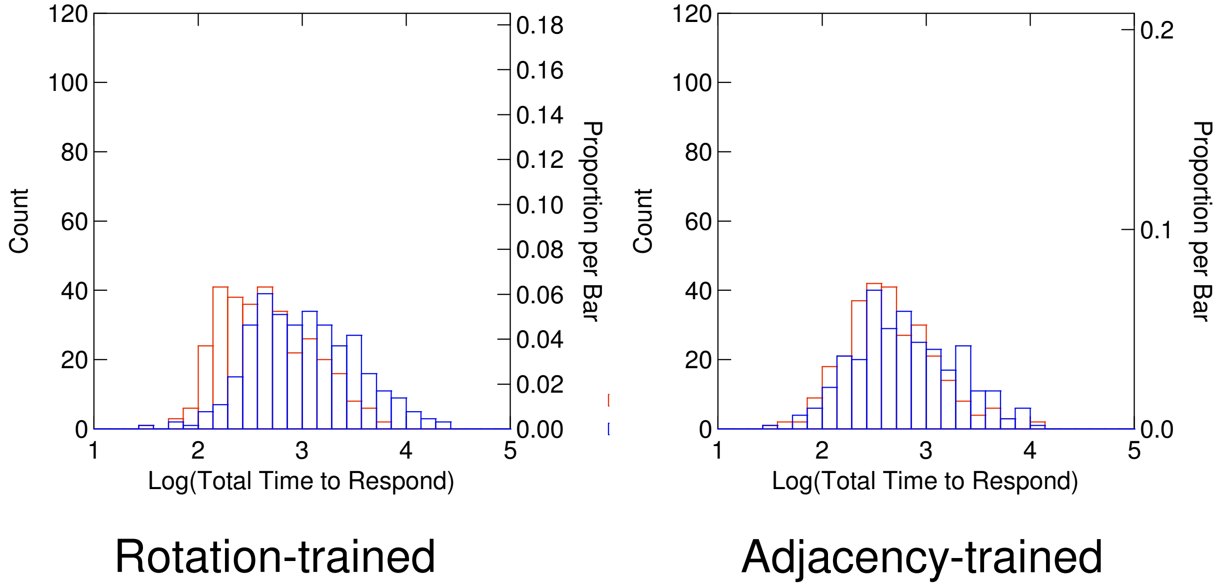


Figure 21. Transformed Total Time to Respond distribution by training group and phase. Red (dotted) is the look forward phase (phase 4) and blue (solid) is the look back phase (phase 5).

4.5.6 Question 6

Were the subjects in the adjacency-trained group better able to remember spatial relationships taught in their computerized training?

The adjacency-trained group remembered significantly (Table 3) more relationships between landmarks located on different module walls. The answers given to the post-testing repeat checklists (Appendix C) were examined; each had a count of the number of connections (connecting lines) between landmarks within each module for the single module cases. The connections were of two types; connections between objects on the same surface (e.g. the windows were above the display screens on the instrument panel in the command module) and connections between objects on different surfaces (e.g. the handhold bar on the ceiling was next to the porthole on the wall in the command module). Connections between objects on different surfaces within the same module were studied because that would be the indicator of how well a subject was integrating the separate surfaces into a cohesive picture and were called Intra-Command module connections and Intra-EVA Module connections respectively. For the combined module two types of information were reported and analyzed; number of wall pairs between modules (the instrument panel in the Command module was adjacent to the ceiling of the EVA module would be one), called Combined Module Adjacent Walls, and number of orientation cues recalled in testing (the arrow on the airlock in the EVA module pointed towards the animal racks in the Command module would be an example of one), called Combined Module Relative Orientations. These numbers were then compared between groups using the robust non-parametric Kruskal-Wallis test because we could not assume normality.

The adjacency-trained group was explicitly taught more connections than the rotation-trained group so these results are expected, but they can also be seen as verification that the subjects did listen to the training.

Table 3. Results of Kruskal-Wallis One-Way Analysis of Variance on groups recall of inter-wall connections. Group's average connections are listed as well as the maximum possible number of connections.

Connections	Maximum	Group: Adjacency	Group: Rotation	Test Statistic	p-value
Intra-Command Module	14	4.1	1.5	7.5	<0.01
Intra-EVA Module	14	5.9	3.0	9.5	0.02
Combined Module Adjacent Walls	4	3.8	1.5	10.5	0.02
Combined Module Relative Orientations	4	3.5	1.0	7	<0.01

5 Discussion

5.1 Difference from previous work

The spatial task was similar to that used by Benveniste (2004) and (Oman 2006). As seen in Figure 22, our subject's average time to respond (15s) was somewhat shorter than previous experiments (24s for Benveniste and 22s for Oman). Several factors may have contributed to this. First, the two modules used in the current experiment had somewhat similar structures, with a principal control panel area providing a major landmark, and each surface had readily identifiable, namable objects on it. Second, the gamepad button syntax was changed, and may have allowed the subjects to respond faster. Third, it is possible that adding post-tour checklists and feedback improved the performance of both our groups. Fourth, during the training trials the cue wall was left in view so that the subject could look back at it while placing and orienting the target wall. For the training trials in the previous experiments the cue wall was removed before the subject looked at the image of the target wall, so each had to remember the orientation of the module as well as the placement of the target wall.

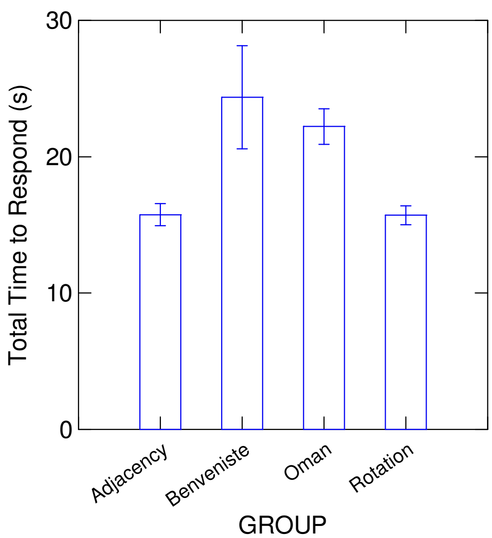


Figure 22. Comparison of Total Times to Respond among different training types on similar testing phases. The look forward phase (phase 4) was used from this experiment, Phase 5 from Benveniste, and Phase 4 from Oman (Figure 3). Error bars are standard error of the mean of untransformed data.

5.2 Training group differences

However, the foregoing factors do not explain why our between-group training manipulation did not work as well as we had intended. Why?

First, there may not have been enough difference between the two methods used to train the subjects. Simply taking out the parts of the verbal tour which explicitly point out the functional connections between landmarks may not have been sufficient to prevent many rotation-trained subjects from nonetheless deciding to make connections between adjacent objects and surfaces the same way the adjacency trained group did. Many subjects in Benveniste (2004) and Oman et al (2006) anecdotally learned to do this spontaneously during their computerized training Some or many of the connections the rotation group chose may not have been part of the verbal tour and were therefore not on the post-training relationship checklist so we were not aware the subjects learned them. In the combined module training, our intention was to suggest a different set of mental techniques to each group. It may have been that we didn't place sufficient emphasis on this.

One difference between the two groups training methods was the temporal separation of the landmarks during the verbal tours. We assumed that for the rotation-trained subjects, mentioning landmarks only once, and not stating how they related to each other, would provide temporal separation between objects, and this would make it more difficult for the rotation-trained subjects to remember associations between them. The temporal distance for the adjacency-trained group was decreased by mentioning all connected objects in a pair right after one another. However, the spatial distance between landmarks was identical for both groups since both were using the same environments. There is some reason to think that associations between landmarks are determined more by spatial distance than temporal distance. A paper by McNamara (1992) discusses the effect of spatial and temporal distances and concluded that temporal differences between object descriptions did not significantly affect performance (in this case, Euclidian distance estimation) when the spatial difference between related objects is far. Our landmarks could be considered far apart in the terms of McNamara's paper.

5.3 Gender differences

We noted a difference in the gender of subjects who reported consistent answers on Questions 7 and 8 on the Visualization Questionnaire (Figure 14). In the adjacency-trained group, all the females used the consistent visualization, while in the rotation-trained group all but one of the females used the inconsistent visualization. Males were almost evenly split within both training groups. The gender difference did not achieve significance, perhaps due to the small number of subjects. Certainly it is possible that the women listened better to the instructions than the males did, and were more likely to use the visualization method the training group was supposed to follow. More subjects, of both genders, would be needed in order find if this was a significant difference or not.

5.4 Motion sickness

Four subjects could not complete the experiment due to motion sickness. In two cases the virtual reality head tracker software froze and the tracker had to be repeatedly restarted. This sudden stopping and starting repeatedly probably contributed to the motion sickness complaints they reported. Both of these subjects were in the adjacency-trained group but stopped before they completed a majority of the training. The other two subjects who dropped out due to motion sickness were in the rotation-trained group and no tracker difficulties were noted during their trials. They may have simply been more susceptible to motion sickness. Qualitatively, experimenter did note that the subjects in the rotation-trained group seemed to move their heads more than the subjects in the adjacency-trained group. It was common to see a subject in the rotation-trained group rolling their head sideways over 90 degrees so that they could picture a module presented on its side as visually upright. This uncomfortable positioning also occurred in the adjacency-training group but seemed to lessen as the trials progressed, possibly because that they were becoming more comfortable with visualizing the upright orientation without having to physically see it. Both groups did the same trials in the same order (except for the first 10 trials of the combined modules training (phase 3b)), so it was not due to any difference in target surfaces. If rotation trained subjects tend make more head movements, this could explain why these two subjects experienced sickness. However, if rotation training required more head movement, one would expect an increase the total time to respond, but this was not seen. Future work should track the total angle of head movements made by the subject and correlate with performance and visualization as well as sickness.

If virtual reality training is to become a viable training methodology for spacefarers motion sickness problems must be addressed. One way is to use a better VR system with lower tracker lag, or a system (e.g. CAVE) which does not require the use of a HMD. Another way is to see if subjects can learn spatial relationships using a non-immersive (e.g. desktop) display.

6 Conclusion

The adjacency-training method we developed was not effective in decreasing the time to respond or increasing the accuracy in placement and orientation of module walls between the two virtual modules with inconsistent visual verticals compared with the rotation-training control. However adjacency training method did enhance the ability to transfer spatial knowledge between viewpoints over the rotation-trained subjects. Both groups were trained on how to identify locations in the EVA modules as seen from the command module and they did not perform significantly different in this task. However in the reverse task, where they had to identify locations in the EVA modules as seen from the command module, in which they were not trained, the adjacency-trained group was about 3 seconds faster than the rotation-trained group.

Adjacency training was more effective than the rotation-training in teaching relationships between objects in the modules, as measured by the between wall connections recalled in the post-testing repeat checklist (Table 3). This makes sense because the major component of adjacency training was to emphasize functional relationships. We had thought that this enhanced relationship knowledge would improve performance in the trained subjects, but the experimental results showed that the visualization achieved is a stronger factor, and does not necessarily result from the training manipulation we used.

Subjects who could describe the relationships between the two modules in a spatially consistent way as based on their answers to a post-test visualization questionnaire performed faster ($F(1,9)=7.41$, $p= 0.02$) than the subjects who responded inconsistently. Subjects who reported consistent visualization were distributed approximately evenly among both training methods, meaning that the training method had little effect on which visualization the subject ultimately used. We do not know what makes a subject report visualizations consistently, as visualization consistency no significant dependence on any of the pre-tests we gave (Cube Comparison, Spatial Memory, and Perspective Taking Ability). Though there may be an effect of gender; women may simply be more likely than men to follow visualization instructions given.

