

Passive Haptics Significantly Enhances Virtual Environments

by

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A dissertation submitted to the faculty of the University of North Carolina at Chapel Hill in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Computer Science.

Chapel Hill

2001

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ABSTRACT

BRENT EDWARD INSKO: Passive Haptics Significantly Enhances Virtual Environments (Under the direction of Frederick P. Brooks, Jr.)

One of the most disconcertingly unnatural properties of most virtual environments (VEs) is the ability of the user to pass through objects. I hypothesize that *passive haptics*, augmenting a high-fidelity visual virtual environment with low-fidelity physical objects, will markedly improve both sense of presence and spatial knowledge training transfer. The low-fidelity physical models can be constructed from cheap, easy-to-assemble materials such as styrofoam, plywood, and particle board.

The first study investigated the effects of augmenting a visual-cliff environment with a slight physical ledge on participants' sense of *presence*. I found when participants experienced passive haptics in the VE, they exhibited significantly more behaviors associated with pit avoidance than when experiencing the non-augmented VE. Changes in heart rate and skin conductivity were significantly higher than when they experienced the VE without passive haptics.

The second study investigated passive haptics' effects on performance of a real-world navigation task after training in a virtual environment. Half of the participants trained on maze navigation in a VE augmented with a styrofoam physical model, while half trained in a non-augmented VE but were given visual and audio contact cues. The task was to gain as much information as possible about the layout of the environment. Participants knew before the VE session that their training would be tested by navigating an identical real maze environment while blindfolded.

Significant differences in the time to complete the blindfolded navigation task and significant differences in the number of collisions with objects were found between the participants trained in an augmented VE and the participants trained in a non-augmented VE. 11 of 15 participants trained without passive haptics bumped into the next-to-last obstacle encountered in the testing session and turned the wrong direction to navigate around it; only 2 of 15 participants trained with passive haptics made the same navigation error. On the other hand, the assessment of the participants' cognitive maps of the virtual environment did not find significant differences between groups as measured by sketch maps and object dimension estimation.

ACKNOWLEDGMENTS

Thanks to

Frederick P. Brooks, Jr. for being my advisor and for his insights and encouragement;

Frederick P. Brooks, Jr., Mary C. Whitton, Russell M. Taylor II, Peter C. Gordon and Mark Hollins for serving on my doctoral dissertation committee and for all that they have taught me about doing research;

Frederick P. Brooks, Jr. for suggesting passive haptics as a dissertation topic;

Mark Harris, Paul Zimmons, Paul McLaurin, the Effective Virtual Environments and Walkthrough project teams for software support, Kurtis Keller, David Harrison, and Stephen Brumback for equipment support, and Tim Quigg, Darlene Freedman, Paul Morris and Janet Jones for administrative support;

Mike Meehan for his work and collaboration on the experiments;

My participants for their contributions to this work;

The Department of Computer Science and the following projects and P.I.s for RA support during my time at UNC: GRIP (Frederick P. Brooks, Jr.), Image Based Rendering (Anselmo Lastra), and Effective Virtual Environments (Frederick P. Brooks, Jr.);

My advisor at Transylvania University Tylene S. Garrett for encouraging me and beginning my interest in computer graphics;

For financial support for equipment used in this work: NIH National Center for Research Resources, Grant Number P41 RR 02170, and The Link Foundation;

and most importantly,

My parents, Lynn and Judy, my brother Brad, and the rest of my family for their love, support, and belief in me for all these years;

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Chapter 1

Introduction

1.1 Introduction

Virtual reality systems enable users to explore computer-generated 3D spaces. Unlike the real world in which information is provided to all of the senses, these systems provide computer-generated visual stimuli. Some systems supply auditory cues and platform motion as well. Users assume that the virtual environments (VEs) generated by computers will obey the same laws of physics that exist in the real world, namely that one can run into walls and bump into objects (Slater & Usoh, 1992). One of the most disconcertingly unnatural properties of virtual environments is the ability of users to pass through the visual objects, Figure 1-1.



Figure 1.1: User's virtual body passing through a counter.

This ability reminds users that the perceived environment is not *real*, decreasing their sense of presence. The concept of psychological presence has several definitions in the literature (Sheridan, 1992; Zeltzer, 1992; Lombard & Ditton, 1997). I chose to work with the following explicit definition of presence (and implicit definition of virtual environment) from Slater and Usoh (1993):

"The extent to which human participants in a virtual environment allow themselves to be convinced while experiencing the effects of a computer-synthesized virtual environment that they are somewhere other than where they physically are - that 'somewhere' being determined by the image, sounds, and physical sensations provided by the computer-synthesized virtual environment to their senses."

This is generally summarized as the sense of "being there" in the computer-generated environment. Can a VE be improved by eliminating the ability to pass through objects, e.g. will the VE seem more real, induce a stronger sense of presence, and provide increased training transfer from the virtual environment to the real environment?

The most successful real-world simulators, namely high-fidelity flight, ship, and automobile simulators, physically replicate anything that the user might touch, from steering mechanisms to dials and buttons. This is physically feasible in such simulators because the user is typically confined within a vehicle while the virtual environment passes by outside the vehicle, Figure 1-2. It is economically feasible because there are hundreds of users for each interior replication, and the alternative is training hundreds of users in the real vehicles, which is far more costly.



Figure 1-2. Automobile simulator.

However, in a real-walking virtual environment such as a VE architectural walkthrough application, physically replicating the detail of every object that the user might interact with would be costly and time consuming; indeed it would nullify all the advantages that a VE could offer.

An alternate strategy used in computer games to prevent the user from passing through walls and objects is to simply stop the user's avatar, or virtual body, at the surface of the object. This technique however causes problems in real-walking virtual environments. Take for instance a real-walking virtual environment in which a virtual wall is five paces in front of the user. The user takes ten paces in the direction of the wall. The avatar stops at the virtual wall at five paces, but the user in the real world continues moving five more paces. Then the user turns to walk back to the starting point. Now he and his avatar are no longer in the same "place"; the avatar is five paces from the starting point in the virtual environment whereas the user is ten paces away from the start in the real environment.

The solution is to merge the techniques from simulators and games – to stop the user by using physical objects to prevent object penetration in both the real and virtual environments. I hypothesize that using low-fidelity, static, real objects to augment a high-fidelity visual virtual environment will increase presence and increase spatial knowledge training transfer.

This use of physical objects to provide feedback to the user through their shape is a technique called *passive haptics* (Lindeman et al., 1999). The objects I use are considered low-fidelity because they do not exactly replicate their virtual counterparts. They do not replicate such properties as texture, thermal conductivity, and mass, nor do they replicate fine geometric details of the visual objects such as handles on cabinet drawers, Figure 1-5.

Passive haptics is designed for visually-immersive, real-walking virtual environments. Visually-immersive virtual environments provide visual cues from the virtual environment only, while blocking those from the real environment. This permits the use of lower-fidelity physical objects, because all the visual objects are drawn by the computer and displayed in a head-mounted display (HMD). Once the user is in the HMD, the physical objects are never seen directly, only felt. Real-walking virtual environments are distinct from “fly-through” environments in which movement through the environment is implemented by moving the virtual environment past the user while the user remains stationary in the real world. If the virtual world moved past the user, passive haptics would not work – the real objects would no longer be registered with their virtual counterparts.

I further hypothesize that adding physical objects will improve virtual environments because they make the objects feel to the user as if the objects are there. Humans “tend to think of touch as a ‘reality sense.’ We [humans] can test the reality of an image by trying to touch the object” (Heller & Schiff, 1991). Thus, touching objects is an important part of making them seem real.

Prior research suggests that there are benefits to physical replication of objects in immersive virtual environments. A study on *tactile augmentation*, the use of exact physical replications of virtual objects, was performed at the HIT Lab at the University of Washington. In this study, nineteen participants either picked up a virtual kitchen plate with a wand device representing their hand in the VE, or picked up the virtual plate by grasping the real plate with their real hand.

The actual object was tracked so that the visual representation would correspond to the haptic representation as the subject moved the object. The use of the actual object significantly ($p < 0.006$) increased the self-reported solidity and weight not only of the object that was touched but also other objects in the scene (Hoffman et al., 1996). Users in this study were stationary and interacted only with the plate.

Prior research also suggests that a low-fidelity physical model, rather than an exact replication may be adequate. Although this creates a sensory conflict due to the low-fidelity haptic information not exactly matching the high-fidelity visual information, studies have shown that when the visual and haptic senses are in conflict, vision dominates in most cases, such as perception of size, length and shapes of objects, and perception of spatial location (Heller & Schiff, 1991). For example, in a study by Rock and Victor (1964), the experimenters

“arranged an optical compression of the object along one axis that the subject could simultaneously see and feel. Whether the subject made a response by vision, by touch, or by drawing, the conflict was resolved entirely in favor of the visual information” (Heller & Schiff, 1991).

As long as the discrepancy between the visual information and the haptic information does not get too large, the visual information will dominate and the discrepancy will not become apparent (Warren & Cleaves, 1971). This phenomenon is called *visual capture*.

1.2 New Approaches

This document presents research investigating the augmentation of a wide-area immersive virtual environment with a low-resolution physical model of that environment, a technique called *passive haptics*. Our low-resolution physical models are constructed from cheap, easy-to-assemble materials such as styrofoam, plywood, and particle board. Figure 1.3 shows a view of a virtual environment, and Figure 1.4 shows a corresponding view of the physical model. Notice that details, such as the door and drawer handles, are not present in the physical model.



