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Effects of Travel Technique on Cognition in Virtual Environments

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Abstract

We compared four different methods of travel in an immersive virtual environment and their effect on cognition using a between-subjects experimental design. The task was to answer a set of questions based on Crook's condensation of Bloom's taxonomy to assess the participants' cognition of a virtual room with respect to knowledge, understanding and application, and higher mental processes. Participants were also asked to draw a sketch map of the testing virtual environment and the objects within it. Users' sense of presence was measured using the Steed-Usoh-Slater Presence Questionnaire.

Our results suggest that for applications where problem solving and interpretation of material is important, or where opportunity to train is minimal, then having a large tracked space so that the participant can physically walk around the virtual environment provides benefits over common virtual travel techniques.

1. Introduction

1.1 Motivation

Numerous techniques have been implemented in Virtual Environments (VEs) to allow a participant to move about a virtual space. In general they can be categorized as either techniques that try to replicate the energy and motions of walking, or as purely virtual travel techniques. Examples of the former include treadmills [1, 2] and walking in place schemes [3, 4, 5]. Examples of the latter usually use a joystick to "fly" though a space in a direction specified by either head orientation or a handheld pointer [6]. All of these approaches assume that the physical tracked space available to the user is smaller than the virtual space that is to be experienced. However, recent advances in wide area position tracking technology now enable us to track a user's movement through spaces that are much more expansive than the two to three- meter diameter spaces normally tracked by electromagnetic tracking devices [7]. This upgrade in available technology allows us to create virtual environments that a user can experience by simply walking around in the environment in the same way she would walk around a physical space. It also provides us the opportunity to measure the relative efficacy of experiencing a space via normal walking versus any of the simulated walking metaphors. In this study our goal was to investigate the differences between exploring a virtual environment using common joystick-based travel techniques and being able to actually walk about the space in a natural manner.

1.2 Previous Work

Immersive virtual environments provide the participant with a first person perspective from the "inside" of a virtual space. View-point control is usually accomplished by a combination of head motion and by some travel technique that may be entirely virtual (such as a joystick) or that may try to replicate real-world modes of travel such as walking or riding in a vehicle. Although numerous techniques have been proposed for travel, there have been surprisingly few analytic comparisons reported in the literature of the relative effectiveness of different travel modalities for different types of tasks.

Bowman, Koller and Hodges [6] have conducted experiments on virtual joystick-based travel in immersive virtual environments that indicate that "pointing" techniques are advantageous relative to "gaze-directed" steering techniques for a relative motion task. They also report that motion techniques that instantly teleport users to new locations are correlated with increased user disorientation. In the evaluation of systems that try to replicate the energy and motions of walking, reported sense of presence has been rated higher in real walking and walking in place compared to joystick 'flying' conditions [8]. In studies that compared actually walking through a virtual maze to virtual travel, Chance et al [9] found a significant difference between walking as compared to joystick controlled travel in participants' ability to indicate the direction to unseen target objects from a terminal location in the maze. A secondary finding of this study was that the degree of motion sickness depended upon travel mode, with the lowest incidence occurring in the real walking mode.

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2. User Study

Cognition is defined as the process of receiving, processing, storing, and using information [10]. As opposed to perceptual motor tasks (e.g., pick up a pen), cognitive tasks require problem-solving decisions on actions (e.g., pick up a red pen).

In context of cognition, we asked the following question:

- *Is there an effect on cognition if we explore a virtual space by walking around in a natural manner as compared to using a virtual travel technique?*

To investigate this question, we designed a study comparing common travel techniques to actually walking in a large tracked area. The task was to explore a virtual room for five minutes. Participants were told that they would be asked questions about the room at the end of their exploration.

2.1. Study Design and Methods

Design. The experiment was a between-subjects design. The independent variable was the travel method. The dependent variables were performance on a cognition questionnaire and sketch map accuracy. The participants were randomly assigned to one of the four conditions described below.