Another reason the training manipulation might not have worked could be due to subjects in the rotation-training group discovering the advantages of remembering adjacency relationships, and simply picking their own landmarks and making up their own adjacency rules. The realistic environments provided hundreds of possible relationships that were not formally taught in the adjacency training and which were then not addressed in the post-training or post-testing questionnaires for either group. Several subjects mentioned that they remembered a distinctive green protrusion on one of the walls, not mentioned in the training, and used that in the placement and orientation tasks. If enough subjects in the rotation group – and possibly the adjacency group – did this, it could explain the lack of a significant training effect.

Both groups responded significantly differently to cue surface orientations, in terms of time to respond to the cue, but the groups did not respond significantly differently than each other. This shows that an orientation independent mental model apparently was not achieved by either group. It may be possible, but not using the short duration (1-2 hr) training and test that we employed.

The experiment teaches us that perhaps we were not using the correct training philosophy to increase subject accuracy and lower time to respond. Future research into this type of training should still emphasize the functional relationships, as our training did, but it should also more strongly encourage subjects to think of the two modules as a consistent environment rather than two inconsistent reference frames. Some possible ways to do this emerge. First, one could over train the subjects so that more eventually “break-through” and achieve consistent visualization. If this works, more study into when this transition occurs could reduce the amount of training required. This could be done by repeated training over several days (as extending the current training into a longer single session would probably be unacceptable due to fatigue effects). Another approach is, instead of teaching the two modules independently, as this training did, to teach the second module as an extension of the first or the whole combined module could be taught as a single module. This could be done with actual the actual environments or even with surrogate environments so subjects would have a better idea of what is meant by a consistent visualization. Determining what cognitive characteristics promote consistent visualization should be helpful in designing training. Knowing which subjects are more likely to have an inconsistent visualization will allow the trainer to focus more effort on convincing them to use consistent visualization.

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8 Appendices

8.1 Appendix A – Spatial Memory Test

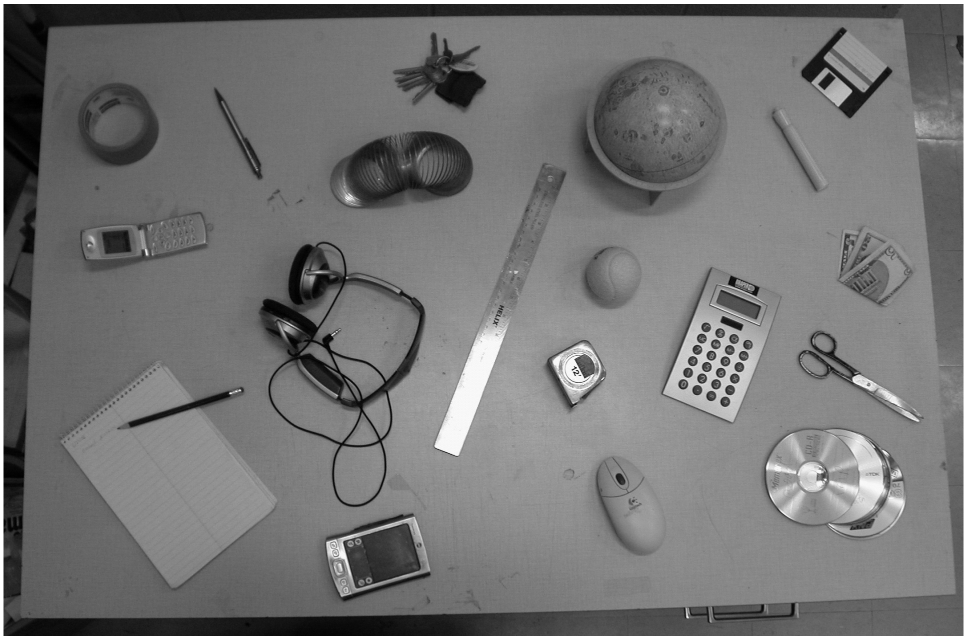


Figure 23. Picture shown to subjects which they had to memorize.

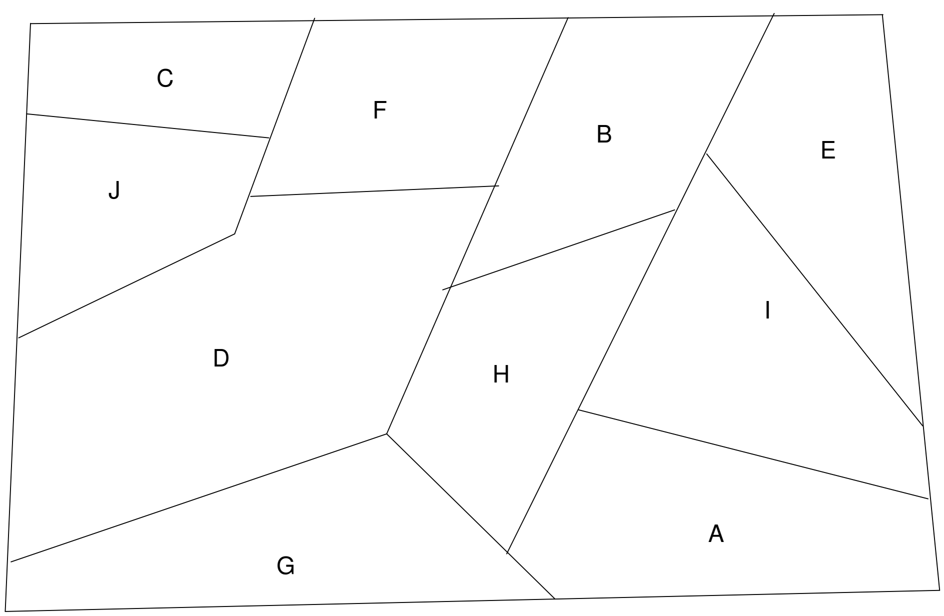


Figure 24. Blank photo with regions subjects had to place listed objects in.

Please write the letter of the region of each of these objects.

Computer Mouse ___

Cell Phone ___

Pencil ___

Tennis Ball ___

Moon Globe ___

Headphones ____

Money ____

Keys ____

Calculator____

Palm Pilot ____

Please answer the following True/False questions about the relationships between the objects. (Subjects were not given a time limit to answer these questions, but were encouraged to answer as quickly as possible.)

<u>True/False</u>

T F The Calculator is to the right of the Headphones

T F The Tape Measure is to the left of the Scissors

T F The CDs are above the Highlighter

T F The Palm Pilot is next to the Headphones

T F The Highlighter is on the Notebook

T F The Tennis Ball is to the right of the Money

T F The Duct Tape is next to the Moon Globe

T F The Mouse is to the left of the CDs

T F The Ruler is to the right of the Highlighter

T F The Keys are between the Calculator and the Scissors

T F The Slinky is above the Palm Pilot

T F The Floppy Disk is next to the Highlighter

T F The handle of the Scissors is closer to the Calculator than the blades

T F The tip of the Pencil is closer to the Ruler than the eraser

T F The Cell Phone is above the Notebook

8.2 Appendix B – Verbal Tour

Instructions to Subjects:

(Details left out of Rotation Training group in *italics*)

Procedure briefing & demonstration

In today's experiment you will be learning the interior spatial layout of two adjacent modules within a hypothetical spacecraft. One is called the "command module" and the other the "EVA module". You'll be wearing a head mounted display, so you can look around the inside of each of the modules. Your main task is to remember where equipment and displays are located *relative to one another. We'll be stressing functional relationships between various equipment items, which may make spatial relationships easier to remember*. For each module, I'll first give you a verbal tour of the module, and then ask you questions to see what you remember. Then we'll switch to computerized training, and finally to computerized testing. We'll teach you each module separately and then show you how they are attached to one another.

There will be seven steps in the experiment, each lasting 10-20 minutes depending on how quickly you work. Between each step we'll encourage you to take a short break, so you don't get tired.

1. Command module verbal tour and training
2. Command module computerized training
3. EVA module verbal tour and training
4. EVA module computerized training
5. Combined modules verbal tour
6. Combined modules computerized training
7. Combined modules computerized testing

During the training steps you will be told if you have made a mistake, so you can correct it next time. During the testing steps, you won't be told about your errors, so we can measure how well you learned.

During the verbal tours of the modules, you'll wear the head mounted display so you can look around the inside of each module. Each module interior is like the inside of a six-sided cube, but each of the interior surfaces has different equipment mounted on it.
I'll give you a verbal tour of each module, and show you what's where, *and then suggest some ways that you can remember how the different surfaces relate to one another*. Then, I'll ask you to give me a tour, and point out *the relationships between* objects that you can remember.

Learning the interiors isn't as easy as it might seem, because you will need to remember where things are, even when you are floating in a different orientation, the way an astronaut has to. It will be a challenge to spatially orient yourself. It may also take you a while to get used to wearing the head mounted display and learn to use the game pad control. If the display feels uncomfortable or makes you too dizzy or anything, let us know - you can take more breaks. We want this to remain challenging and fun. As in all experiments involving human subjects, you can withdraw at any time for any reason, if you choose.

After the verbal tour, computer guided training starts. Before you put on the head mounted display, lets look at the computer screen together, and I'll show you how this different computerized training task works: (demonstrate)

To challenge your memory, you will see only one wall at a time. The rest of the walls will appear just as red-wire framed edges. From your view of this one wall, and your knowledge of what's where, see if you can figure out how you are oriented in the module. After you think you know how you are oriented based on this cue, push the proceed button on left side the gamepad with your left hand. Next, the computer will show you a picture of one of the missing walls. We call this the "target" picture. Your task now is to place this target picture on the correct surface, and rotate it so it is in the proper relative orientation. To do this, push the proceed button a second time. The wire frame will turn yellow, and a big red "X" will appear on the wall you are currently looking at. Turn your head so the "X" moves to the wall where the picture belongs. If you need to momentarily look back at the cue wall you can. Once the X is on the correct surface, push the proceed button again with your left hand. This locks the target to the wall surface, but the orientation may not be correct. Push the "proceed" button again as many times as necessary till the target is in the correct orientation. Then push the select button. All the walls will now appear in their correct orientation, and you will be able to see if you positioned the target correctly or not. Then push the "proceed" button again to move on to the next trial. Remember that "proceed" is always an action button, and "select" is always a "this is my answer – I'm finished" button. That's the basic idea. We'd like you to do the task as quickly as you can, giving equal priority to speed and accuracy. Any questions? I will walk you through the first computerized trial, when the time comes.

You'll earn $10/hour for your participation in the experiment. To provide a little extra incentive during testing, if you answer 95% of all the test questions correctly we'll pay you a $5 bonus on top of your regular pay, and if you respond in less than 15s on average, we'll pay you an additional $5 on top of that.

Now put on the head mounted display, and I'll give you a tour of the "command" module.

1. Verbal Tour of Command Module

This is the command module. You are looking at the command module instrument panel. It has seven large blue display screens and various dials and various switches used to control your spacecraft. The flight control computer keypads and radios are in a center mounted console. *The commander and pilot normally sit on blue cloth seats which you can see folded up on the adjacent walls, at the same level as the blue displays.* Their feet normally rest on pairs of rudder pedals visible beneath the panel. Above the panel are windows. Above the windows, *next to the ceiling* are three bar graph display units.