Figure 1-3. Visual Virtual Kitchen.



Figure 1-4. Passive Haptic Kitchen.

I studied the following effects of this augmentation:

- Level of presence in a stress-inducing environment. Michael Meehan, a fellow graduate student, and I measured physiological, behavioral, and subjective presence as subjects performed a task in an environment with a stress-inducing visual cliff. I concentrated on the effects of passive haptics on presence, while Michael concentrated on the measures of presence and their correlation (Meehan, 2001). The independent variable was the presence or absence of a small physical ledge registered with the potentially stress-inducing visual ledge.

- Development of cognitive maps (mental models of the environment) in virtual environments with and without passive haptics. The goal was to determine if the haptic information provided by the physical augmentation led to better cognitive mapping of the environment.
- Spatial knowledge training-transfer from a virtual environment to a real one. The purpose of this study was to determine if the addition of haptic cues to training in a virtual environment would lead to better performance in a real-world maze navigation task.

The following thesis statement summarizes the investigated hypotheses.

1.3 Thesis statement

Augmenting fully-immersive virtual environments with passive haptics increases presence in a stress-inducing environment and improves cognitive mapping and increases training transfer in a maze-like environment.

1.4 Summary of findings presented and discussed in Chapters 2, 3 and 4

I investigated presence, cognitive mapping, and training transfer in virtual environments with low-fidelity, static, touchable objects, and in VEs without these objects and found the following statistically significant results ($p < 0.05$):

Augmenting a stress-inducing environment with passive haptics significantly increases presence. Behavioral measures, reported presence, change in heart rate, and change in skin conductance all showed presence was significantly higher in an environment augmented with passive haptics than the same environment without passive haptics. The change in skin temperature also showed higher presence, though it was not statistically significant.

Augmenting a virtual environment with passive haptics significantly improves cognitive mapping of that environment. Cognitive mapping, forming a mental model of an environment, was better in a virtual environment augmented with passive haptics than a non-augmented VE, as measured by time to complete the navigation and the number of collisions

with objects in a real-world maze navigation task. Sketch maps and dimension estimates did not show significant differences.

Spatial knowledge training is significantly more effective when training in a virtual environment augmented with passive haptics. Performance in a real-world maze navigation task, as measured by time and error, was superior when training occurred in a virtual environment augmented with passive haptics than in the same virtual environment without passive haptics.

It should be emphasized that these results occurred using a crude physical model only roughly registered to within one inch of the visual model. I wanted to show that a little effort in providing haptics adds significant effectiveness to the virtual environment.

Costs. Surprisingly, the construction of the physical model takes substantially less effort than the creation of the corresponding high-fidelity visual models. My colleagues and I have constructed several environments. The physical model has always been less effort to construct than the visual model.

Future Work. Areas for future research include the following:

- For what tasks will passive haptics augmentation improve performance? Prior work has shown that using hand-held props improves task performance in neurosurgical planning (Hinckley, 1994) and user interfaces (Lindeman, 1999). I speculate that performance of tasks such as design, design validation, and design modification will improve when using passive haptics. I have so far studied presence, cognitive map formation, and training effectiveness, but not task performance.
- How does training effectiveness in a virtual environment augmented with passive haptics compare to training in the real world?

1.5 Definition of terms

Head-mounted display (HMD). A display worn on the head to provide a view of a computer-generated scene. In my studies, I used a stereoscopic binocular HMD. This is distinct from HMDs that provide one view to one eye, and from those that provide the same view to both eyes.

Virtual Environment (VE). A perceived environment consisting of computer-generated images, sounds, and other sensations. In my studies, this environment surrounded the user and was displayed using an HMD. I assume that graphics and tracking systems provide dynamic, geometrically correct perspective views from arbitrary viewpoints, and the user can move his head to change views. Furthermore, the system must respond interactively to the user's input, especially motion of the viewpoint. The response must be fast enough that the inevitable delay is not distracting.

Passive haptics. A technique that incorporates passive physical objects into virtual environments to physically simulate the virtual objects.

1.6 Overview

Chapter 2 presents the methods, results, and analysis of the study on presence. Chapter 3 presents the methods, results, and analysis of the studies of cognitive mapping and spatial knowledge training transfer. Chapter 4 relates the results of this experiment to previous findings, discusses the costs of passive haptic augmentation, and proposes areas for future work. The Appendices include documents from the experiments as well as the raw experimental data.

Chapter 2

User Study 1 – Effects of Passive Haptics on Presence

2.1 Introduction

This study conducted from April through June 2000 examined the effects of passive haptics on presence in a visual-cliff environment. Presence was measured by observing behaviors associated with cliff avoidance, monitoring physiological signs of arousal and stress, and the UCL Presence Questionnaire. Specific physiological responses examined include changes in heart rate, skin conductance (a measure of sweat activity), and skin temperature.

2.2 A priori hypothesis

H1. *Participants experience a greater sense of presence in virtual environments augmented with passive haptics than in virtual environments without passive haptics.*

2.3 Methods

2.3.1 Participants

Number, age, and gender

60 people participated in the study. Data lost due to equipment and procedure failures left 52 participants' data to be included in the analysis; 36 were male. The participants ranged in age from 18 to 45.

Criteria for exclusion of participants

The following criteria were used to exclude participants before the start of the experiment:

- Participants who could not use stereopsis for depth perception,
- Participants who were not ambulatory,
- Participants with a history of epilepsy, seizures, or strong susceptibility to motion sickness,

- Participants who reported not being in their usual state of good physical fitness at the time of the experiment (including participants who recently used sedatives, tranquilizers, decongestants, anti-histamines, alcohol, or other medication),
- Participants uncomfortable with the system, or who had difficulty fitting the display to their heads (a brief demonstration was done at the beginning of the session),
- Participants who had more than three prior exposures to a virtual reality system.

Recruiting and inducements

Participants were recruited from undergraduate computer science courses, from posting on bulletin boards around campus, and from posting on computer newsgroups. Participants had no prior knowledge of the goals of the study. Participation was voluntary. Participants were paid six dollars per hour regardless of whether they completed the study.

2.3.2 Apparatus

Common Apparatus

This section describes elements common to both the presence study, described in this chapter, and training transfer study, discussed in chapter 3.

Head Tracking Device



Figure 2-1. HiBall Tracker

Head tracking was performed by a UNC HiBall optical tracker (Ward, 1992; Welch, 1997). This tracker works over a range of 10m by 4m with 0.2 millimeter positional resolution and angular precision better than 0.03 degree. It updates position and orientation at

approximately 1.5kHz. These updates are filtered over 25 ms before they are sent to the application at a sampling rate of 70Hz.

Limb Tracking Device



Figure 2-2. Polhemus FastTrak magnetic tracker and equipment.

A Polhemus FastTrak magnetic tracker tracked two or more of the participant's limbs (Polhemus, 2001). The participants carried part of the tracking system, the magnetic-field source, in a backpack. For the presence experiment, a Polhemus sensor embedded in a joystick tracked one hand. Sensors strapped just below the participants' knees tracked the legs. In the training experiment, gloves fitted with the tracking sensors tracked both hands.

Display System

A Virtual Research V8 head-mounted display with true VGA resolution of (640x3) x 480 pixels per eye was used in both experiments (Virtual Research, 2001). This display device consists of two 1.3-inch-diagonal active matrix LCDs with an aspect ratio of 4:3 and a field of view of 60 degrees diagonal at 100% stereo overlap. The V8 with the HiBall tracker mounted on it weighed 2.5 pounds.



Figure 2-3. V8 Head-Mounted Display with HiBall

Image Generation

One graphics pipe of a Reality Monster, a 32-processor SGI Onyx2 computer, was used to generate the images. The pipe consists of an Infinite Reality2 Engine with four R12000 processors, four raster managers, and 64MB texture memory (SGI, 2001).

System Frame Rate and Lag

The system maintained a frame update rate of 20 to 30 Hz stereo in both experiments. Lag was measured with a custom device, Figure 2-4. The mean system lag in both experiments was 110ms.



Figure 2-4. Device constructed for measuring system lag.

A HiBall tracker is attached to a pendulum. At rest (its lowest point), the pendulum arm prevents light emitted by an LED located at the base from activating photocell A. When the pendulum arm swings to the left of its rest position, as detected by the HiBall, the VR system displays a white screen in the HMD; when the pendulum swings to the right of its rest position, the VR system displays a black screen. Photocell B detected the change from black to white and vice-versa in the HMD. When the pendulum arm swings, as it passes its lowest point, the path between the light source and photocell A is blocked then clear causing a change in resistance in the photocell. This change is detected using an oscilloscope attached to photocell A. Simultaneously, the HiBall detects passing the lowest point and tells the VR system to switch from displaying a black screen to a white screen or vice-versa. This change is detected in the HMD using photocell B. Overall system lag is the time difference between the change in resistance in photocell A and the change in resistance in photocell B.

Physical Model and Registration with Visual Model

Not all of the objects in the virtual environments were physically modeled. Small virtual objects such as a lamp, a radio, and a plant were not physically modeled. For the objects that were, the physical model was constructed to within 0.5 inches of the visual model. The HiBall tracker mounted on a wand or a head-mounted display was used to register the physical model as close as possible to the visual model, generally within one inch.