Conditions and Rationale. One of the most commonly implemented methods of locomotion in a virtual environment is to use a handheld button device that moves the user in the direction that she is looking when a button is pressed. There are several variations to this approach. We can simulate "flying" if we allow the user to move in her look-at direction with no constraints. Virtual "walking" is usually implemented by moving the user in a 2D plane parallel to the ground plane of the environment.

The most common tracking technologies are either six-degrees of freedom (position and orientation) trackers with a limited effective range, or three-degrees of freedom (orientation-only) tracking devices. With the former the user can use normal body motion, such as squatting down or moving the head side-to-side, as she experiences a VE. With the latter approach, the user can change her view of the world by turning her head in a natural way, but her position can only be changed via virtual techniques such as button pushes on a hand-held device.

For this study we compared the following four conditions:

1. **Real Walking (RW)** – Participant position and orientation are tracked in a physical tracked space the same size as the virtual room. The participant walks around the virtual room in a natural manner (Fig.1).

Figure 1. Participant in RW condition

2. **Virtual Walking using Six-Degrees-of-Freedom Tracking (VW6) –** Participant's head position and orientation are tracked but the physical tracked space is smaller than the virtual room. The participant uses a wireless joystick to navigate about the room. When a button is pressed, the participant is translated forward or backward (depending on the button) along the participant's look-at vector in a plane parallel to the floor. The participant stands within a 1.2m by 1.2m enclosure that both gives them something to hold on to for balance, and simulates the reduced tracking volume of common electromagnetic and acoustic tracking devices (Figure 2).

Figure 2. Participant in VW condition

3. **Virtual Walking using Three-Degrees-of-Freedom Tracking (VW3)** – Participant head orientation (yaw, pitch, and roll) is tracked. A joystick is used to implement virtual walking. The participant's viewpoint is moved in a plane parallel to the floor of the room. The viewpoint can also be moved up and down relative to the floor of the room with a different set of buttons. The participant stands within the same 1.2m by 1.2m enclosure used in the VW6 condition.

4. **Joystick with a Monitor (M)** – The participant sits in front of a 17-inch flat panel display at a distance such that the field-of-view is equal to the HMD conditions (Figure 3). She navigates about the room in a manner identical to the VW3 condition (button arrangement, etc.) except that the joystick now controls the view direction.

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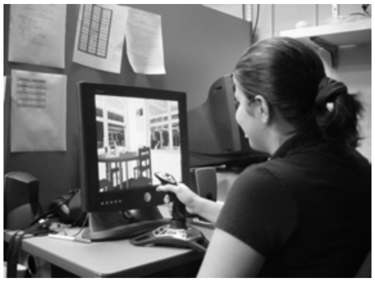

Figure 3. Participant in M condition

One way to view our choices of what to test in this experiment is as a comparison of cost and capability versus performance. Large area six-degrees-of-freedom (RW) tracking systems are expensive in both dollars and space requirements as compared to orientation-only tracking (VW3). Limited range six-degrees-of-freedom trackers (VW6) are somewhere in between with respect to cost and space. The inclusion of the monitor condition (M) was to give us a degree of "ground truth" for the comparative usefulness of immersive VR for the tasks that we evaluated. All conditions had a 60 degree diagonal field of view. Table 1 summarizes the salient properties of each condition.

Table 1. Condition properties

	Tracked DoF	Tracked Volume	Immersive?
RW	6	4.5m x 4.6m x 2.6 m	Yes
VW6	6	1.2m x 1.2m x 2.6m	Yes
VW3	3	-	Yes
M	0	-	No

2.2. The Environment and Equipment

Equipment. For the RW, VW6, and VW3 conditions, participants wore a stereoscopic V8 HMD (640 X 480 resolution in each eye) that was tracked by a 3rdTech HiBall 3100 tracking system. The HiBall updates position and orientation at approximately 1.5kHz. Our HiBall system has a tracked volume of 4.5m x 4.6m x 2.6m. For condition M, we used a 17 inch flat screen monitor. We used a Logitech Wireless Joystick.

All the conditions ran on a Pentium 4 Dell PC with an nVidia GeForce4 Ti 4200 graphics card. Condition M ran at 60 FPS, while the three HMD conditions ran between 24-30 FPS in stereo.