Next, look at the wall to your right. The blue pilot's seat is on the lower left side of this wall, *adjacent to the instrument panel*. Beneath the seat is a white intercom control panel*, used to communicate with the EVA module, and discussed later*. High on the right, *beneath the ceiling light,* is an Ultrasound unit display screen, and beneath it is a locker marked "Ultrasound". *This equipment is used to study animals stowed in drawers located in the next wall to the right.*

Beneath the Ultrasound, nearer the floor are three other lockers containing food and water reservoirs *for the animals*.

Next, look at the next wall to your right. *Notice it is opposite the instrument panel.* On the left side of this wall are the 12 black animal holding drawers, each with a silver diagonal handle. Beneath them in the same rack is an autofeeding controller which distributes food and water *from the reservoirs in the rack to the left.* On the upper right side of the same wall is a large glove box with a transparent front. You work on the animals by inserting your hands through the two white circles*, and putting your feet under the yellow foot restraint bar mounted on the floor. The temperature in the glove box is monitored and controlled using the small blue control panel just to the right, on the adjacent wall.*

In order to view the last wall without tangling your head mounted display cables, turn left 270 degrees to face the large circular porthole. To the left of the porthole is the *glove box* temperature control. Below that, *next to the floor* are three *intermodule* power cables *that we'll discuss later*. Looking out the circular window, you can see an EVA astronaut outside. *The easiest way to look out the window is to reach up and hold onto the yellow handrail, mounted on this side of the ceiling, just beside the light.* Further to the right, *and level with the instrument panel* is the folded blue commander's seat.

Now look up at the ceiling. Notice the row of three stowage lockers that form an aisle *between the instrument panel and the glovebox, and* flanked on each side by the row lights. The two *lockers closest to the instrument panel* are full, as indicated by the stowage labels beside them. The third locker –the one without a label *and closest to the glovebox – will be used to stow glovebox samples, and* is currently empty.

Finally, look down at the deck. Notice the yellow foot restraint bar *is adjacent to the glovebox wall*. In the center of the deck is a large docking adapter, outlined with yellow and black stripes, with a central hatch that leads to the next module. The hatch is open, but is blocked with a white curtain. Later on in your training we'll remove the curtain, you'll be able to see through this hatch.

These are some of the main features of the Command module.
To see how much you remember, take off the head mounted display.

Now imagine you are facing the instrument panel.
Tell me what features of the module you remember, *and the relationships between them*

These are the landmarks *and relationships* you forgot:

2. Command Module Computerized Training

(Start command module computer training trials
Walk the subject through the first trial if necessary.)
Ok, you have 29 training trials left. Remember, we want equal priority for speed and accuracy.
I'll walk you through the first trial if you need help.
(break)

3. EVA Module verbal tour and training

Now we move on to learning the EVA module. It is where you prepare for EVA before entering the airlock through a hatch in the floor. You are looking at the EVA module control panel. It has two grey display screens with adjacent controls. *The screen on the left is used to check out the suits stowed in the locker immediately to your left. The screen in the middle and the controls on the right are used to control the airlock beneath the floor. Hanging on the wall to the right of the panel is a communications headset used by the airlock operator to communicate with those in the airlock.* Notice the air and hydraulic lines that run from beneath the control panel down through the floor. *On the floor is a single steel foot restraint bar.* Above the panel is a large green support strut, *and connectors to air ducting in the ceiling.*

Immediately to your right is a pink wall with a docking adapter hatch in the center. This hatch leads to the Command module. The hatch itself has been slid upwards into a slot *in the ceiling*. A white curtain covers the open hatch for now. The airlock operator headset is velcroed to the left of the hatch. Signs ("Speed Limit" and "To FGB") on the silver colored hatch *make it easy to know which adjacent surface is the ceiling and which is the floor. Notice that the arrow-like handle in the center of the airlock hatch on the floor points toward this Command module hatch.* On the right side is a vertical strip of Velcro anchors*, used to temporarily stow EVA tools that are permanently stowed in the lockers to the righ*t.

On the wall to the right of the hatch are three racks. The 5 black drawers with white knobs on the left rack are the EVA tool lockers *I just mentioned*. Beneath them is a white electrical power switching panel *we'll discuss later*. The middle rack is partially filled with scientific equipment. On the right at waist height is a general purpose workbench. The desk area is well lit from *both* within *and two lights on the ceiling above,* and has 8 drawers in the back for stowage. *The lights are controlled using the blue switch panel on the adjacent right wall. Since this desk is used for long periods, there is a double rail foot restraint mounted on the floor beneath this rack.*

In order to view the last wall without tangling your HMD cables, turn left 270 degrees so you are facing the space suit stowage locker on the wall. Notice that the suit locker is on the right of the wall*, adjacent to the space suit checkout display on the instrument panel. Also, notice the air conditioning duct on the ceiling that runs from above the suit checkout panel around the corner and into the suit stowage locker.*

Continuing with the ceiling, notice that *in addition to the suit locker* air conditioning duct, it has numerous individual lights, not the long light rows like the command module ceiling. There is only one ceiling locker, the pink one *located above the scientific equipment rack.*

Finally, on the center of the green floor is a circular hatch leading to the EVA airlock. *When the hatch is closed, the arrow handle points towards the command module hatch, and away from the space suit locker. As previously noted*, there is a double foot restraint on the *workbench* side, and a single foot restraint on the *control panel* side.

Now remove the head mounted display.

Now imagine you are facing the EVA module control panel.
Tell me what features of the module you remember*, and the relationships between them.*

These are the landmarks *and relationships* you forgot:

4. EVA Module Computerized Training
(Run through first trial)
Ok, you have 29 left. Remember, we want equal priority for speed and accuracy.
(break)

Combined Module Task Briefing

This part of the training teaches you relationships between the two modules you have just learned.

For the rest of your training, the computerized task will be slightly different. Before you put on the head mounted display, lets look at the computer screen together, and I'll show you how this different computerized training task works: (demonstrate)

As before, you'll first see one wall of the module that you are in – the "cue wall". Based on your prior training, you should be able to figure out how you are oriented, and where things are in this local module. When you know how you are oriented, push proceed on the gamepad. Next, the other module will appear outlined in a yellow wire frame. Your view of the other module will be looking through the other walls, as if you had x-ray vision. "Target" details appear on one of the wireframe walls – but it is important to remember that the target wall may not be located on the correct surface. You need to determine where the target wall goes, and orient it properly relative to the module you are in. Push proceed as many times as necessary to move the wall to the correct wireframe surface . Once the wall is on the correct wireframe surface push select to anchor it there, and then push proceed to rotate the target to the proper relative orientation. When the target is in the correct orientation, push the select button again to finalize your answer. After you answer, all the surfaces will appear, so you will be able to see if you positioned the target correctly or not. Then hit proceed again to move on to the next training question. Remember "proceed" is the action button and "select" is the answer button. When we get to it, I will walk you through the first computerized trial

In the first 10 trials the target wall will be directly adjacent to the cue wall. In subsequent trials it may appear on any of the surfaces in the far module.
Any questions? I will walk you through the first computerized trial, when the time comes.

(Subject dons the head mounted display)

5. Combined Command Module-EVA Module Verbal Tour

You are located in the command module. Look around to confirm that everything is where you remember it was. Notice the white curtain over the hatch has been removed, so you can see the second module attached below.

I will remove the hatch wall to make the far module easier to see.

Next I'll show you how the two modules are connected.

It is important to learn the relationships between *each of the adjacent walls in* the two modules. Previous testing shows this is the easiest way to remember the spatial relationships between the two modules, and qualify for a bonus payment on testing.

First face the command module instrument panel. Looking into the EVA module, you can see that immediately adjacent to the command module instrument panel, in the same plane, is the ceiling of the EVA module. The air conditioning duct is furthest away from you, and runs to the suit locker on the far wall. Now turn right and look at the Ultrasound/food stowage wall in the Command module. Notice that the intercom panel beneath the blue seat is immediately adjacent to the communications headset on the opposite side of the hatch and to the airlock control panel in the EVA module.

Turning further to the right, to face the glove box, notice that the airlock hatch arrow in the EVA module points towards the glovebox. The airlock and the animals are located on the same side of the spacecraft.

Turning around 270 degrees to the left, to face the round window, you realize that in emergencies, the intermodule power cables stowed on the round window wall can be connected through the open hatch to the electrical power switching panel on the left side of the workbench wall, in case the main power bus is lost.

Finally, notice that the EVA stowage locker and the ceiling of the command module are on opposite ends of the spacecraft, facing each other. The locker/light axis is parallel with the suit locker axis.

Again, remember that the instrument panel is adjacent to the EVA ceiling, the ultrasound wall is adjacent to the EVA control panel, the animal racks are adjacent to the airlock hatch, and the astronaut window is adjacent to the EVA tools.

(Only in Rotation Training)
[First face the command module instrument panel. Looking into the EVA module, you can see that the space suit stowage wall is now directly below you as the new floor. This means that the pink hatch of the EVA module shares a wall with the floor hatch of the Command module. It might be easiest to think of the relationships between the modules as a pitch and a roll. To remain upright in both modules you would have to move down from this module and then rotate foreword and roll over.

The ceiling of the EVA module is down and in front. To the right is the airlock control panel. To the left and down is the EVA tool back wall, and behind you and below is the airlock hatch. Please look around at the two modules.

Again, remember that the two modules are connected through a pitch and a roll.]

Now please remove the head mounted display .
Imagine yourself facing the command module instrument panel.
Now describe features in the two modules and the relationships between them

These are the landmarks and relationships you forgot:

6. Combined Command Module EVA Module Computerized Training

Next, the head mounted display back on. I'll walk you through the first trial.
(Run through first trial)
Ok, you have 35 left. Remember, we put equal priority on speed and accuracy.

7. Combined Modules Computerized Testing

Now we're going to test your spatial knowledge of the combined modules. We are testing some of the skills you would need to find emergency equipment in the case of heavy smoke or a surprise power failure. There are two phases to the testing. In the first part you will be located in the command module, and looking towards the EVA module. In the second phase, you will be in the EVA module and looking towards the command module. You should take a short break between them.

The task is the same as the previous step, but with no feedback between trials. Again I will give you a single cue wall with which to orient yourself. When you are oriented, push proceed as before, and then the other module will appear with a target wall already in it, except this time the cue wall will have disappeared. Your task is to put that target wall on the correct wireframe surface using the proceed button, push select, and then push proceed to orient it correctly as in the previous phase. When it is in the correct orientation and position hit the select button to move on to the next trial. Remember, if you have a greater than 95% accuracy rate and an average response time of less than 15s you will make up to $10 more.