Model Creation & Detail

The visual models used in the studies were created using Kinetix 3D Studio Max. The models were shaded using precomputed radiosity lighting created with Lightscape from Autodesk. Both models contained approximately 20,000 polygons, and under 48 MB of textures.

Software

The display software was implemented using the UNC-CH GLVU library built on OpenGL (GLVU, 2001). Communication with the tracker and button devices was done using the UNC-CH Virtual Realty Peripheral Network library (VRPN, 2001).

Simulator Sickness Questionnaire

The Simulator Sickness Questionnaire (Kennedy et al., 1993) was used to measure reported simulator sickness induced by exposure to the virtual environment system. The SSQ lists 16 common symptoms rated by the participant on a four-point scale (0=none, 1=slight, 2=moderate, 3=severe). These ratings combine to form three subscale scores – nausea, oculomotor discomfort, disorientation – as well as a total severity score. Examples of the symptoms are general discomfort, sweating, nausea, blurred vision, fatigue, headache, dizziness, and vertigo. The questionnaire is reproduced in Appendix A.4. The Total Severity score uses all of the symptoms, reflects the overall extent of symptom severity, and is therefore the best index of whether or not a sickness problem exists. Using the scoring system described in Appendix A.4, the Total Severity score ranges from zero to 235.6. Scores found in VE systems published in the literature range from 9 to 29.

Specific Experiment Apparatus – Presence Experiment

The virtual environment consisted of two rooms separated by a closed door: the Training Room and the Pit Room, Figure 2-5. The Training Room contained a plant, a painting, two marble counters, a window with a view of an outside environment, a lamp, a pedestal, and a radio. Two books were placed in the training room, a green book placed on the counter close to the radio, and a blue book placed on the pedestal. The participant could carry the books from place to place in the environment. Gravity was modeled for the books; if the participant

released the book, it would fall until it collided with another object. It would then rotate to rest on its closest flat side. The books were completely virtual; they had no real counterparts.



Figure 2-5. Virtual Environment with Visual Pit.

The Pit Room consisted of a 2-foot-wide ledge around a 20-foot drop into a room containing living room furniture: couches, lamps, tables, and bookshelves. A chair sat on the far side of the ledge opposite the door. In front of the door, a 2-foot-wide portion of the ledge protruded 27 inches from the rest of the ledge, similar to a diving board.



Figure 2-6. Testing Edge of Physical Precipice.

The passive haptics model of the marble counters was constructed from styrofoam blocks and particle board. The walls of the Pit Room were built from styrofoam blocks. Plywood was used to construct the 1.5-inch-thick physical ledge and the 2.25-inch-thick diving board, Figure 2-6. A real radio placed at the location of the virtual radio conveyed instructions to the participants. There were no other auditory stimuli designed into the experiment. A real chair in the Pit Room and a real pedestal in the Training Room were registered with their virtual counterparts.

Subjective presence was measured using the University College of London (UCL) Presence Questionnaire (Usoh et al., 1999). This questionnaire assesses three factors: reported presence – assesses the extent to which participants report feeling present, reported behavioral presence – assesses the extent to which the participants report acting present, and ease of locomotion – assesses the ease of moving through the virtual environment. The questionnaire consists of 13 questions answered on a one to seven scale. The questionnaire is scored by counting the number of five, six, and seven responses (Meehan, 2001). The reported presence score ranges from zero to seven, whereas reported behavioral presence and ease of locomotion range from zero to three.

A ProComp+ tethered telemetry system was used to record physiological measures (ProComp, 2001). Finger-mounted sensors measured skin temperature and skin conductance; a three-electrode electrocardiograph with electrodes placed on the participant's chest measured heart rate. When a person experiences stress, they exhibit physiological changes such as increased heart rate, increased skin conductance caused by increased sweat production, and a decrease in skin temperature due to the body heat concentrating in the core (Weiderhold et al., 1998). We measured these changes as the participant moved from the Training Room into the Pit Room by taking the mean value exhibited while in the Training Room and subtracting that from the mean value exhibited while in the Pit Room. We reversed the change in skin temperature to measure the difference from the Pit Room to the Training Room so that this measure would increase, rather than decrease, as expected presence increased.

Cohen Acrophobia Questionnaire

The Cohen Acrophobia Questionnaire (Appendix A.5) used in this study describes twenty situations involving heights, with rating scales for anxiety, from zero to six, and avoidance, from zero to three (Cohen, 1977). The questionnaire yields a total score ranging from zero to 180 and anxiety and avoidance subscale scores. It has been proven more sensitive to treatment outcome than behavioral tests and able to distinguish between phobics and non-phobics (Cohen, 1977).

2.3.3 Design

The experiment was within-subject. The independent variable was passive haptics; the dependent variable was the participants' sense of presence. We controlled the independent variable by either including or omitting the plywood model of the ledge in the Pit Room. All participants experienced the virtual environment both with and without passive haptics. The experiment was counterbalanced on the order of presentation of the passive haptics condition.

2.3.4 Procedure

Experiment Schedule. Each participant visited the lab on two different days, one session per day. During one session, the participant experienced the virtual environment with the

physical ledge, Figure 2-7, during the other session the physical ledge was omitted, Figure 2-8. Each session, including task, questionnaires, and discussion time, lasted approximately one hour.



Figure 2-7. Physical ledge.



Figure 2-8. No physical ledge.

A participant first read the Participant Instructions (Appendix A.2) and was asked if he had any questions. Then he signed the Informed Consent (Appendix A.1) form. The participant then filled out a Simulator Sickness Questionnaire and an Acrophobia Questionnaire. The participant was then taken to the lab for the initial exposure to the virtual environment. He could see the physical layout of the Training Room, but the view into the Pit Room was blocked. Once the equipment was shown and described to the participant, he was fitted with the head-mounted display, backpack, and joystick for tracking his hand. He trained to move about the virtual environment and to pick up the virtual books.

Meehan (2001) found a sharp drop-off in physiological response to the virtual pit between the first and second exposures with gradual decreases between subsequent exposures, an orienting effect. Because the large difference in response between first and second exposure could overwhelm any differences caused by manipulation of the experimental condition, we included an orienting pre-exposure to the pit as part of the training session. The door to the Pit Room opened briefly so that the participant could see the pit inside. Then the participant filled out another SSQ and the UCL presence questionnaire.

Afterwards, the participant removed his shoes and placed sanitary booties on his feet to allow him to feel the physical ledge with his feet directly. Then, the physiology monitoring equipment, head-mounted display, backpack, and joystick were fitted. Magnetic sensors were strapped to the participant's legs just below the knees to track leg movement. The avatar's legs were then checked in the virtual environment for alignment with the user's legs.

Instructions, recorded on CD for consistency across participants, were then played on a real CD player placed to coincide with the virtual radio. The instructions were told in the form of a story to be easier to remember. The participant moved around the environment to become accustomed with how the avatar moved with his body. Then he looked at the various items in the environment. Next, he practiced picking up the green book, carrying it, and dropping it onto the counter next to the window. Then he picked up the blue book. Next, the door to the Pit Room opened and the participant carried the book into the Pit Room. He then walked out onto the edge of the "diving board" and was instructed to curl his toes over the edge for a

ten count. Then, he carried the book to the chair, placed it in the chair, and returned to the Training Room. Once his physiological reactions leveled off, the VR session ended and the equipment was removed. The participant then answered another Simulator Sickness Questionnaire and a UCL Presence Questionnaire, and was orally debriefed.

During the participant's second visit to the lab, all of the above steps were repeated except for the participant instructions, informed consent, and initial exposure to the environment.

Task

The task was to carry the virtual blue book into the Pit Room and stand on the edge of the "diving board" for a ten count. Then move to the chair on the far side of the ledge by any path of one's choice, place the book in the seat of the chair, and return to the Training Room.

Data collection

We collected data from the tracking systems, physiological monitoring equipment, observed behaviors, and various questionnaires. The HiBall tracking system measured and recorded the locations of the participant's feet, hands, and head approximately 70 times per second. Task completion time and button-press events (book grasping) were recorded. Finger skin temperature, electrodermal response, and heart rate were measured 32 times per second. Observed behavioral presence was measured by scoring movements, thought to be reactions to the virtual pit, post-session from videotapes. Scored behaviors included head-mounted display adjustments, slowed movement, taking baby steps, leaning against the wall, peering into the Virtual Pit, and walking across the Virtual Pit. The complete list of scored behaviors (Appendix A.6) was constructed before the experiment from behaviors exhibited during demonstrations of the system and a pilot study. One experimenter scored the behaviors. Subjective presence was measured by the UCL Presence Questionnaire. Other questionnaires were used to assess the participant's level of acrophobia at the start and end of each session and level of discomfort or simulator sickness experienced in the environment.

2.4 Results

Statistical tests produce p -values. This p -value is the probability that the test shows a pattern in the data when there really is no pattern, a false positive. A maximum tolerable probability is set before conducting the statistical test called the significance level α . The most

commonly used α is 0.05 (Kleinbaum et al., 1998); it was used here. If the computed p -value is less than the a priori set α , then the statistical result is considered significant. If the p -value is less than 0.05, then there is no more than a five-percent chance that the test has falsely detected a pattern.