Training VE. Immediately before exploring the testing VE, participants practiced navigation in a training virtual environment. The training VE had four different colored cubes at different locations in a single room. We asked the participants to locate and travel to each of these cubes.

Testing VE. The testing VE was a single room measuring, 4.2x4.5x2.6 meters. We populated the room with furniture, pictures, books, magazines, etc (Figures 4a and 4b).

Figure 4a. Top down view of testing VE

Figure 4b. First person view of testing VE

Several objects in the testing VE were grouped into themes. The books were all by Steven King, the pictures were all of nature, and the magazines were all about golf. In addition, there were several sports items distributed throughout the room.

2. 3. Measures

We used the following measures: a cognition questionnaire (CQ) based on a condensed version of Bloom's Taxonomy of the Cognitive Domain [11], a sketch map [12], and the Steed-Usoh-Slater (SUS) Presence Questionnaire [13]. Additional measures were used to help determine if there were any confounding factors affecting the results between the different conditions.

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Cognition Questionnaire (CQ). We created a set of 27 questions to assess the participants' cognition of the VE. These questions were selected and modified from an original set of 37 questions used in a pilot study (n=12).

The questions were based on Bloom's taxonomy [11]. Bloom's original taxonomy describes six cognitive categories: Knowledge, Comprehension, Application, Analysis, Synthesis, and Evaluation. We followed Crook's condensation of the six categories into three [14]:

- **Knowledge**: the recall or recognition of specific information
- **Understanding and Application**: combines *comprehension* (understanding of facts and principles, interpretation of material) and *application* (solving problems, applying concepts and principles to new situations)
- **Higher Mental Processes**: combines *analysis* (recognition of unstated assumptions or logical fallacies, ability to distinguish between facts and inferences), *synthesis* (integration of learning from different areas or solving problems by creative thinking), and *evaluation* (judging and assessing).

The questions focused on objects evenly distributed about the room, such that roughly the same number and category of questions were asked about each part of the room.

The following are example questions from each category:

1. **Knowledge:**
   - How wide was the couch?
   - How many darts were in the dartboard?
2. **Understanding and Application:**
   - What was the common theme of the paintings?
   - How many people are coming to eat? How did you come to your answer?
3. **Higher Mental Processes:**
   - Name all the objects made out of wood.
   - Given the genre of books in the room, name a book that the residents might buy.

Each question was worth 1 point, for a maximum score of 27. Most of the questions (19) had a single answer for a possible score of either a 0 (wrong) or a 1 (correct). The remaining questions were posed such that an answer could be partially correct or approximately the correct answer. Answers were ranked by how close each participant's response was to the correct answer. We quantized the rankings to these questions and gave scores of 0, 0.25, 0.5, 0.75, or 1.

Sketch Maps. Participants were asked to draw a top-down view, a sketch map, of the testing VE and the objects within it. Then, each participant's sketch map was given a set of *goodness* and *object positioning* scores.

Maps were ranked for *goodness* on a scale of 1 (poor) to 5 (excellent) by three graders who were blind to subject identity as was done by [12]. The map *goodness* rating is a subjective measure of how useful the map would be as a navigational VE tool. The graders ignored drawing ability and concentrated on overall room layout accuracy. The final *goodness* score for a map was an average of the scores given by the three graders.

Maps were also graded on the relative position of the objects within the VE. Each map was given two scores:

- A total object position score based on how many objects in the room were correctly positioned in the sketch. There were a total of 63 objects in the room.
- A significant object position score where the five most commonly drawn objects were scored.

An object was counted if its relative position to other objects in the sketch map was correct. The specific object position was not important.

Other Measures. We measured sense-of-presence using the Steed-Usoh-Slater Presence Questionnaire (SUS) [13], spatial ability using Guilford-Zimmerman Aptitude Survey Part 5: Spatial Orientation [15], simulator sickness using the Kennedy – Lane Simulator Sickness Questionnaire (SSQ) [16], and visual memory using the Kit of Factor-Referenced Cognitive Test Factor MV-1: Shape Memory Test [17]. In addition, each participant was video taped and his/her position and orientation were automatically logged during the experimental session in the VE.