8.3 Appendix C – Recall Checklists

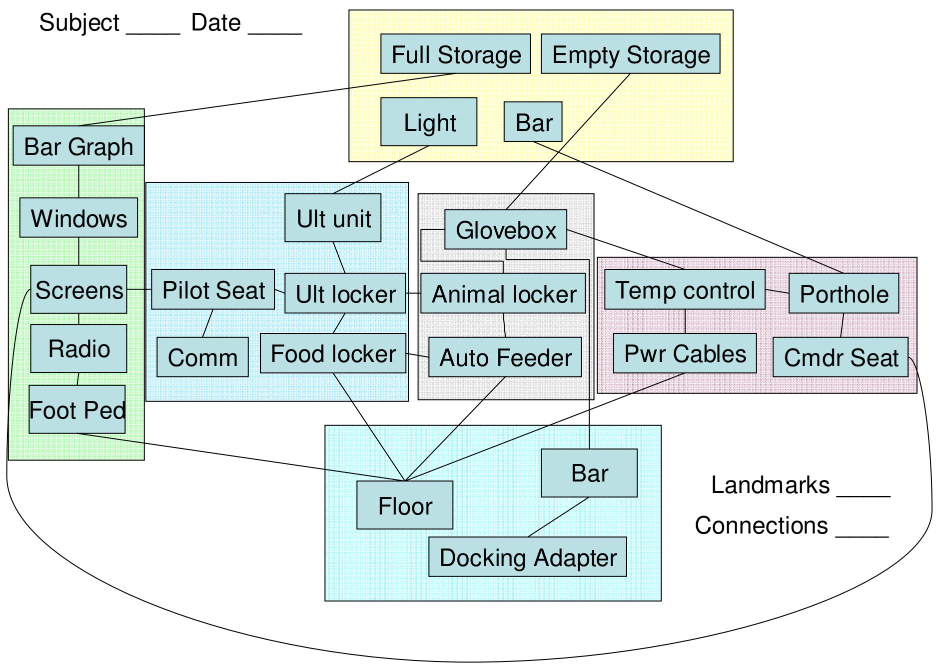


Figure 25. Checklist for Command module recall.

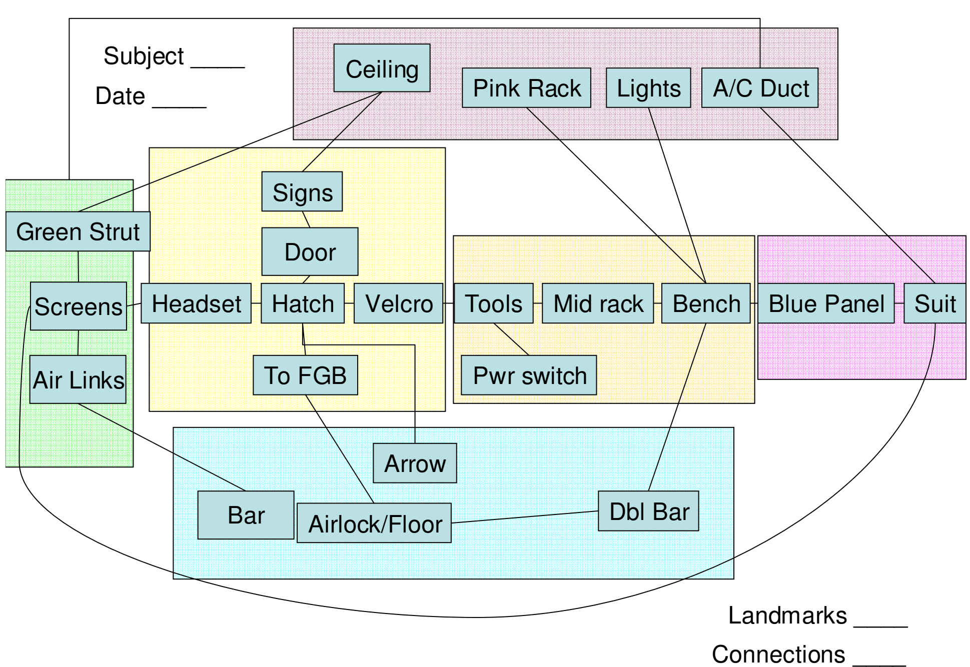
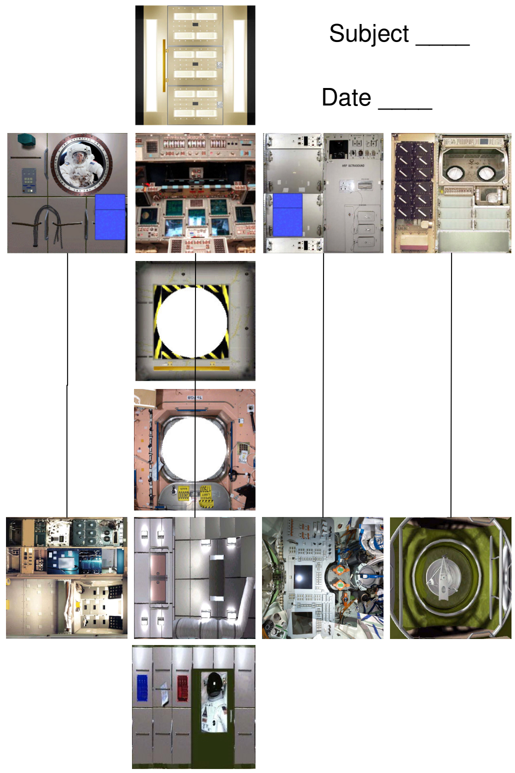


Figure 26. Checklist for EVA module recall.



Connections ____

Adjacencies ____

Figure 27. Checklist for Combined module recall.

8.4 Appendix D – Strategy and Visualization Questionnaire

1. Which texture (A-F) did you consider the "front" of the Command Module? ____
2. Which texture (A-F) did you consider the "top" of the Command Module? _____
3. Which texture (G-L) did you consider the "front" of the EVA Module? _____
4. Which texture (G-L) did you consider the "top" of the EVA Module? _____

5. In the last 3 phases, did you consider the combined modules to be:
    a. one combined large module
    b. two connected independent modules

6. Which of the following statements is the closest to the strategy you used in the combined module testing?
    a. I remembered how 2 or more pairs of walls were connected between the modules
    b. I remembered how 1 pair of walls were connected and then how the other walls in that module related to that pair
    c. I remembered how the modules were rotated relative to one another and used that relationship to orient myself in the far module
    d. Other

        Please elaborate____

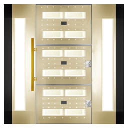
7. When you were in the Command module, where did you think the EVA module was?
    a. Above
    b. Below
    c. In Front
    d. Behind
    e. Left
    f. Right

8. When you were in the EVA module, where did you think the Command module was?
    a. Above
    b. Below
    c. In Front
    d. Behind
    e. Left
    f. Right

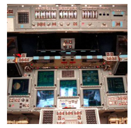
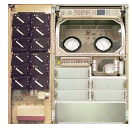
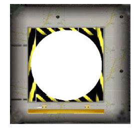
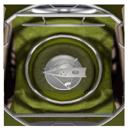
****_Only the final 10 subjects answered these last two questions._*******

9. Which configuration (1-4) matches what you pictured in the first testing phase? ___

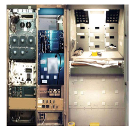
10. Which configuration (5-8) matches what you pictured in the second testing phase? ___


A

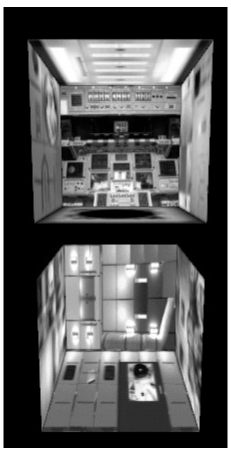
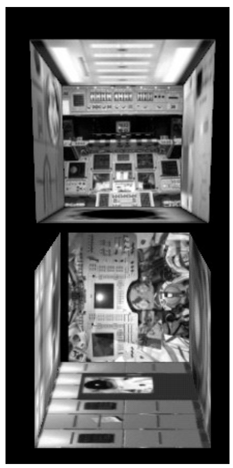
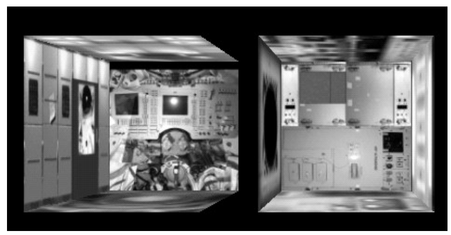
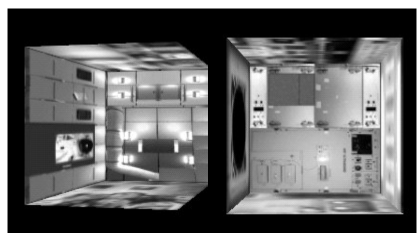
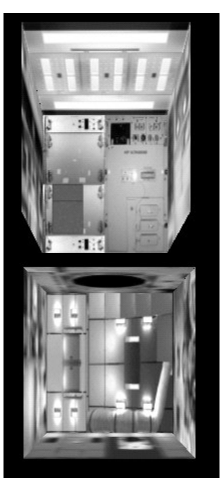
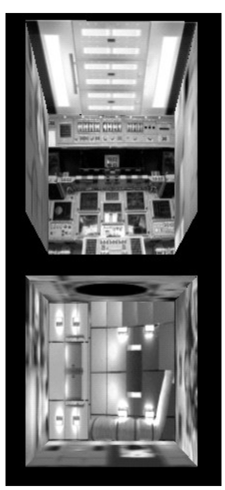
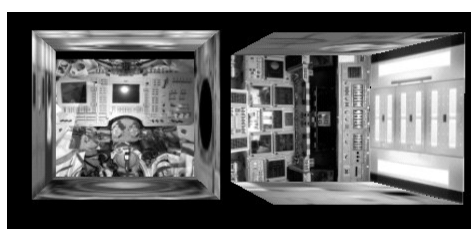
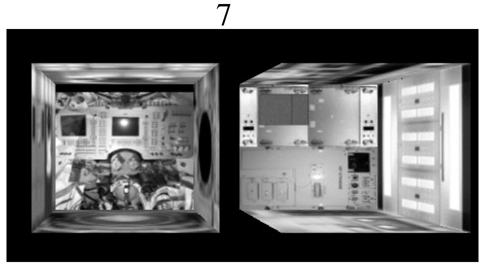
B

C

D

E

F

G

H

I

J

K

L

1

2

3

4

5

6

7

8

8.5 Appendix E – Trial Sequence

Only 3 orientations were used, upright (0), sideways (1), and upside down (2). Right and left turns were considered equal, and were only presented once. Sequences were organized so all three orientations appeared twice every six trials whenever possible. Each target was presented with a different cue in 3 different orientations.