The analysis performed was a balanced univariate repeated measures analysis of variance (ANOVA). Half of the participants experienced the virtual environment with passive haptics during their first session, then experienced the virtual environment without passive haptics in the second session. The other half experienced the virtual environment without passive haptics first. SPSS for Windows software was used for the analysis (SPSS, 2001). The ANOVA produces the following statistics of interest:

- Eta-squared, η^2 , which gives the proportion of variance in the dependent variable accounted for by the independent terms, this value is analogous to R^2 in regression analysis (Note from Levine & Hullet (2000): care must be taken when calculating η^2 in SPSS for Windows, the values reported for η^2 are actually partial η^2 values and would overestimate effect size. Full η^2 values must be hand computed),
- The F statistic for the model being used to fit the data and probability p of obtaining a larger F value, indicating whether the model is significant or not (Kleinbaum et al., 1998),
- The F and p values for each independent term in the model, indicating whether the term is significant ($p < 0.05$) or not.

The following analysis sequence was followed (Kleinbaum et al., 1998):

- Plot the data for each relevant independent and dependent variable. Review summary statistics (mean, standard deviation, median, minimum, maximum). The data is checked for outliers, datapoints lying more than 3 standard deviations from the median. No outliers were removed from the data for this experiment.

- Test a repeated-measures ANOVA model using passive haptics as the independent variable.. Then compute the F and p statistics for the model. If the model is not significant, stop, because passive haptics is not an important predictor, otherwise include this variable in the model and proceed.
- Next, add the variable order-of-presentation to the model. If its partial p -value is significant, keep it in the model and proceed, if not remove it and proceed.
- At each subsequent step, calculate the partial p -value for the covariates gender and acrophobia scores not yet in the model, and then add to the model the variable with the smallest partial p -value (if it is statistically significant). At any step, if the smallest partial p -value is not significant, do not include that variable and terminate the procedure.

Data Presentation

Although I will discuss the mean and standard deviation in the text, a boxplot or “box and whiskers plot” will summarize the shape of the distribution of the data. The “box” in a boxplot shows the median score as a horizontal line and the first quartile (25th percentile) and third quartile (75th percentile) of the distribution as the lower and upper parts of the box (Kleinbaum et al., 1998). The median is the score at the 50th percentile: half of all participants get a score higher than the median, half get a score that is lower. The 25th percentile is the point at which 25% of the participants score lower. The 75th percentile is the point at which 75% of the participants score lower. Thus, the area in the "box" represents the middle 50% of the participants. The "whiskers" shown above and below the boxes technically represent the largest and smallest observed scores that are less than 1.5 box lengths from the end of the box (Kleinbaum et al., 1998). So the “whiskers” extent out to the largest and smallest observed scores or 1.5 box lengths from the end of the box, whichever is shortest. All subsequent boxplots share the same format.

Effects of Passive Haptics on Behavioral Presence

Behaviors were scored post-session from videotapes. There were 33 complete behavioral data sets recorded. The rest were lost through procedure and equipment failure. Details on what behaviors were recorded can be found in Appendix A.7. The score on the behavioral

index was computed by counting the number of behaviors associated with presence in a stress-inducing environment and subtracting from that the number of behaviors exhibited that might show interruptions in presence. Figure 2-9 shows a boxplot of the behavioral scores.

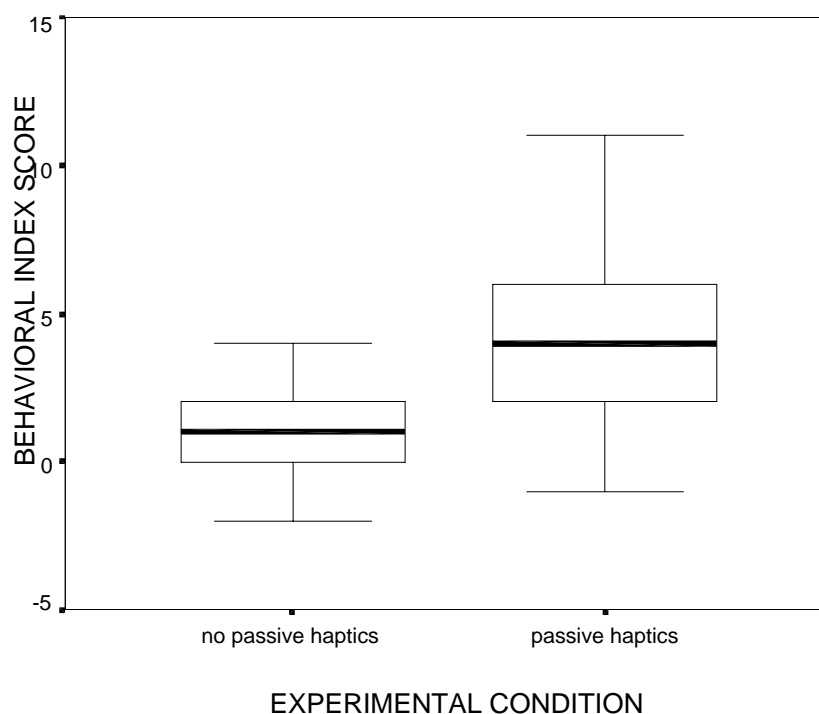


Figure 2-9. Behavioral Index scores.

The mean behavioral index score for the passive haptics session was 4.4 ($\sigma = 2.9$) with the mean score for the non-passive haptics session was 1.3 ($\sigma = 1.8$). Passive haptics accounted for 55.1 % of the variance in the behavioral index scores. The differences between the passive-haptics and non-passive-haptics VE sessions was significant ($p < 0.001$); the statistics are: $\eta^2 = 0.55$ and $F(1,32) = 42$.

The results were analyzed to determine if the order of experiencing haptic augmentation added significantly to the passive haptics model. A partial p -value of 0.71 was calculated with order added to the model, meaning order was not significant and was therefore left out

of the final model. The other covariates were similarly checked for added significance. Neither of the two scores derived from the Acrophobia Questionnaire contributed to predicting behavior scores, with partial p -values of 0.77 for the anxiety score and 0.87 for the avoidance score. Gender also did not significantly predict scores on the behavior index with a partial p -value of 0.84. No significant interactions between passive haptics and the other independent variables (order, gender, anxiety score, and avoidance score) were found.

Effects of Passive Haptics on Subjective Presence

52 participants' data were included in the analysis of the three scores derived from the UCL Presence Questionnaire (reported presence, reported behavioral presence, and ease of locomotion). Figures 2-10 and 2-11 show the boxplots of the reported presence and reported behavioral presence data. Range of possible scores is zero to seven.

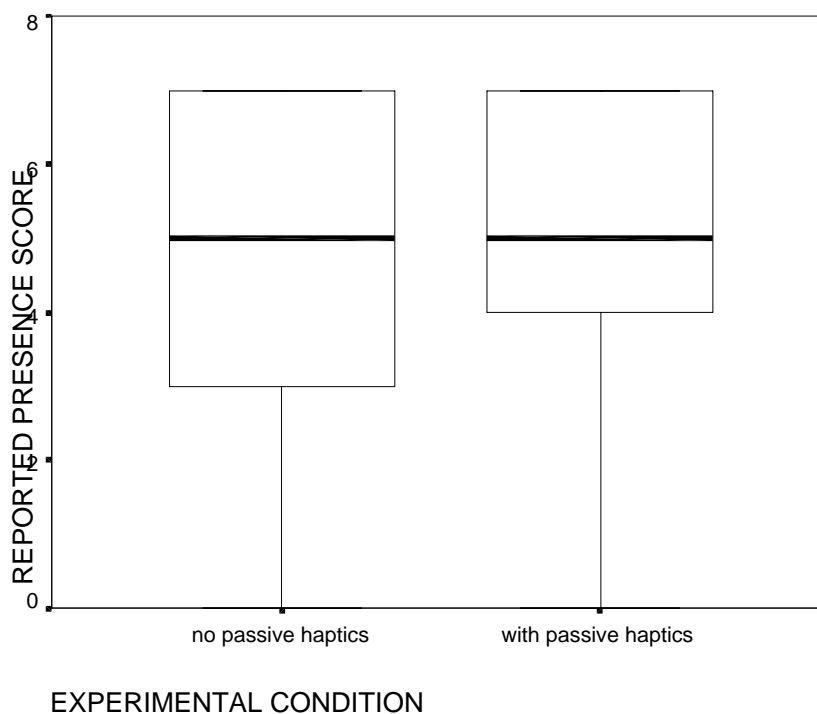


Figure 2-10. Reported Presence scores.

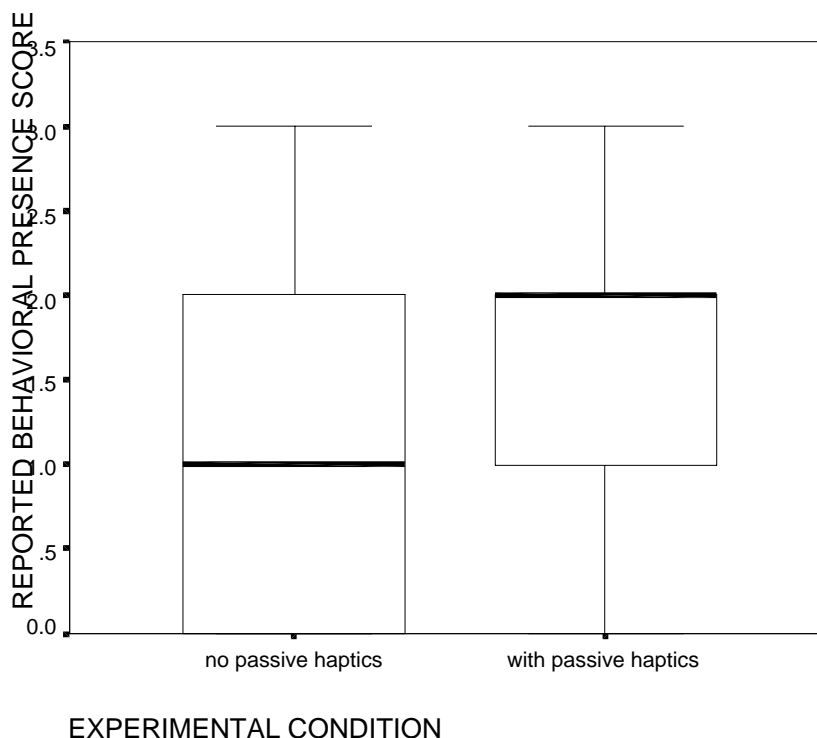


Figure 2-11. Reported Behavioral Presence scores.