2.4. Experiment Procedures

The pre-testing, experiment session, and post-testing took each participant approximately one hour to complete.

Pre-Experiment. The participant first read the Participant Information Sheet and was asked if she had any questions. She then read and signed the Informed Consent Form. Next, the participant filled out questionnaires about demographics, computer use, computer anxiety, and simulator sickness. She then took the Guilford-Zimmerman (GZ) Spatial Ability test.

Experiment. Next, the participant entered a different area of the lab where the experimenter showed and explained to her the equipment particular to her condition. The participant then was fitted with the equipment and practiced navigation in the training environment.

After the training session, the testing VE was loaded. The participant was asked to explore the environment for five minutes.

Post-Experiment. The participant filled out another simulator sickness questionnaire and the SUS Presence Questionnaire. Next, the participant filled out the cognition questionnaire. She also filled out the visual memory test. She was then asked to draw a top-down sketch map of the VE. Finally, the participant was orally debriefed.

3. Results

Participants. 49 participants completed the study. We discarded data from three participants who failed to complete a minimum of 66% of the cognition questionnaire. In addition, due to procedure failures, cognition questionnaire data from two participants was not collected.

This left us with 44 participants' data (7 females and 37 males) to be included in the analysis of the cognition questionnaires (eleven from each condition), and 46 in the remainder of the questionnaires, sketch maps, and debriefing (eleven participants in RW, twelve in VW6, eleven in VW3, and twelve in M).

Participants were recruited from summer school courses, fliers, and by word-of-mouth. The average age of participants was 27 [18…63]. Participants were required to have taken or be currently enrolled in a higher-level mathematics (e.g. Calculus I) class and be able to comfortably communicate in written English. The mathematics requirement was intended to reduce variability in spatial ability between subjects[1].

There was no significant difference among groups in computer use, video game experience, and prior VR experience. Due to the low number of female participants in the study (7 of 44), we were unable to perform comparative analysis across gender.

For data analysis, we used a one-way-between-subjects ANOVA with α=0.05 level for significance. For post hoc analysis, we used the Tukey HSD (Honestly Significant Difference) test. To highlight certain differences, we also used the LSD (Least Significant Difference) post hoc test.

3.1. Experiment Data

Although the difference in the total score on the CQ was not statistically significant, the results become interesting when broken down by categories: Knowledge (K), Understanding and Application (U&A), and Higher Mental Processes (HMP) (Figure 5).

In the ANOVA on *Understanding and Application* scores, the difference across conditions was just short of significance, p = 0.053 (Table 2, second row). A post hoc Tukey test revealed only a strong trend between RW and VW6, and between RW and M. A post hoc LSD test revealed significance between both RW and VW6, and between RW and M, and a strong trend between RW and VW3 (Table 3).

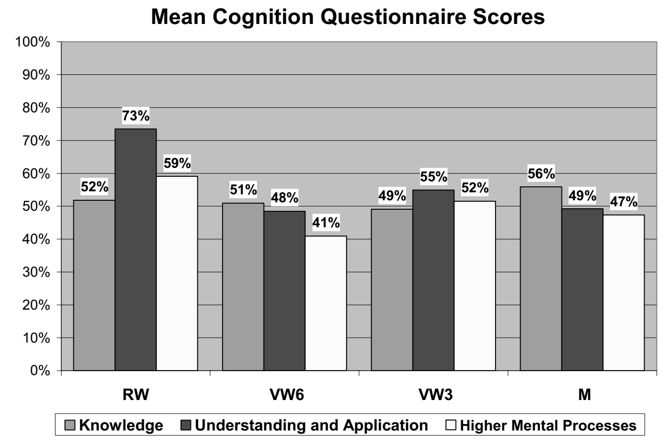

Figure 5. Cognition overall scores

Table 2. ANOVAS among groups: cognition questionnaire and sketch maps

Source	*P-value*
Cognition - Knowledge	0.636
Cognition - Understanding and Application	0.053$^+$
Cognition - Higher Mental Processes	0.090$^+$
Sketch Maps - Significant Object Position	0.231*
Sketch Maps - Total Object Position	0.151*
Sketch Maps - Goodness	0.614