1 Module (Phase 1 and 2) training sequence

Trial	CUE	TARGET	ORIENT	NOISE
1	2	1	0	0
2	1	0	0	0
3	3	1	0	1
4	0	1	0	0
5	1	2	1	1
6	2	3	1	2
7	3	4	2	2
8	4	5	2	3
9	5	0	0	0
10	4	1	0	1
11	3	2	1	2
12	2	4	2	3
13	1	5	2	3
14	0	2	1	2
15	1	3	1	0
16	0	3	1	0
17	3	5	2	1
18	4	0	0	2
19	5	4	2	3
20	0	5	2	3
21	4	3	1	2
22	2	5	2	0
23	1	4	2	0
24	5	3	1	1
25	4	2	1	1
26	3	0	0	1
27	5	2	1	3
28	0	4	2	1
29	5	1	0	0
30	2	0	0	1

2 Module Adjacency Training Phase 3

Trial	CUE	TARGET	ORIENT	NOISE
1	2	5	0	2
2	0	4	0	1
3	1	2	0	0
4	3	0	0	1
5	1	2	1	2
6	2	5	1	1
7	0	4	2	2
8	1	2	2	1
9	2	5	2	0
10	3	0	1	0
11	1	0	0	2
12	3	4	0	1
13	2	0	1	0
14	0	5	2	1
15	1	5	2	2
16	0	2	1	1
17	2	4	2	2
18	3	0	2	2
19	3	4	1	0
20	3	2	1	0
21	2	0	2	2
22	0	5	0	1
23	1	0	2	2
24	1	5	1	0
25	3	2	0	1
26	0	4	1	0
27	0	2	2	0
28	2	0	0	1
29	0	5	1	2
30	3	2	2	2
31	2	4	1	2
32	1	5	0	2
33	3	4	2	0
34	2	4	0	2
35	1	0	1	0
36	0	2	0	0

2 Module Rotation Training Phase 3

And Phase 4 for both groups

Trial	CUE	TARGET	ORIENT	NOISE
1	1	0	0	2
2	2	5	0	2
3	3	4	0	1
4	0	4	0	1
5	2	0	1	0
6	0	5	2	1
7	3	0	2	2
8	1	2	1	2
9	1	5	2	2
10	0	2	1	1
11	2	4	2	2
12	3	4	1	0
13	3	2	1	0
14	2	0	2	2
15	0	5	0	1
16	1	0	2	2
17	1	5	1	0
18	3	2	0	1
19	0	2	2	0
20	2	0	0	1
21	0	5	1	2
22	3	2	2	2
23	2	4	1	2
24	1	5	0	2
25	1	2	0	0
26	2	5	1	1
27	3	4	2	0
28	0	4	1	0
29	2	4	0	2
30	0	4	2	2
31	3	0	0	1
32	1	0	1	0
33	1	2	2	1
34	0	2	0	0
35	2	5	2	0
36	3	0	1	0

Phase 5 for both groups

Trial	CUE	TARGET	ORIENT	NOISE
1	0	1	1	2
2	0	2	2	0
3	0	3	3	2
4	2	0	2	1
5	5	2	1	2
6	5	0	3	1
7	4	3	1	1
8	2	1	2	2
9	5	1	3	2
10	4	0	1	1
11	4	2	3	2
12	4	3	2	0
13	2	3	2	0
14	0	2	3	2
15	5	0	1	1
16	0	1	3	2
17	5	1	2	0
18	2	3	1	1
19	2	0	3	0
20	0	2	1	1
21	5	0	2	2
22	2	3	3	2
23	4	2	2	2
24	5	1	1	2
25	2	1	1	0
26	5	2	2	1
27	4	3	3	0
28	4	0	2	0
29	4	2	1	2
30	4	0	3	2
31	0	3	1	1
32	0	1	2	0
33	2	1	3	1
34	2	0	1	0
35	5	2	3	0
36	0	3	2	0