Neither the reported presence score ($p = 0.065$), nor the ease of locomotion score ($p = 0.31$) showed significant differences between the passive-haptics and no-passive-haptics VE sessions. The reported behavioral presence score did show a significant difference between groups ($p < 0.05$). The mean reported behavioral presence for the passive haptics session was 1.5 ($\sigma = 2.0$) with the mean score for the non-passive haptics session was 1.1 ($\sigma = 1.0$). The range of possible scores was zero to three. Passive haptics accounted for 13% of the variance in the reported behavior presence scores. The statistics are: $\eta^2 = 0.13$, $F(1,51) = 5.1$, $p = 0.07$.

Order of presentation ($p = 0.51$) was not a significant factor when added to the model. Gender was not found to be significant ($p = 0.18$). Neither of the acrophobia scores, avoidance ($p = 0.70$) or anxiety ($p = 0.89$) were significant when added to the model. No significant interactions among passive haptics and the other independent variables were found.

Effects of Passive Haptics on Heart Rate

46 participants' data were included in the heart rate analysis. The change in the participant's heart rate when passing from the Training Room to while he was in the Pit Room was measured. Figure 2-12 shows the boxplot for the passive haptics and non-passive haptics VE sessions.

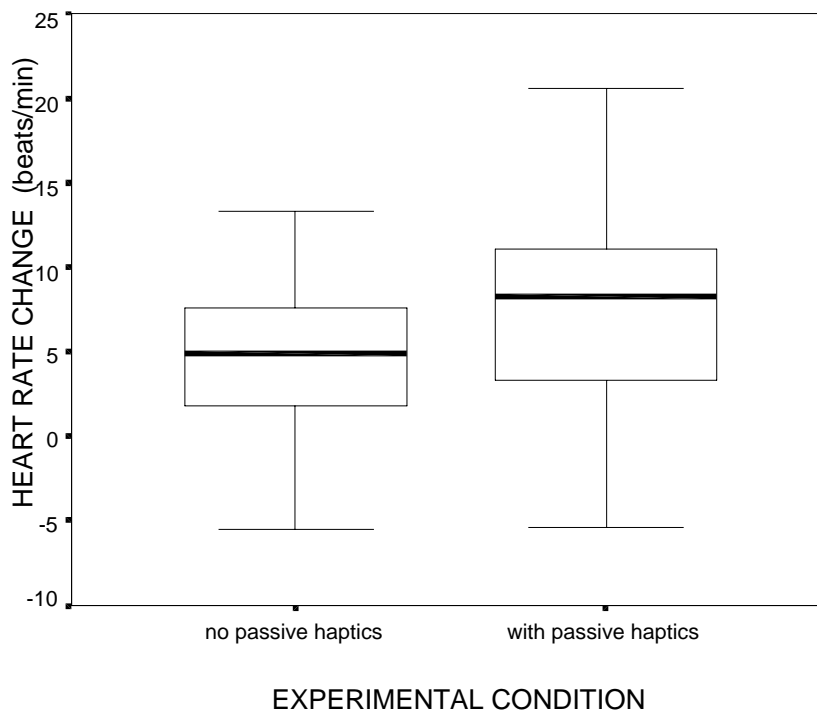


Figure 2-12. Heart Rate change differences between sessions.

The mean change in heart rate for the passive haptics session was 7.6 beats per minute ($\sigma = 6.8$ bpm) with the mean change in heart rate for the non-passive haptics session was 4.9 bpm ($\sigma = 5.5$ bpm). Passive haptics accounted for 12% of the variance in the change in heart rate. The difference between the passive haptics and non-passive haptics VE sessions was significant ($p < 0.05$); the statistics are: $\eta^2 = 0.12$, $F(1,45) = 6.3$, $p = 0.016$. The maximum increase in heart rate occurred in the passive haptics group; that participant's heart rate increased by 28 beats per minute.

Order of presentation ($p = 0.670$) was not a significant factor when added to the model. Gender was not found to be significant ($p = 0.103$). Neither of the acrophobia scores, avoidance ($p = 0.701$) or anxiety ($p = 0.887$) were significant. No significant interactions among passive haptics and the other independent variables were found.

Effects of Passive Haptics on Skin Conductance

50 participants' data were included in the skin conductance analysis. The change in the participants' skin conductance from the Training Room to the Pit Room was measured in millimhos, or millisiemens. A *mho*, also called a siemen, is the inverse of an ohm (the metric unit of resistance). Figure 2-13 shows the boxplot for skin conductance in the passive haptics and non-passive haptics VE sessions.

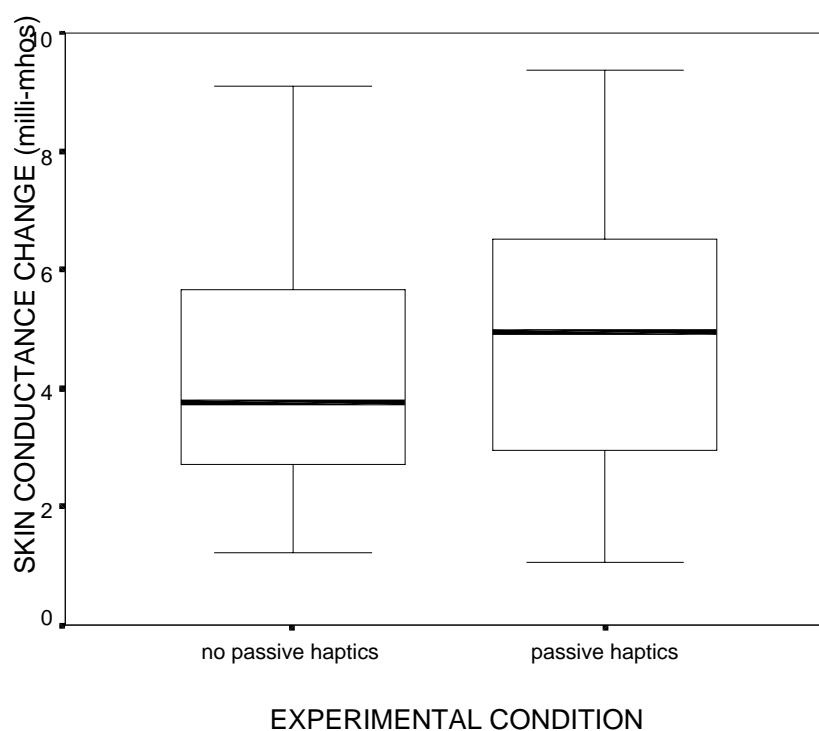


Figure 2-13. Electrodermal response changes.

The mean change in skin conductance for the passive haptics session was 5.2 millimhos ($\sigma = 2.6$ millimhos), and the mean change in skin conductance for the non-passive haptics session was 4.4 millimhos ($\sigma = 2.4$ millimhos). Passive haptics accounted for 7.9% of the

variation in the change in skin conductance. The difference between the passive haptics and non-passive haptics VE sessions was significant ($p < 0.05$); the statistics are: $\eta^2 = 0.079$, $F(1,49) = 4.4$, $p = 0.040$.

Adding order of presentation to the model with passive haptics was not significant ($p = 0.668$). Gender ($p = 0.152$), avoidance score ($p = 0.253$), and anxiety score ($p = 0.263$) did not add significantly to the model. No significant interactions between passive haptics and the other independent variables were found.

Effects of Passive Haptics on Skin Temperature

49 participants' data were included in this analysis. For this variable, because the peripheral skin temperature decreases with exposure to stress-inducing stimuli, the participant's average skin temperature in the Pit Room was subtracted from his average temperature in the Training Room. This results in a variable that should increase as presence increases. Figure 2-14 shows the boxplot for skin temperature change in the passive haptics and non-passive haptics VE sessions.