Post Hoc Analysis in $^+$ Table 3 and * Table 4

Table 3. Post hoc tests on cognition questionnaire U&A and HMP categories

		U&A ^{o}	HMP $^\lambda$
RW - VW6	Tukey HSD	0.070$^+$	0.064$^+$
	LSD	0.015*	0.014*
RW - VW3	Tukey HSD	0.252	0.709
	LSD	0.067$^+$	0.291
RW - M	Tukey HSD	0.082$^+$	0.358
	LSD	0.018*	0.105
VW6 - VW3	Tukey HSD	0.914	0.448
	LSD	0.518	0.142
VW6 - M	Tukey HSD	1.000	0.800
	LSD	0.939	0.368
VW3 - M	Tukey HSD	0.939	0.935
	LSD	0.568	0.559

*Significant at the α=0.05 level
$^+$ Requires further investigation
^{o} Denotes *Understanding and Application*
$^\lambda$ Denotes *Higher Mental Processes*

[1] Obtained through personal correspondence from Dr. Edward Johnson, Professor Emeritus of Cognitive Psychology at UNC Chapel Hill.

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In the ANOVA on the *Higher Mental Processes* scores, the difference across conditions was insignificant, but meaningful (Table 2, third row). A post hoc Tukey test between RW and VW6 shows a strong trend, and a post hoc LSD test shows significance to the α=0.05 level (Table 3, first row).

Although the ANOVAs across conditions for sketch map object position scores were not statistically significant (Table 2), a post hoc LSD test revealed significance in the sketch map total object position scores between RW and M, and a strong trend in the significant object scores between RW and M (Table 4).

Table 4. Sketch maps post hoc RW vs. M

Source		*P-value*
Significant Objects	Tukey HSD	0.214
	LSD	0.055+
All Objects	Tukey HSD	0.125
	LSD	0.029*

Significant at the *α=0.05 level,
+ requires further investigation

3.2. Other Factors

Spatial ability, computer anxiety, and visual memory were not significantly different among groups (Table 5). Simulator sickness was also insignificant among groups (Table 6, first row).

Table 5. ANOVAS among groups: spatial ability, computer anxiety, and visual memory

Source	*P-value*
Spatial Ability	0.955
Computer Anxiety	0.386
Visual Memory	0.176

Table 6. ANOVAS among groups: SSQ, SUS mean and count, and self reported presence

Source	*P-value*
Simulator Sickness Questionnaire	0.690
SUS Presence Mean	0.002**
SUS Presence Count	0.148
Self Reported Presence	0.065+

** Significant at the α=0.005 level
+ Post Hoc analysis performed

The correlation between spatial ability and performance on the CQ was r = 0.294. The critical value of the correlation coefficient r for N=44 is 0.297. This means that the correlation was not statistically significant.

An ANOVA across all conditions for the SUS Presence Means showed statistical significance with a p-value of 0.002 (Table 6, second row). A post hoc Tukey test revealed significance between all the HMD conditions and the monitor condition (Table 7).

The subjective response to the debriefing session question: "What percentage of the time you were in the lab did you feel you were in the virtual environment?" is labeled as *Self Reported Presence*. Self Reported Presence was just short of significance among groups with a p-value of 0.065 (Table 6, last row). A post hoc Tukey test revealed only a significance between the RW and M conditions (p = 0.048).