8.6 Appendix F – Code for Computerized Training and Testing.

```
############################################
# 1 Module Training
# Created by David Benveniste
# Modified by Dan Buckland and Claire Cizaire
#
# Revised version of B&B experimental program
# The cue is diplayed first and the subject uses
# the joypad buttons to designate the target and orient #
it while the cue remains up
############################################

ON = 1
OFF= 0
HMD = ON


# timer flags

START_TRIAL = 0
SHOW_TARGET = 1
SHOW_CUE = 2
RECORD_WALLS = 3
MEMORY_TASK = 4
SEARCH_TARGET = 5
ORI_TARGET = 6
DISP_FEEDBACK = 7
END_EXP = 8
END_TRIAL = 9
WAIT = 10

# joypad buttons to be used

B1 = 1
B2 = 2
B3 = 4
B4 = 8
B5 = 16
B6 = 32
B7 = 64
B8 = 128

import ipc
import viz
import sid
import time
import vizmat
import math
from string import *

# Choose which stimulus file to use
FILENAME = 'BucklandTrials1Mod.txt'

############################
# VR SETUP (HMD AND TRACKER)
############################

if HMD == ON:
	viz.cursor(viz.OFF)
	viz.go(viz.STEREO|viz.HMD)
	#headTrack = viz.addsensor('is600')
	headTrack = viz.add('intersense.dls')
	# Uses only 3 dof to prevent drifting of the
scene
	# To switch back to 6 dof use command(1)
	# headTrack.command(11)
	viz.tracker()



else:
	viz.cursor(viz.OFF)
	viz.go()


viz.eyeheight(0)
viz.override()
view = viz.get(viz.MAIN_VIEWPOINT)

##Settings
PHASE = viz.input('Phase?')

if PHASE == 1:
	PHS = '1'
elif PHASE == 2:
	PHS = '2'
else:
	PHS = '6'

NAME = viz.input('Subject Name')
SUBJECT = '..\\'+NAME + '_mod1_phs' + PHS + '.txt'


#Room number (0 for phase 1 (first module) or 1 for
phase 2 (second module))
if PHASE == 1:
	room_num = 0
else:
	room_num = 1

#############################################
#############################
#GEOMETRY
```

```
#############################################
##############################

viz.clearcolor(0,0,0)

## display for targets loaded in a different scene
target = []

target.append(viz.add('../experiment_rooms/no_object.wrl',viz.HEAD,2))
target.append(viz.add('../experiment_rooms/no_object.wrl',viz.HEAD,2))
target.append(viz.add('../experiment_rooms/no_object.wrl',viz.HEAD,2))
target.append(viz.add('../experiment_rooms/no_object.wrl',viz.HEAD,2))
target.append(viz.add('../experiment_rooms/no_object.wrl',viz.HEAD,2))
target.append(viz.add('../experiment_rooms/no_object.wrl',viz.HEAD,2))
## plane to display the target
target.append(viz.add('../experiment_rooms/hplane3x3.wrl',viz.HEAD,2))

for i in range(0,len(target)):
	target[i].visible(0)
	target[i].translate(0,1.82,0)
	target[i].rotate(1,0,0,-90)
	target[i].translate(0,0,4)

print target
# Generic room
room = []
for i in range(0, 6):
	print i
	room.append(viz.add('../experiment_rooms/hplane3x3.wrl',viz.WORLD,1))

## 3D objects
object = []
for i in range(0,12):
	object.append(room[i%6].add('../experiment_rooms/no_object.wrl',viz.WORLD,1))


iTex = []

# 1st room textures
iTex.append(viz.addtexture('../experiment_rooms/textures/tex/side_glovebox2.jpg'))
iTex.append(viz.addtexture('../experiment_rooms/textures/tex/JEM_10x1.jpg'))
iTex.append(viz.addtexture('../experiment_rooms/textures/tex/EL-2000-00036fixed.jpg'))
iTex.append(viz.addtexture('../experiment_rooms/textures/tex/side_windowx1.jpg'))
iTex.append(viz.addtexture('../experiment_rooms/textures/tex/Bnodehatchhole.gif'))
iTex.append(viz.addtexture('../experiment_rooms/textures/tex/TOPx22.jpg'))
#2nd room
if PHASE == 2:
	iTex.append(viz.addtexture('../experiment_rooms/textures/tex/RB1ax2Z2.jpg'))
	iTex.append(viz.addtexture('../experiment_rooms/textures/tex/node_aft_pink_hatch.gif'))
	iTex.append(viz.addtexture('../experiment_rooms/textures/tex/050223_controlpanel_3.jpg'))
	iTex.append(viz.addtexture('../experiment_rooms/textures/tex/spacesuit.jpg'))
	iTex.append(viz.addtexture('../experiment_rooms/textures/tex/rus_hatch2.jpg'))
	iTex.append(viz.addtexture('../experiment_rooms/textures/tex/Brservtop.jpg'))




# Red transparency texture
#rTex = viz.addtexture('gb_noise.jpg') #test for nontransparent textures
rTex = viz.addtexture('../experiment_rooms/textures/reticleBe3.tif')
# Yellow transparency texture
#yTex = viz.addtexture('gb_noise.jpg')
yTex = viz.addtexture('../experiment_rooms/textures/reticleBe4.tif')
# red transparency texture with yellow frame to chose the target
rTexYS = viz.addtexture('../experiment_rooms/textures/reticleBe5&square.tif')
#texture for end of phase
EndOfPhase = viz.addtexture('../experiment_rooms/textures/all_done.jpg')

#Text object to display messages not in final sequence-db
mytext = viz.add(viz.TEXT3D,'text',viz.HEAD,1)
mytext.scale(0.05,0.1,0.1)
mytext.alignment(viz.TEXT_CENTER_BOTTOM)
mytext.translate(0,0,0.5)
mytext.color(0.9,0.2,0.1)
mytext.visible(0)

##########################
#POSITIONS
##########################
```

```
# Defining the starting configuration of the environment
START_POS = []
START_POS.append(vizmat.Transform())
for i in range(0,12):
	START_POS.append(vizmat.Transform())
	START_POS[i].makeIdent()

START_POS[0].makeRot(0,1,0,180)
START_POS[0].postRot(1,0,0,90)
START_POS[1].postRot(1,0,0,-90)
START_POS[1].postRot(0,1,0,90)
START_POS[2].postRot(1,0,0,-90)
START_POS[3].postRot(1,0,0,-90)
START_POS[3].postRot(0,1,0,-90)
START_POS[5].postRot(1,0,0,180)

if HMD == ON:
	for i in range(0,6):
		START_POS[i].postRot(0,1,0,-90)

# Defining the current configuration of the environment
current_pos = []
for i in range(0,12):
	current_pos.append(vizmat.Transform())
	current_pos[i].makeIdent()

#transform object to go from starting position to current position
trans = vizmat.Transform()
noisePos = vizmat.Transform()

################################################################
# Read stimules file and open data file for experimental trials
################################################################

def InitializeExp():

	global file
	global data
	global allCue
	global allTarget
	global allOri
	global allNoise

	file = open(FILENAME,'r')
	print 'opened stim file: ', FILENAME
	#'r' for reading
	data = open(SUBJECT,'a')
	print 'created output file:', SUBJECT
	#'a' for append
	data.write('%Subject name:' + SUBJECT + '\n')
	data.write('%Test performed on:' + time.ctime() + '\n')
	data.write('%stimulus name:' + FILENAME + ' module'+ str(room_num)+'\n')
	data.write('%columns:'+'\n')
	data.write('%Trial#'+'\t'+'Cue'+'\t')
	data.write('Ori'+'\t'+'Target'+'\t'+'TargAns'+'\t' +'OriAns'+'\t')
	data.write('T_Cue'+'\t'+'T_targ'+'\t'+'T_ans'+'\t' +'T_ori'+'\t'+'T_FB'+'\n')

	#Experiment stimulus file
	all = file.readlines()
	allCue = []
	allOri = []
	allTarget = []
	allNoise = []
	print 'stimulus file with ',len(all)-1,' trials'
	for i in range(1,len(all)):
		access = all[i]
		s = split(access)
		allCue.append(eval(s[0]))
		allTarget.append(eval(s[1]))
		allOri.append(eval(s[2]))
		allNoise.append(eval(s[3]))
	file.close()
########################################
# subroutines
########################################

def showTarget(target_num):
	global target
	for obj in target:
		obj.visible(0)
	target[len(target)-1].visible(1)
	target[len(target)-1].texture(iTex[target_num],'plane')
	target[len(target)-1].appearance(viz.DECAL)
	viz.fov(39,1.333)
	viz.setscene(2)
	viz.clearcolor(0,0,0)
	if target_num in range(0,len(target)-1):
		target[target_num].visible(1)		# display object

def showCues(cue):
	global fov
	viz.fov(fov,1.333)
	viz.setscene(1)
	viz.clearcolor(0,0,0)
	for wall in room:
		wall.texture(rTex,'plane')
		wall.appearance(viz.MODULATE)
	for obj in object:
		obj.visible(0)
```

```
		room[cue].texture(iTex[cue+room_num*6],'pl
ane')
		room[cue].appearance(viz.DECAL)
		object[cue+room_num*6].visible(1)

def orientRoom(cue,ori):
	global current_pos
	global trans

	#defining a intermediate transformation
	#that sets the entry face to be behind the user
	trans.set(START_POS[cue])
	trans.invertOrtho()
	trans.postMult(START_POS[2])
	if HMD == OFF:
		trans.postRot(0,0,1,ori*90)
	elif HMD == ON:
		trans.postRot(1,0,0,ori*90)
	for i in range(0,6):
		current_pos[i].set(START_POS[i])
		current_pos[i].postMult(trans)
		room[i].update(current_pos[i])

	object[i+6*room_num].update(current_pos[i])

#######################################
# TIMER FOR EXPERIMENTAL TRIALS
#######################################


def ExptTimer(timer):

	global currentTrial
	global trans
	global noisePos
	global startTime
	global T_cue
	global T_targ
	global T_ans
	global T_ori
	global T_FB
	global button
	global dir
	global cue
	global ori
	global target
	global target_num
	global noise
	global task
	global THRESHOLD

	THRESHOLD = 0.75

	if timer == WAIT:

		if sid.buttons() in (B7,B8):
			while sid.buttons() is not 0:
				pass
			else:
				print		'button
unpressed, starting task', task
				viz.starttimer(task)

		else:
#
			viz.starttimer(WAIT)

	if timer == SHOW_CUE:
		print 'starting trial ', currentTrial
		dir = 6
		button = 0
		viz.fov(fov,1.333)
		startTime = time.time()
		cue = allCue[currentTrial]
		ori = allOri[currentTrial]
		noise = allNoise[currentTrial]
		orientRoom(cue,ori)
		for i in range(0,6):
			room[i].texture(rTex,'plane')

	room[i].appearance(viz.MODULATE)

	object[i+room_num*6].visible(0)

	room[cue].texture(iTex[cue+room_num*6],'pl
ane')
		room[cue].appearance(viz.DECAL)
		object[cue+room_num*6].visible(1)
		viz.setscene(1)
		viz.clearcolor(0,0,0)
		task				=
SHOW_TARGET#MEMORY_TASK
		viz.starttimer(WAIT)

	elif timer == SHOW_TARGET:
		dir = 6
		button = 0
		T_targ = time.time()
		T_cue = round(T_targ - startTime,2)
		target_num				=
allTarget[currentTrial]+6*room_num
		showTarget(target_num)
		task		=		MEMORY_TASK
#SHOW_CUE
		viz.starttimer(WAIT)


	elif timer == MEMORY_TASK:
		T_ans = time.time()
		T_targ = round(T_ans - T_targ,2)
		for i in range(0,6):
			room[i].texture(yTex,'plane')
```

```
room[i].appearance(viz.MODULATE)

object[i+room_num*6].visible(0)
        button = 0

room[cue].texture(iTex[cue+room_num*6],'pl
ane')
        room[cue].appearance(viz.DECAL)
        object[cue+room_num*6].visible(1)
        viz.setscene(1)
        viz.clearcolor(0,0,0)
        viz.fov(fov,1.333)
        task = SEARCH_TARGET
        viz.starttimer(SEARCH_TARGET)

elif timer == SEARCH_TARGET:
        if (time.time() - startTime) > 180:
                if button == 0:
                        dir = 6 # no answer
was given
                task = DISP_FEEDBACK
                viz.starttimer(task)
        else :
                if not (button in (B7,B8)): #
no button pressed yet
                        myL =
viz.get(viz.HEAD_LOOK)[0:3]
                        message_disp = ''
                        for i in range(0,6):
                                if i <> cue:

myV = current_pos[i].get()[4:8]

room[i].texture(yTex,'plane')

room[i].appearance(viz.MODULATE)

prod = -myV[0]*myL[0]-
myV[1]*myL[1]+myV[2]*myL[2]
                                        if
i <4:

print myV[i]


message_disp = message_disp+'wall #
'+str(i)+'\nscalar prod:'+str(prod)+'\n'
                                        if
prod > THRESHOLD:

dir = i

room[i].texture(rTexYS,'plane')

room[i].appearance(viz.MODULATE)

mytext.message(message_disp)
                        button =
sid.buttons()

mytext.message('looking at
face:'+str(dir)+'\nanswer is face:'+str(target_num))

viz.starttimer(SEARCH_TARGET)
                else:
                        if dir <> cue:
                                button = 0
                                T_ori =
time.time()
                                T_ans =
round(T_ori - T_ans,2)
                                task =
ORI_TARGET
                                noise =
allNoise[currentTrial]

noisePos.set(current_pos[dir])

noisePos.preRot(0,1,0,90*noise)
                                print
target_num

object[target_num].update(noisePos)

room[dir].update(noisePos)

object[target_num].visible(1)

room[dir].texture(iTex[target_num],'plane')

room[dir].appearance(viz.DECAL)
                                while
sid.buttons() is not 0:

pass
                                else:

print 'button unpressed, starting task', task

viz.starttimer(task)
                        else:

viz.starttimer(task)

elif timer == ORI_TARGET:
        if not (button in (B3,B2)):
                if sid.buttons() == B7:
                        noise = (noise +