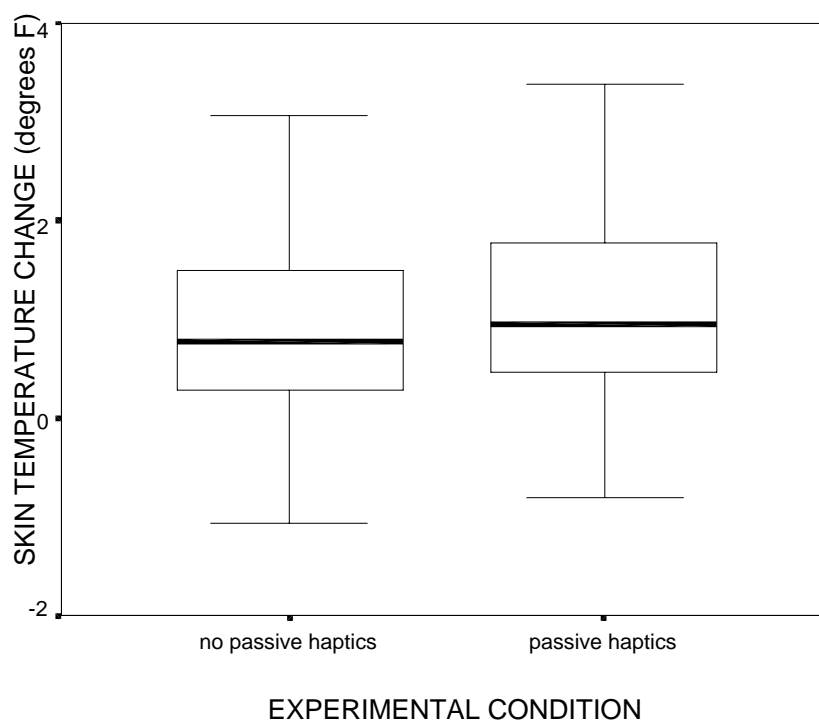


Figure 2-14. Skin temperature change data.

The mean change in skin temperature for the passive haptics session was 1.2 degrees Fahrenheit ($\sigma = 1.1$ °F) with the mean change in skin temperature for the non-passive haptics session was 0.9 °F ($\sigma = 1.3$ °F). Passive haptics was not found to produce a significant difference in skin temperature change, though it showed a trend toward increasing the amount of change ($p = 0.063$).

Other Results

Effects of Passive Haptics on SSQ scores

Participants answered the Simulator Sickness questionnaire five times through the course of the experiment; during their initial session before beginning the experiment, after their initial exposure to the environment, then after the experimental condition. They also answered it at the beginning of their second session and after that session's experimental condition. The administration of the SSQ at the beginning of each session was simply to ensure that each participant was in a good state of health before participating in the experimental conditions. This analysis used only the SSQ scores reported after the experimental conditions.

When scored, the SSQ gives four numbers: a "total severity" and three diagnostic subscale scores (nausea, disorientation, and oculomotor discomfort). I used Total Severity as the main indicator of sickness, following Kennedy (1993) and Kolasinski (1996). Figure 2-15 shows the boxplot of the total severity scores for the passive-haptics and no-passive-haptics conditions.

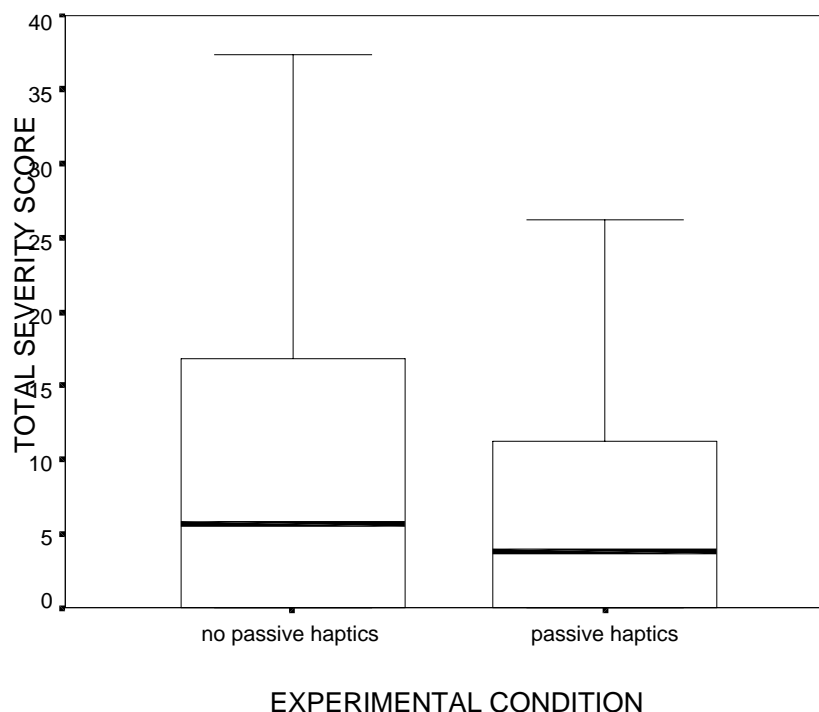


Figure 2-15. Total Simulator Sickness Severity scores.

Passive haptics did not have a significant effect on total severity of simulator sickness ($p = 0.533$). Section 3.3.5 contains a comparison of simulator sickness reported in this study, the training study, and other published studies.

2.5 Discussion

Results of this study support the hypothesis that augmenting virtual environments with passive haptics increases presence. Observed behaviors, reported behavioral presence, heart rate change, and change in skin conductance all showed statistically significant increases when passive haptics augmented the virtual environment. Subject-reported presence and change in skin temperature trended toward significance. Skin temperature tends to be a slowly adapting measure (Weiderhold et al., 1998), and, on average, the participants spent ninety seconds in the Pit Room, which may not have been enough time for the skin temperature to respond to the stimulus. The reported presence measure on the UCL questionnaire might not have been sensitive enough to detect a difference in presence.

Furthermore, this questionnaire is self-assessed after the session is completed, and cannot measure the time-varying quality of presence as well as some of the physiological measures.

Chapter 3

User Study 2 – Effects of Passive Haptics on Training Transfer

3.1 Introduction

This study, conducted between December 11 and 20, 2000, examined the effects of passive haptics on cognitive mapping and spatial knowledge training transfer. Sketch maps and estimation of virtual object dimensions measured cognitive mapping. Completion time and number of collisions in a blindfolded real-world maze navigation task, as in Waller et al. (1998), measured both cognitive mapping and spatial knowledge training transfer.

3.2 A priori hypotheses

H1. *Spatial knowledge training in a virtual environment augmented with passive haptics will produce increased spatial knowledge transfer when compared to training in a non-augmented VE.*

H2. *Participants will form better cognitive maps while experiencing a virtual environment with passive haptics than when experiencing a VE without passive haptics.*

3.3 Methods

3.3.1 Participants

Number, age and gender.

A total of 33 college students (16 females) participated in the study. Three participants' data were excluded from analysis because their virtual experience was monoscopic due to procedural error. The participants ranged in age from 19 to 23.

Criteria for exclusion of participants

The following criteria were used to exclude participants before the start of the experiment:

- Participants who could not use stereopsis for depth perception,
- Participants who were colorblind,
- Participants who were not ambulatory,
- Participants with a history of epilepsy, seizures, or strong susceptibility to motion sickness,
- Participants who reported not being in their usual state of good physical fitness at the time of the experiment (including participants who had recently used sedatives, tranquilizers, decongestants, anti-histamines, alcohol, or other medication),
- Participants uncomfortable with the system, or who had difficulty fitting the display to their heads (a brief demonstration was done at the beginning of the session).

No participants were excluded from the study based on these criteria.

Recruiting and inducements

Participants were recruited from undergraduate computer science courses and had no prior knowledge of the goals of the study. Participation was voluntary. Participants were paid \$10 per hour regardless of whether they completed the study.

3.3.2 Apparatus

All equipment and material described in the Common Apparatus section in Section 2.3.2 were also used in this experiment. The virtual environment consisted of a room furnished with rectangular-solid objects forming a single-path maze, Figures 3-1 and 3-2. These objects were of solid color. This was to prevent participants from using textures on the objects to gain information on their shape and size. Patterned textures were used on the floor, walls, and ceiling to prevent disorientation. The path the participants walked consisted

of 11 turns. Most of the objects were colored gray. Four virtual objects were color-coded red, blue, green, and yellow for identification during testing after the VE session.

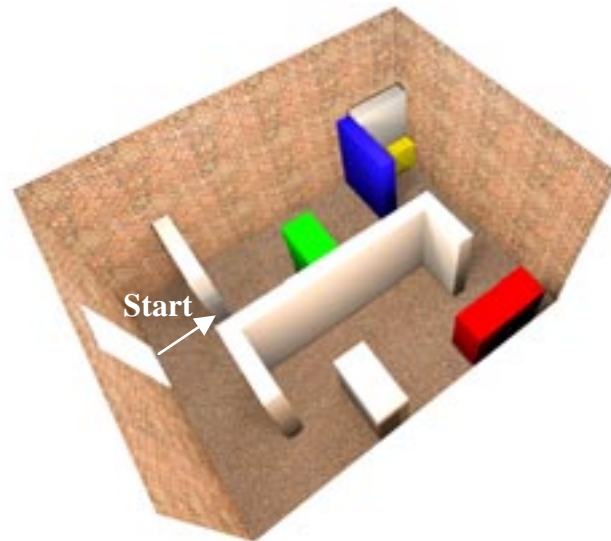


Figure 3-1. Virtual Training Room.