Table 7. Tukey Test: SUS presence mean

	P-value
RW - VW6	0.883
RW - VW3	0.999
RW - M	0.004***
VW6 - VW3	0.932
VW6 - M	0.024*
VW3 - M	0.006**

Significant at the *α=0.05 level, **α=0.01, ***α=0.005

4. Discussion

4.1. Debriefing Trends

Analysis of the post-experience interviews resulted in the following trends:

- When asked "What percentage of the time you were in the lab did you feel you were in the virtual environment?" The mean response of the participants in RW was 69.1% (s.d. = 24.9), 52.1% in VW6 (s.d. = 31.7), 58.1% in VW3 (s.d. = 33.7), and 33.8% in M (s.d. = 29.9).
- When asked "How long did it take for you to get used to the virtual environment, in terms of navigation and interaction?" The mean response of the participants in RW was 15.5 seconds (s.d. = 18), 54.2 seconds in VW6 (s.d. = 43), 34.8 seconds in VW3 (s.d. = 26), and 117.5 seconds in M (s.d. = 104).
- 55% of the RW and 17% of the M participants reported that they tried to avoid objects.
- 0% of the RW and 33% of the M participants reported that navigation was difficult.
- 36% of the RW and 8% of the M participants thought that the experience was realistic.

4.2. Observations

Time in training: The time taken to perform the training tasks differed in each VE condition. Participants in condition M took a noticeably longer time to train than it took for participants in other conditions. Generally, participants in conditions VW6 and VW3 took a longer time to train than participants in condition RW.

Path Visualizations: Participants' position and orientation in both the virtual environment and the real lab were logged during their exposure to the virtual environment. This information allowed us to visualize the path the participant took in the VE.

Figures 6 – 9 show example path visualizations for the different conditions. The thin green lines indicate view direction. The grey lines indicate path.

Based on the visualizations we noticed the following:

- A distinguishing factor is the concentration of the positioning along the path where travel paused and observation occurred. Observation positions in conditions M and VW3 were concentrated in locations such as in corners or against walls, while observation positions in VW6 and RW were concentrated near objects or in the center of the room.
- Participants in condition RW did not collide with virtual objects as often as did participants in other conditions.
- Participants in condition M did collide with virtual objects more often than did participants in other conditions.

Figure 6. RW path visualization

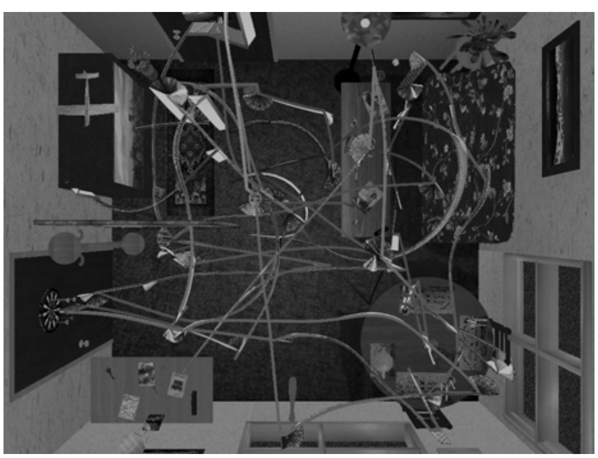

Figure 7. M path visualization

- While attempting to gain a better view of virtual objects, most participants in condition RW leaned over lower objects (such as a coffee table) to avoid collisions.
- Participants in condition VW3 did not physically move within the confined space as much as the participants did in condition VW6.
- Path visualization of participants in condition RW (figure 6) is different than the path visualizations of participants in other conditions, because participants in RW do not have to travel in the direction they are looking.