1)%4
                        while
sid.buttons()<>0:
```

```
                                        pass
                                elif sid.buttons() == B8:
                                        noise = (noise -
1)%4
                                        while
sid.buttons()<>0:
                                                pass
                                button = sid.buttons()

        noisePos.set(current_pos[dir])

        noisePos.preRot(0,1,0,90*noise)

        object[target_num].update(noisePos)
                                room[dir].update(noisePos)

        viz.starttimer(ORI_TARGET,0.1)
                        else:
                                task = DISP_FEEDBACK
                                while sid.buttons() is not 0:
                                        pass
                                else:
                                        print 'button
unpressed, starting task', task
                                        button = 0
                                        viz.starttimer(task)



        elif timer == DISP_FEEDBACK:

                T_FB = time.time()
                T_ori = round(T_FB - T_ori,2)
                for i in range(0,6):

        room[i].update(current_pos[i])

        object[i+room_num*6].update(current_pos[i])

        room[i].texture(iTex[i+room_num*6],'plane')

        room[i].appearance(viz.DECAL)

        object[i+room_num*6].visible(1)
                task = END_TRIAL
                viz.starttimer(WAIT)

        elif timer == END_TRIAL:
                T_FB = round(time.time() - T_FB,2)
                # Writing the trial results to the result
file
                Trial_R =
str(currentTrial)+'\t'+str(cue)+'\t'+str(ori)
                Trial_R = Trial_R
+'\t'+str(target_num)+'\t'+str(dir+room_num*6)
                Trial_R = Trial_R
+'\t'+str(noise)+'\t'+str(T_targ)+'\t'+str(T_cue)
                Trial_R = Trial_R
+'\t'+str(T_ans)+'\t'+str(T_ori)+'\t'+str(T_FB)
                Trial_R = Trial_R +'\n'
                data.write(Trial_R)
                #moving to next trial
                currentTrial = currentTrial + 1
                if currentTrial > len(allTarget)-1:#
The first line of the file is just comments
                        task = END_EXP
                else :
                        task = SHOW_CUE
                viz.starttimer(task)

        elif timer == END_EXP:
                data.close()
                print 'end of experiment'
                viz.setscene(2)
                viz.clearcolor(0,0,0)
                viz.fov(40,1.333)
                for obj in target:
                        obj.visible(0)
                target[len(target)-1].visible(1)
                target[len(target)-
1].texture(EndOfPhase,'plane')


########################
# keyboard function to start the experiment
########################

def startExpKeyboard(key):
        global currentTrial
        global button
        global task
        global fov


        if key == 's':
                InitializeExp()
                currentTrial = 0
                orientRoom(2,0)
                for obj in object:
                        obj.visible(0)
                for i in range(0,6):

        room[i].texture(iTex[i+room_num*6],'plane')

        room[i].appearance(viz.DECAL)

        object[i+room_num*6].visible(1)
                task = SHOW_CUE
                fov = 70
                viz.fov(fov,1.333)
```

```
		button = 0
	elif key == ' ':
		viz.starttimer(task)
		print 'task', task
	elif key == viz.KEY_UP:
		fov = fov + 1
		viz.fov(fov,1.333)
		print 'field of view set to', fov, 'deg in the vertical direction'
	elif key == viz.KEY_DOWN:
		fov = fov - 1
		viz.fov(fov,1.333)
		print 'field of view set to', fov, 'deg in the vertical direction'
	elif key == 'h': #get position of the hand
		print handTrack.get()
	elif key == 't':
		message = viz.input('enter new text to display')
	elif key == '+':

	viz.translate(viz.HEAD_POS,Tvec[0],Tvec[1], Tvec[2])
	elif key == '-':
		viz.translate(viz.HEAD_POS,-Tvec[0],-Tvec[1],-Tvec[2])
	elif key == 'z': #back up the view point along z-axis
		Tvec = 0,0,1
	elif key == 'y': #back up the view point along z-axis
		Tvec = 0,1,0
	elif key == 'x': #back up the view point along x-axis
		Tvec = 1,0,0
	elif key == 'p': #pitch the view point 90 deg
		viz.rotate(viz.BODY_ORI,0,90,0)
	elif key == 'w': #yaw the view point 90 deg
		viz.rotate(viz.BODY_ORI,90,0,0)

if HMD == OFF:
	def mousemove(x,y):
		euler = view.get(viz.HEAD_EULER)
		euler[0] += x*0.55
		euler[0] = viz.clamp(euler[0],-180.0,180.0)
		euler[1] += y*0.5
		euler[1] = viz.clamp(euler[1],-90.0,90.0)
		view.rotate(euler,viz.HEAD_ORI)

	def mousedown(button):
		if button == viz.MOUSEBUTTON_LEFT:
			view.reset(viz.HEAD_ORI)
		elif button == viz.MOUSEBUTTON_RIGHT:
			view.reset(viz.HEAD_ORI)

	viz.callback(viz.MOUSEBUTTON_EVENT, mousedown)
	viz.callback(viz.MOUSEMOVE_EVENT,mousemove)
	viz.mousedata(viz.RELATIVE,viz.RELATIVE)


fov = 70
viz.callback(viz.TIMER_EVENT,'ExptTimer')
viz.callback(viz.KEYBOARD_EVENT,'startExpKeyboard')
```

```
###########################################
# 2 Module Training and Testing
# the target is in the far module
# Created by David Benveniste
# Modified by Dan Buckland and Claire Cizaire
#
# Revised version of B&B experimental program
# The cue is diplayed first and the subject uses
# the joypad buttons to designate the target and orient it
###########################################

ON = 1
OFF= 0

##Settings
HMD = ON


# timer flags

START_TRIAL = 0
SHOW_TARGET = 1
SHOW_CUE = 2
RECORD_WALLS = 3
MEMORY_TASK = 4
SEARCH_HATCH = 5
SEARCH_TARGET = 6
DISP_FEEDBACK = 7
END_EXP = 8
END_TRIAL = 9
WAIT = 10
TRAIN_MEMORY_TASK = 11
LMEMORY_TASK = 12
LSEARCH_TARGET = 13
TRAIN_SEARCH_TARGET = 14
ORI_TARGET = 15
MEMORY_TASK_TRAIN = 16
PLACE_TARGET = 17

# joypad buttons to be used

B1 = 1
B2 = 2
B3 = 4
B4 = 8
B5 = 16
B6 = 32
B7 = 64
B8 = 128
B9 = 256
B10 = 512


import viz
import sid
import time
import vizmat
import math
from string import *

#FeedBack or not feedback?
#Feedback is ON for phase 3, OFF for phases 4 and 5 -
moved lower
T_FB = 0
# Test condition
# Ground configuration, 2nd module simply translated
GC = 0
FC5 = 5
# test condition to be used
# Legacy numbers from David's code

############################
# VR SETUP (HMD AND TRACKER)
############################

if HMD == ON:
	viz.cursor(viz.OFF)
	viz.go(viz.STEREO|viz.HMD)
	#headTrack = viz.addsensor('is600')
	headTrack = viz.add('intersense.dls')
	# Uses only 3 dof to prevent drifting of the
scene
	# To switch back to 6 dof use command(1)
#	headTrack.command(11)
	viz.tracker()

else:
	viz.cursor(viz.OFF)
	viz.go()

viz.eyeheight(0)
viz.override()
fov = 70
viz.fov(fov,1.333)
view = viz.get(viz.MAIN_VIEWPOINT)

#placeholder for number of tries
tries = 1

PHASE = viz.input('Phase?')
if PHASE == 3:
	#0 = Hatch, 1 = Adjacency
	ADJ = viz.input('Training?')

NAME = viz.input('Subject Name?')

#To run code for debugging and coding
#PHASE = 3
#NAME = 'TimerTest1'
#FILENAME = 'BucklandTrials.txt'

if PHASE == 3:
```

```
	feedback = ON
	condition = FC5
	TRAIN = ON
	LB = OFF
	if ADJ == 0:
		FILENAME = 'BucklandTrialsHatch.txt'
	else:
		FILENAME = 'BucklandTrialsAdj.txt'
	PHS ='3'
if PHASE == 4:
	feedback = OFF
	condition = FC5
	TRAIN = OFF
	LB = OFF
	FILENAME = 'BucklandTrialsHatch.txt'
	PHS ='4'
elif PHASE == 5:
	feedback = OFF
	condition = FC5
	TRAIN = OFF
	LB = ON
	FILENAME = 'BucklandTrialsLB.txt'
	PHS ='5'



SUBJECT = '..\\'+NAME + '_mod2_phs' + PHS + '.txt'

#if TRAIN == OFF:
Ltarget_num = 0
LT_targlook = 0
LT_targpick = 0
T_MC = 0
T_ori = 0


##########################
#POSITIONS
##########################

# Defining the starting configuration of the environment
# method to set all the walls in one room
# to their correct position
# a room consists of a table with 6 elements
# the numbers follow the mnemonics proposed
# by Jason Richards:
# 0, behind; 1, right; 2, ahead; 3, left;
# 4, floor; 5, ceiling
# These numbers should be considered modulo 6 since
# there are 2 rooms (indexes 0 to 5 and 6 to 11)

START_POS = []
START_POS.append(vizmat.Transform())
for i in range(0,12):
	START_POS.append(vizmat.Transform())
	START_POS[i].makeIdent()

#START_POS[i] describes the ABSOLUTE position of the i_th wall in rotation
START_POS[1].postRot(0,1,0,-90)
START_POS[2].postRot(0,1,0,180)
START_POS[3].postRot(0,1,0,90)
START_POS[4].postRot(0,0,1,180)
START_POS[4].postRot(1,0,0,-90)
START_POS[5].postRot(0,0,1,180)
START_POS[5].postRot(1,0,0,+90)

#the relative position of walls in second module are the same as in the first one this moves them to starting position 4m away in z
for i in range(0,6):
	START_POS[i+6].set(START_POS[i])
	START_POS[i+6].postTrans(0,0,4)
current_pos = []
for i in range(0,12):
	current_pos.append(vizmat.Transform())
	current_pos[i].makeIdent()
#transform object to go from starting position to current position
trans = vizmat.Transform()
noisePos = vizmat.Transform()
#object transform (corrective term for the start position)
OBJ_T =vizmat.Transform()
OBJ_T.makeRot(0,1,0,180)
OBJ_T.postRot(1,0,0,90)

##########################################################################
#GEOMETRY
########################################################################
target = []
#target.append(viz.add('../experiment_rooms/hplane3x3.wrl',viz.HEAD,2))
target.append(viz.add('../experiment_rooms/wall0.wrl',viz.HEAD,2))
for i in range(0,len(target)):
	target[i].visible(0)
	target[i].translate(0,1.82,0)
	target[i].rotate(0,1,0,180)
	target[i].translate(0,0,4)


room = []
for i in range(0,12):
	room.append(viz.add('../experiment_rooms/wall0.wrl',viz.WORLD,1))

### Objects to place room textures on
```

```
object = []
for i in range(0,12):
	object.append(room[i].add('../experiment_rooms/no_object.wrl',viz.WORLD,1))


for i in range(0,12):
	object[i].update(OBJ_T)

iTex = []

	if LB == OFF:
	# 1st room textures

	iTex.append(viz.addtexture('../experiment_rooms/textures/tex/side_glovebox2.jpg'))

	iTex.append(viz.addtexture('../experiment_rooms/textures/tex/JEM_10x1.jpg'))

	iTex.append(viz.addtexture('../experiment_rooms/textures/tex/EL-2000-00036fixed.jpg'))

	iTex.append(viz.addtexture('../experiment_rooms/textures/tex/side_windowx1.jpg'))

	iTex.append(viz.addtexture('../experiment_rooms/textures/tex/Bnodehatchhole.gif'))

	iTex.append(viz.addtexture('../experiment_rooms/textures/tex/TOPx22.jpg'))
#2nd room

	iTex.append(viz.addtexture('../experiment_rooms/textures/tex/RB1ax2Z2.jpg'))

	iTex.append(viz.addtexture('../experiment_rooms/textures/tex/node_aft_pink_hatch.gif'))

	iTex.append(viz.addtexture('../experiment_rooms/textures/tex/050223_controlpanel_3.jpg'))

	iTex.append(viz.addtexture('../experiment_rooms/textures/tex/spacesuit.jpg'))

	iTex.append(viz.addtexture('../experiment_rooms/textures/tex/rus_hatch2.jpg'))

	iTex.append(viz.addtexture('../experiment_rooms/textures/tex/Brservtop.jpg'))
	else:
	#Local Room

	iTex.append(viz.addtexture('../experiment_rooms/textures/tex/RB1ax2Z2.jpg'))

	iTex.append(viz.addtexture('../experiment_rooms/textures/tex/node_aft_pink_hatch.gif'))

	iTex.append(viz.addtexture('../experiment_rooms/textures/tex/050223_controlpanel_3.jpg'))

	iTex.append(viz.addtexture('../experiment_rooms/textures/tex/spacesuit.jpg'))

	iTex.append(viz.addtexture('../experiment_rooms/textures/tex/rus_hatch2.jpg'))

	iTex.append(viz.addtexture('../experiment_rooms/textures/tex/Brservtop.jpg'))
	#Remote Room

	iTex.append(viz.addtexture('../experiment_rooms/textures/tex/side_glovebox2.jpg'))

	iTex.append(viz.addtexture('../experiment_rooms/textures/tex/JEM_10x1.jpg'))

	iTex.append(viz.addtexture('../experiment_rooms/textures/tex/EL-2000-00036fixed.jpg'))

	iTex.append(viz.addtexture('../experiment_rooms/textures/tex/side_windowx1.jpg'))

	iTex.append(viz.addtexture('../experiment_rooms/textures/tex/Bnodehatchhole.gif'))

	iTex.append(viz.addtexture('../experiment_rooms/textures/tex/TOPx22.jpg'))



# Red transparency texture
#rTex = viz.addtexture('gb_noise.jpg') #test for nontransparent textures
rTex = viz.addtexture('../experiment_rooms/textures/reticleBe3.tif')
rTexh = viz.addtexture('../experiment_rooms/textures/reticleBe3h2.gif')