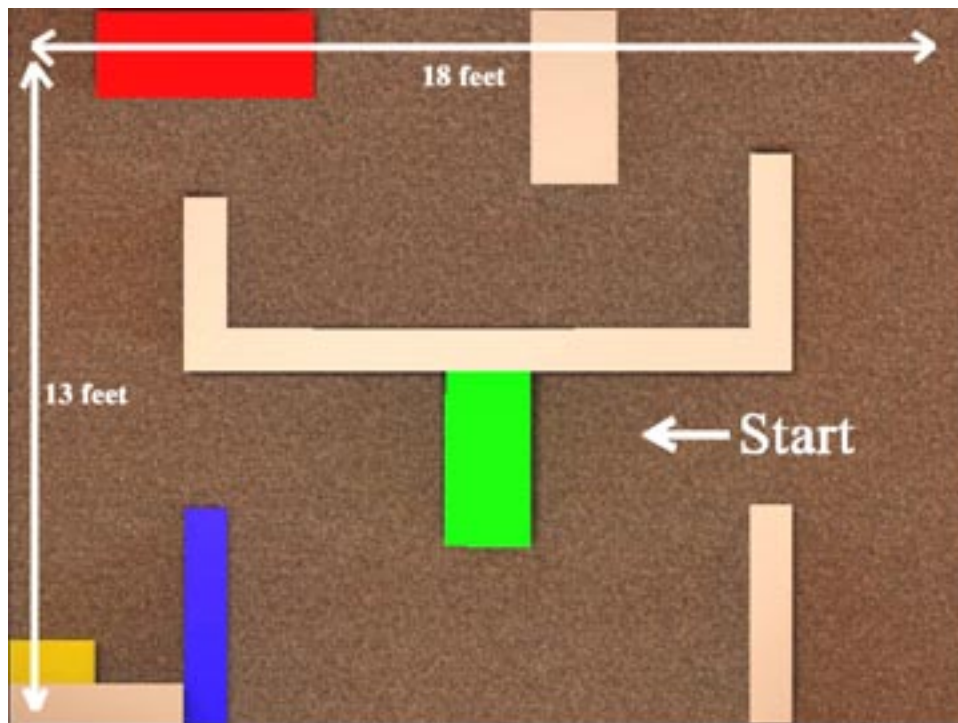


Figure 3-2. Map of Training Room.

Two identical passive haptics models were built from styrofoam bricks and cardboard. One was used in the VE lab for the training condition with passive haptics. In order that all

participants would be tested using the same real setup, the second haptics model was constructed in another lab.

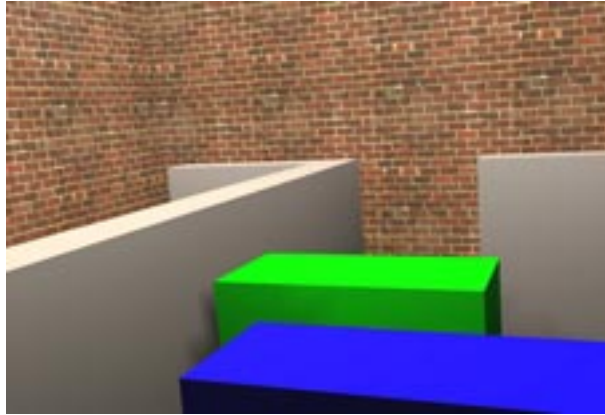


Figure 3-3. Virtual View of Training Environment.



Figure 3-4. Real Training Environment with Passive Haptics.

Measures

The Guilford-Zimmerman Spatial Orientation test was administered to participants so that the scores could be used to control for individual differences in orientation ability (Guilford-Zimmerman Aptitude Survey, 1976). This multiple-choice test has 60 items, each with five possible answers. Participants were instructed to complete as many items as possible within 10 minutes. The test was scored to correct for guessing. This test has been used previously in a VR navigation study (Satalich, 1995).

The Witmer and Singer Presence Questionnaire was used to measure the participants' sense of presence. This questionnaire proposes to measure presence by examining participant's perception of factors believed to contribute to presence (discussed further in Section 4.1.1). The scores range from zero to 13. Sketch Maps were used to evaluate the participants' cognitive maps of the virtual environment, as in Billinghurst et al., (1995).

For height estimation, a six-foot by three-foot sheet of paper was attached to a wall for the participants to mark the estimated heights of the virtual objects. The virtual objects ranged in height from 24 inches to 60 inches. The participants used markers of the same color as the objects. Another six-foot by three-foot sheet of paper was placed on a table for the participants to mark the estimated width of the space between two virtual objects.

3.3.3 Design

The experiment was between-subjects. The independent variable was passive haptics; the dependent variables were cognitive mapping and training effectiveness. We controlled the independent variable by either including or omitting the styrofoam model during training. One group of participants experienced the virtual environment with passive haptics, the other without.

The participants who experienced the virtual environment not augmented with the styrofoam model were given audio and visual contact cues. When either hand collided with a virtual object, that hand would turn red, Figure 3-5.

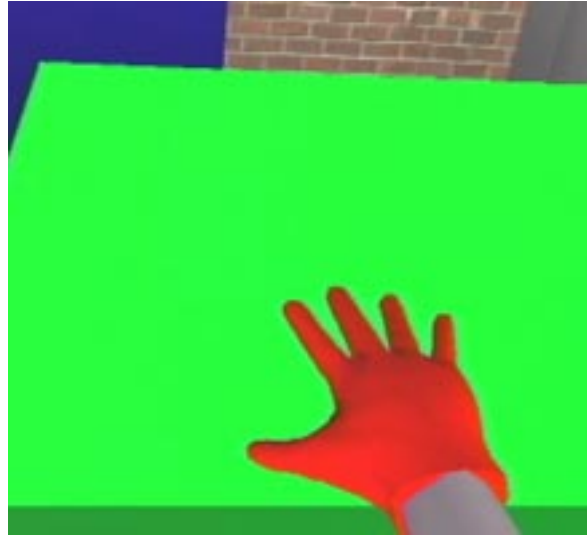


Figure 3-5. Avatar’s hand turns red when touching objects.

Simultaneously, a hand-specific sound would be heard – a left-hand contact caused buzzing; a right-hand contact caused clicking. Those participants trained in a virtual environment augmented with passive haptics did not have such cues. They had the physical cues and the visual observation, unaugmented for collision detection. Everything else was identical across experimental conditions.

3.3.4 Procedure

Experiment Schedule. Each participant visited the lab once, and experienced one of the two experimental conditions. Each session, including task, questionnaires, testing, and discussion time, lasted about 1.5 hours.

Participants first read the Participant Instruction (Appendix B.2) form and were asked if they had any questions. Then they signed the Informed Consent (Appendix B.1) form. Next, participants saw examples of the equipment: an HMD and the HiBall tracker. Participants then filled out a Simulator Sickness Questionnaire (Appendix A.4). After that, participants read over the instructions for the Guilford Zimmerman Spatial Orientation test. They were then given ten minutes to take the test. Then they were given instructions on what to do upon entering the virtual environment: make three clockwise laps through the environment, touch all of the objects in the environments, and try to get a sense of the layout of the room.

Next, participants were taken to the hallway outside the lab and outfitted with the VR gear. The equipment consisted of the HMD, a backpack containing the magnetic source for the magnetic tracker, and fingerless weightlifting gloves fitted with magnetic sensors. Participants did not see the lab before entering it. Next, a stereo-depth vision test was performed using the HMD as the display device. Then the equipment was checked to make sure the participant could see his avatar's hands registered to within one inch of his real hands. Once everything was ready, the participant proceeded to make three laps through the environment, touching the various objects. Once done, the participant was guided back into the hallway and the equipment removed.

The participants were taken back to the interview room to complete the post-session Simulator Sickness Questionnaire. Then participants took as much time as needed to sketch a map of the VE on a blank 8.5 x 11-inch sheet of paper. No instructions on how to do this were given. Next participants marked the heights of the four colored objects on a six-foot strip of paper attached to the wall. Participants used colored markers that matched the colors of the virtual objects. Next participants marked the distance between two obstacles on a six-foot strip of paper spread out on a table. Then participants filled out the Witmer and Singer Presence Questionnaire (Appendix B.5).

Participants were then taken to the lab housing the physical layout for testing. After being instructed: "Complete one lap through the environment as quickly as possible, though safely; and do not touch any of the objects, it will be considered a penalty," they were blindfolded and guided to the start point. Time to complete the lap, the number of object collisions, and the location of wrong turns were recorded. The testing was also videotaped. Following testing, participants were given a minute to look over the physical layout and comment on anything that seemed different from the virtual environment.

Tasks. Participants were to walk three laps around the virtual environment while touching the various objects. The task was to gain as much information on the layout of the virtual environment as possible. The participants knew before entering the virtual environment that they would be tested by navigating an identical real environment while blindfolded.

Data Collection. A tracking system measured and recorded the locations of the participant's head and hands approximately 70 times per second while in the virtual environment. Sketch maps and virtual object dimension estimates, both drawn on blank paper, were collected. A stopwatch was used to measure the participant's time to complete the blindfolded navigation task. The number of collisions was noted and verified against video and audio recordings. Questionnaires were used to assess the participant's sense of presence and level of discomfort, or simulator sickness, experienced in the environment.

3.4 Results

As in the presence study, I chose an α equal to 0.05. The analysis performed was a univariate analysis of variance (ANOVA). SPSS for Windows software was used for the analysis. ANOVA is a special case of multiple regression analysis, which fits a linear model to a set of data. For example, a simple linear regression model to test how well a dependent variable, Y , is predicted by two independent variables, X_1 and X_2 , is $Y = b_0 + b_1X_1 + b_2X_2$. The best-fit values for the regression coefficients, b_i , are found using a least-squares method. Then the F and p statistics are computed for the overall model and for each independent term. It produces the following statistics of interest:

- The model R^2 , which gives the proportion of variance in the dependent variable accounted for by the independent terms,
- The F statistic for the model and probability p of obtaining a larger F value, indicating whether the model is significant or not,
- The F and p values for each independent term in the model, indicating whether the term is significant or not.