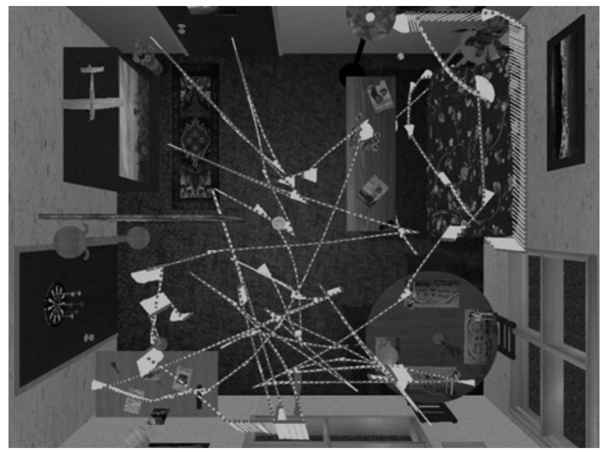

Figure 8. VW3 path visualization

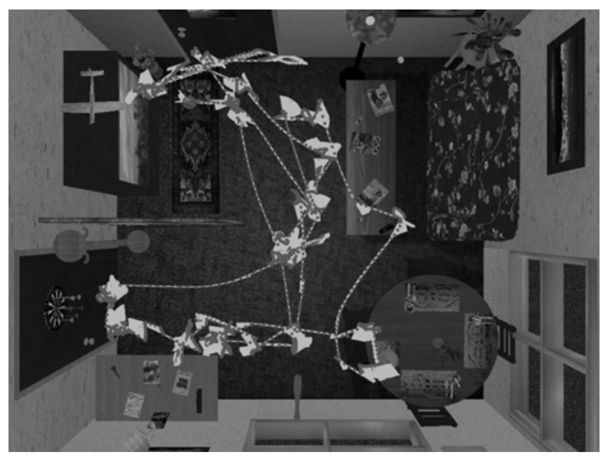

Figure 9. VW6 path visualization

4.3. Summary

On the understanding and application portion of the cognition questionnaire, participants in RW performed significantly better than participants in M and VW6. There was also a strong trend toward better performance of RW as compared to VW3 for understanding and application. Participants in RW performed significantly better than participants in VW6 with respect to higher mental processes. There was a strong trend toward better performance with RW as compared to M for higher mental processes.

Sketch map total object position scores were significantly better for participants in RW as compared to participants in M.

Sense of Presence on the SUS Questionnaire was significantly higher for all the HMD conditions as compared to the monitor condition. There was no difference in sense of presence among any of the conditions in which the participant wore the HMD. In the debriefing, there was only a significant difference in Self Reported Presence between RW and M. This difference was strongly supported by comments from the participants during the debriefing. For example:

- Participant 31 from RW commented "I was afraid to hit my shin on the table."
- Participant 47 from VW6 commented "I almost ran into the divider!"
- Participant 2 from VW3 commented "I wanted to stand on the skateboard"
- Participant 26 from M commented "It did not feel like walking"

It was also clear that participants were much more comfortable with RW as a navigation technique than they were with any of the others. This attitude is illustrated by their answers to the question: "How long did it take for you to get used to the virtual environment, in terms of navigation and interaction? ", our observations as to actual time in training, reported difficulty of navigation during debriefing, and quotes from the debriefing. For example:

- Participant 20 from M commented "I never got used to the navigation!"
- Participant 24 from RW commented regarding navigation: "It was easy... I just walked around!"

Examination of the path visualizations of each condition for all the participants shows a clear difference between RW and all the other conditions with respect to both the movement and head orientation patterns. Of the virtual walking techniques, VW6 was the most similar to RW in terms of movement and head orientation pattern.

Our results suggest that for applications where problem solving and interpretation of material is important or where opportunity to train is minimal, then having a large tracked space so that the participant can walk around the virtual environment provides benefits over common virtual travel techniques.

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Effects of Travel Technique on Cognition in Virtual Environments

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Figure 4a. Top down view of testing VE

Figure 4b. First person view of testing VE

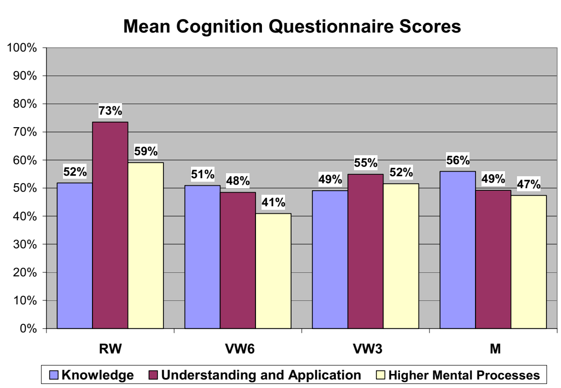

Figure 5. Cognition overall scores

Figure 6. RW path visualization

Figure 7. M path visualization

Figure 8. VW3 path visualization

Figure 9. VW6 path visualization

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