# Yellow transparency texture
#yTex = viz.addtexture('gb_noise.jpg')
yTex = viz.addtexture('../experiment_rooms/textures/reticleBe4.tif')
yTexh = viz.addtexture('../experiment_rooms/textures/reticleBeyelh.gif')
# red transparency texture with red cross to chose the target
```

```
rTexYS =
viz.addtexture('../experiment_rooms/textures/reticleBe5&square.tif')
#texture for end of phase
EndOfPhase =
viz.addtexture('../experiment_rooms/textures/all_done.jpg')
#texture for wrong hatch choice
wrongWall =
viz.addtexture('../experiment_rooms/textures/wrongWall.tif')

#Text object to display messages (unsure if needed now)
mytext = viz.add(viz.TEXT3D,'text',viz.HEAD,1)
mytext.scale(0.02,0.05,0.1)
mytext.alignment(viz.TEXT_RIGHT_BOTTOM)
mytext.translate(0.25,-0.25,0.5)
mytext.color(0.9,0.2,0.1)
mytext.visible(0)

#Rotate textures to start positions and place on 3D planes in [room]
for i in range(0,12):
	room[i].update(START_POS[i])
	room[i].texture(iTex[i],'plane')

#Textures for mutiple choice selection
BLUE_COLOR = [0,0,1]
NONHIGHLIGHT_COLOR = [1,1,1]
quadi = []
for i in range(0,6):  # Displays the 6 2D textures at the bottom of the screen
	quadi.append(viz.add(viz.TEXQUAD,viz.SCREEN))
	quadi[i].scale(1.5,1.5)
	quadi[i].translate(0.14285*(i+1),0.2)
	quadi[i].texture(iTex[i+6])
	quadi[i].visible(0)



##############################################################
# Read stimules file and open data file for experimental trials
##############################################################

def InitializeExp():

	global file
	global data
	global allCue
	global allTarget
	global allOri
	global allNoise
	global allLTar

	file = open(FILENAME,'r')
	print 'opened stim file: ', FILENAME
	#'r' for reading
	data = open(SUBJECT,'a')
	print 'created output file:', SUBJECT
	#'a' for append
	data.write('%Subject name:' + SUBJECT + '\n')
	data.write('%Test performed on:' + time.ctime() + '\n')
	data.write('%stimulus name:' + FILENAME + 'feedback was ')
	if feedback == ON:
		data.write('ON'+'\n')
	elif feedback == OFF:
		data.write('OFF'+'\n')
	data.write('%configuration was (0 is GC, More is FC: '+ str(condition))
	data.write('%columns:'+'\n')
	data.write('%Trial#'+'\t'+'Cue'+'\t')
	data.write('Ori'+'\t'+'Target'+'\t'+'TargAns'+'\t' +'OriAns'+'\t')
	data.write('T_Cue'+'\t'+'T_Place'+'\t'+'T_Ori'+'\t')
	data.write('T_FB'+'\t'+'T_Ans'+'\t'+'T_Tot'+'\t' +'\n'+'\n')

	#Experiment stimulus file
	all = file.readlines()
	allCue = []
	allTarget = []
	allEntry = []
	allOri = []
	allNoise = []
	allLTar = []
	print 'stimulus file with ',len(all)-1,' trials'
	for i in range(1,len(all)):
		access = all[i]
		s = split(access)
		allCue.append(eval(s[0]))
		allTarget.append(eval(s[1]))
		allOri.append(eval(s[2]))
		allNoise.append(eval(s[3]))
#		allLTar.append(eval(s[4]))

	file.close()

########################################
# subroutines
########################################
def place2ndModule(cond):
	global hatchface
```

```
	global backface
	global aheadface
	global START_POS
	temp = vizmat.Transform()
	if LB == OFF:
		if cond == GC: #Ground
configuration
			hatchface = 2
			backface = 6
			temp.makeIdent()
		elif cond == FC5:
			hatchface = 4
			backface = 7
			temp.makeRot(0,1,0,90)
			temp.postRot(1,0,0,90)
			temp.postTrans(0,-4,-4)
	elif LB == ON:
		if cond == GC: #Ground
configuration
			hatchface = 2
			backface = 6
			temp.makeIdent()
		elif cond == FC5:
			hatchface = 1
			backface = 10
			temp.makeRot(0,0,-1,90)
			temp.postRot(-1,0,0,90)
			temp.postTrans(4,0,-4)
	temp.postTrans(0,0,4)
	for i in range(0,6):

	START_POS[i+6].set(START_POS[i])
		START_POS[i+6].postMult(temp)
	if HMD == ON:
		for i in range(0,12):

	START_POS[i].postRot(0,1,0,-90)
	for i in range(0,12):
		room[i].update(START_POS[i])
	if backface == 6:
		aheadface = 8
	elif  backface == 7:
		aheadface = 9
	elif backface == 10:
		aheadface = 11



def orientRoom(cue,ori):
	global trans
	global current_pos
	trans.set(START_POS[cue])
	trans.invertOrtho()
	trans.postMult(START_POS[2])
	if HMD == OFF:
		trans.postRot(0,0,1,ori*90)
	elif HMD == ON:
		trans.postRot(1,0,0,ori*90)
	for i in range(0,12):
		current_pos[i].set(START_POS[i])
		current_pos[i].postMult(trans)
		room[i].update(current_pos[i])
#		object[i].update(current_pos[i])


def showTarget(Ltarget_num):
	global target
	global iTex
	for obj in target:
		obj.visible(0)
	target[0].visible(1)
	target[0].texture(iTex[Ltarget_num],'plane')
	target[0].appearance(viz.DECAL)
	viz.fov(39,1.333)
	viz.setscene(2)
	viz.clearcolor(0,0,0)
#	target[0].visible(1)
	print 'tarrrrr'
#	if Ltarget_num in range(0,len(target)-1):
#		target[Ltarget_num].visible(1)	#
display object

######################################
# TIMER FOR EXPERIMENTAL TRIALS
######################################

def ExptTimer(timer):

	global currentTrial
	global trans
	global noisePos
	global startTime
	global T_cue
	global T_targ
	global LT_targlook
	global LT_targpick
	global T_MC
	global T_ori
	global T_place
	global tries
	global T_ans
	global T_FB
	global T_tot
	global button
	global dirT
	global cue
	global ori
	global target
	global target_num
	global noise
	global noise2
	global task
```

```
	global THRESHOLD
	global feedback
	global Ltarget_num
	global TextList
	global NONHIGHLIGHT_COLOR
	global BLUE_COLOR
	global selected_texture
	global quadi

	THRESHOLD = 0.75

	if timer == WAIT: # Waits for the buttons B7 or B8 to be pressed AND released in order to start the next task
#		print 'waiting for task', task
		if sid.buttons() in (B7,B8):
			while sid.buttons() is not 0:
				pass
			else:
				print 'button unpressed, starting task', task
				viz.starttimer(task)

		else:
#			print 'wait more'
			viz.starttimer(WAIT)

	if timer == SHOW_CUE: # Gives the opportunity to find his/her orientation in the first module, thanks to a cue wall
		dirT = 6
		button = 0
		viz.fov(fov,1.333)
		startTime = time.time()
		mytext.message('SHOW_CUE')
		print 'SHOW_CUE'
		cue = allCue[currentTrial]
		ori = allOri[currentTrial]
		target_num = allTarget[currentTrial]+6
		noise = allNoise[currentTrial]
		dirT = aheadface + allNoise[currentTrial]
		orientRoom(cue,ori)
		for i in range(0,6):
			room[i].texture(rTex,'plane')
			object[i].visible(0)
			room[i].visible(1)
			room[i+6].visible(0)
#		room[4].texture(rTexh,'plane')
		room[cue].texture(iTex[cue],'plane')
		object[cue].visible(1)
		viz.setscene(1)
		if TRAIN == ON:
			task = MEMORY_TASK_TRAIN
		else:
			task = MEMORY_TASK
		viz.starttimer(WAIT)

	elif timer == MEMORY_TASK_TRAIN:
		T_place = time.time()
#		print 'T_ans is defined', T_ans
		T_cue = round(T_place - startTime,2)
		mytext.message('MEMORY_TASK')
		print 'MEMORY_TASK'
		for i in range(0,6):
			room[i].texture(rTex,'plane')
			room[i+6].texture(yTex,'plane')
			room[i+6].visible(1)
			object[i].visible(0)
			object[i+6].visible(0)
		room[cue].texture(iTex[cue],'plane')
		room[cue].appearance(viz.DECAL)
		room[4].texture(rTexh,'plane')
		room[4].alpha(0.5)
		noisePos.set(current_pos[aheadface])
		noisePos.preRot(0,0,1,90*noise)
		print 'aheadface= ', aheadface
		print 'target= ', target_num
		room[aheadface].texture(iTex[target_num],'plane')
#		object[target_num].update(noisePos)
		room[aheadface].update(noisePos)
		button = 0
		task = PLACE_TARGET
		viz.starttimer(PLACE_TARGET)




	elif timer == MEMORY_TASK: # Outlines the two modules and puts the target texture on the far wall of the seconde module in testing mode.
		T_place = time.time()
#		print 'T_ans is defined', T_ans
		T_cue = round(T_place - startTime,2)
		mytext.message('MEMORY_TASK')
		print 'MEMORY_TASK'
		for i in range(0,6):
			room[i].texture(rTex,'plane')
			room[i+6].texture(yTex,'plane')
			room[i+6].visible(1)
			object[i].visible(0)
			object[i+6].visible(0)
		noisePos.set(current_pos[aheadface])
		noisePos.preRot(0,0,1,90*noise)
		print 'aheadface= ', aheadface
		print 'target= ', target_num
```

```
			room[aheadface].texture(iTex[target_num],'pla
ne')
			room[aheadface].update(noisePos)
			button = 0
			viz.setscene(1)
			viz.clearcolor(0,0,0)
			viz.fov(fov,1.333)
			task = PLACE_TARGET
			viz.starttimer(PLACE_TARGET)

	elif timer == PLACE_TARGET: # The subject has to put the texture on the right wall with the gamepad. The position is updated.
			button = sid.buttons()
			if button == B7:
				dirT = dirT + 1
				if	(dirT%6)	==
(backface%6):
#					print	'dirT,
backface',dirT,backface
					dirT = dirT +1
			elif button == B8:
				dirT = dirT - 1
				if	(dirT%6)	==
(backface%6):
					dirT = dirT -1
			elif button in (B3,B2): #moving on to
the next step
				T_ori = time.time()
				T_place	=	round(T_ori	-
T_place,2)
				button = 0
				task = ORI_TARGET

			dirT = (dirT % 6) + 6
			noise = noise%4
			noisePos.set(current_pos[dirT])
			noisePos.preRot(0,0,1,90*noise)
			for i in range(6,12):
				if i <> dirT:

	room[i].texture(yTex,'plane')

	room[i].update(current_pos[i])
			room[dirT].update(noisePos)


	room[dirT].texture(iTex[target_num],'plane')
			# in case the button is still pressed
down
			while sid.buttons() is not 0:
				pass
			viz.starttimer(task,0.1)

	elif timer == ORI_TARGET: # Orienting the placed target. The position is updated.
			button = sid.buttons()
			if button == B7:
				noise = noise + 1
			elif button == B8:
				noise = noise -1
			elif button in (B3,B2): #moving on to
the next step
				button = 0
				T_FB = time.time()
				T_ori	=	round(T_FB	-
T_ori,2)
				if feedback == ON:
					task	=
DISP_FEEDBACK
				else:
					task	=
END_TRIAL
			noise = noise%4
			noisePos.set(current_pos[dirT])
			noisePos.preRot(0,0,1,90*noise)
			room[dirT].update(noisePos)

			# in case the button is still pressed
down
			while sid.buttons() is not 0:
				pass
			viz.starttimer(task,0.1)



	elif timer == DISP_FEEDBACK: #Displays
all walls in correct orientation
			room[hatchface].visible(0)
			for i in range(0,12):

	room[i].texture(iTex[i],'plane')

	room[i].update(current_pos[i])
				object[i].visible(1)
			task = END_TRIAL
			viz.starttimer(WAIT)

	elif timer == END_TRIAL:
			room[hatchface].visible(1)
			print 'hatch should be back in place'
			if feedback == ON:
				T_FB = round(time.time() -
T_FB,2)
			else:
				T_FB = 0
			T_tot	=	round(time.time()	-
startTime,2)
			T_ans = T_tot - T_FB
			mytext.message('END_TRIAL')
```

```
			# Writing the trial results to the result
file

		data.write(str(currentTrial)+'\t'+str(cue)+'\t'+str
(ori))

		data.write('\t'+str(target_num)+'\t'+str(dirT)+'\t
'+str(noise))

		data.write('\t'+str(T_cue)+'\t'+str(T_place))

		data.write('\t'+str(T_ori)+'\t'+str(T_FB))

		data.write('\t'+str(T_ans)+'\t'+str(T_tot))
			data.write('\n')
			#moving to next trial
			currentTrial = currentTrial + 1
			if currentTrial > len(allTarget)-1:#
The first line of the file is just comments
				task = END_EXP
			else :
				tries = 1
				task = SHOW_CUE
			viz.starttimer(task)

		elif timer == END_EXP:
			data.close()
			print 'End of Phase'
			text = viz.add(viz.TEXT3D,'End of
Phase',viz.SCREEN)
			text.scale(0.7,0.7,0.7)

#########################
## keyboard function to start the experiment
#########################

def startExpKeyboard(key):
	global currentTrial
	global button
	global task
	global fov
	global cue_sequence
	global condition


	if key == 's':
		InitializeExp()
		currentTrial = 0
		if LB == OFF:
			orientRoom(2,0)
		else:
			orientRoom(5,3)
		for obj in object:
			obj.visible(1)
		for i in range(0,12):
			room[i].texture(iTex[i],'plane')
		task = SHOW_CUE
		button = 0
		for i in range(0,6):
			room[i].visible(1)
		room[hatchface].visible(0)
		cue_sequence = [0,0]
	elif key == ' ':
		viz.starttimer(task)
		print 'task', task


if HMD == OFF:
	def mousemove(x,y):
		euler = view.get(viz.HEAD_EULER)
		euler[0] += x*0.55
		euler[0] = viz.clamp(euler[0],-
180.0,180.0)
		euler[1] += y*0.5
		euler[1] = viz.clamp(euler[1],-
90.0,90.0)
		view.rotate(euler,viz.HEAD_ORI)

	def mousedown(button):
		if button ==
viz.MOUSEBUTTON_LEFT:
			view.reset(viz.HEAD_ORI)
		elif button ==
viz.MOUSEBUTTON_RIGHT:
			view.reset(viz.HEAD_ORI)

	viz.callback(viz.MOUSEBUTTON_EVENT,
mousedown)
	viz.callback(viz.MOUSEMOVE_EVENT,mou
semove)
	viz.mousedata(viz.RELATIVE,viz.RELATIV
E)

place2ndModule(condition)
viz.callback(viz.TIMER_EVENT,'ExptTimer')
viz.callback(viz.KEYBOARD_EVENT,'startExpKeybo
ard')
```