I used a forward-selection procedure (Kleinbaum et al., 1998) to find the best fitting model; it proceeds as follows:

- Plot the data. Review the summary statistics: mean, standard deviation (σ), median, minimum, and maximum. Remove outliers, considered as any data falling outside $\pm 3\sigma$ from the median. The median is used instead of the mean because it is less affected by outliers and thus gives a better estimate of the average value (Kleinbaum et al., 1998). Only two outliers in 240 datapoints were removed before the subsequent analysis.
- The independent variable most highly correlated with the dependent variable is the first added to the model for analysis of variance (ANOVA). Then compute the F and p statistics for the overall model and for the independent term. If the model is not significant, stop, because no independent variables are important predictors, otherwise include this variable in the model and proceed.
- At each subsequent step, calculate the partial p -value for the variables not yet in the model, and then add to the model the variable with the smallest partial p -value, if it is statistically significant. Repeat until the smallest partial p -value is not significant or all variables are added to the model.

A priori hypotheses

Effects of Passive Haptics on Real-World Navigation Task Completion Time

There were 30 measurements of navigation time. One outlier was removed because the participant had gotten particularly confused during navigation which resulted in a time more than 3 standard deviations above the median navigation time. This left 29 observations.

Figure 3-6 shows the boxplot along with the medians of the completion times for the group trained in a VE augmented with passive haptics, and the group trained in a non-augmented VE.

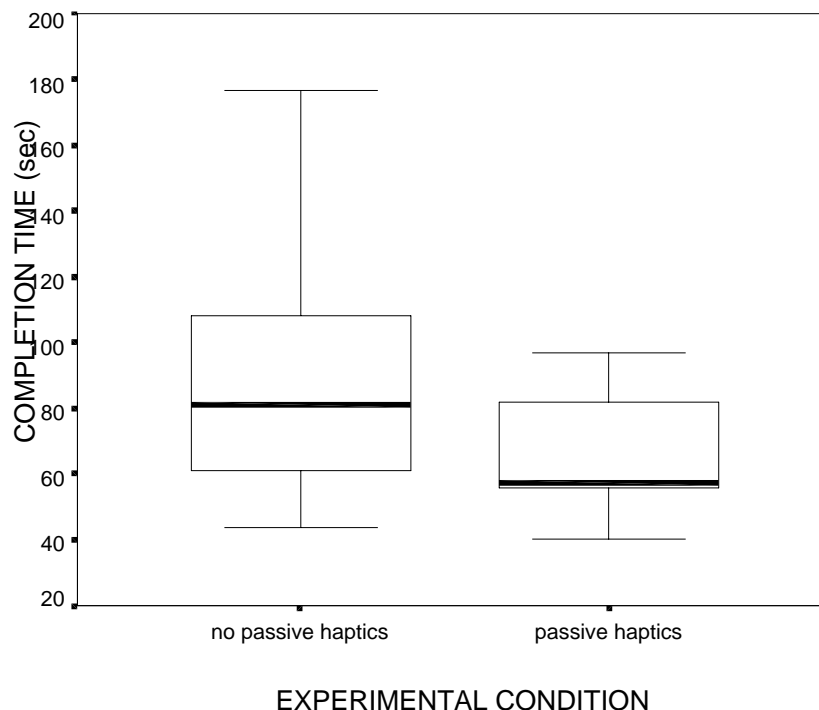


Figure 3-6. Navigation Times in Real World Task.

The mean time to complete the navigation for the passive haptics group was 64.6 seconds ($\sigma = 17.5$ seconds). The mean time to complete the navigation for the non-passive haptics group was 86.6 seconds ($\sigma = 37.0$ seconds). Passive haptics accounted for 13.7% of the variance in completion time. The model fit was significant ($p < 0.05$); the statistics are: $R^2 = 0.137$, $F(1,27) = 4.3$, $p = 0.048$. This implies that the independent term, passive haptics was significant, $p < 0.05$.

The partial p -values were calculated for the covariates spatial orientation score ($p = 0.24$) and gender ($p = 0.64$). Neither value is significant, so neither is added to the final model.

Effects of Passive Haptics on Number of Collisions

There were 30 measurements of the number of collisions. Figure 3-7 shows the boxplot along with the medians of the completion times for the group trained in a VE augmented with passive haptics, and the group trained in a non-augmented VE.

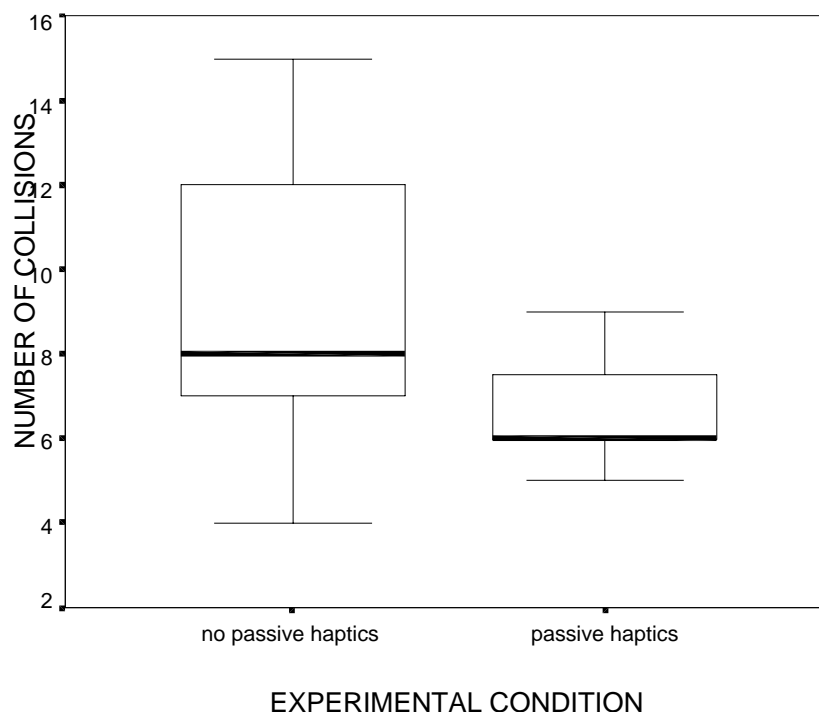


Figure 3-7. Number of Collisions in Real World Task.

The mean number of collisions per person for the passive haptics group was 8.9 collisions ($\sigma = 3.5$ collisions). The mean number of collisions for the non-passive haptics group was 6.6 collisions ($\sigma = 1.4$ collisions). Passive haptics accounted for 18% of the variance in the number of collisions. The model fit was significant ($p < 0.05$); the statistics are: $R^2 = 0.18$, $F(1,28) = 5.9$, $p = 0.021$.

The partial p-values were calculated for the covariates, gender ($p = 0.44$) and spatial orientation score ($p = 0.61$). Neither value is significant, so neither is added to the final model.

Effects of Passive Haptics on Sketch Map Accuracy

There were 29 sketch maps analyzed; one was lost before analysis. Sketch maps were scored on a 1(poor) to 5(excellent) goodness scale by an experimenter blind to the experimental condition, following a procedure similar to that used by Billingham and Weghorst (1998). This scale took into account factors such as overall room layout accuracy, and usefulness of the map. Figure 3-8 shows the boxplot along with the medians of the accuracy of the sketch maps for the group trained in a VE augmented with passive haptics, and the group trained in a non-augmented VE.

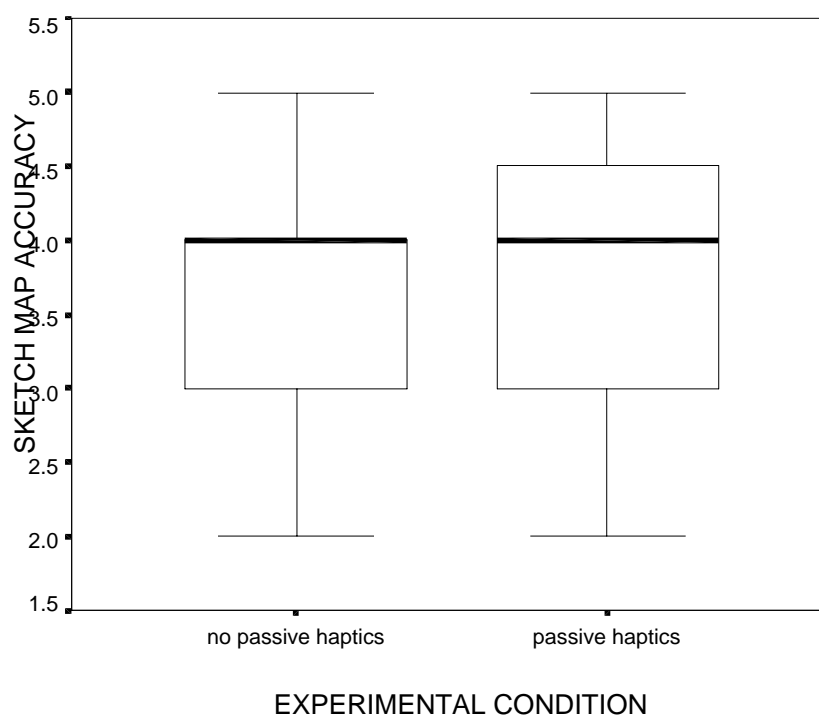


Figure 3-8. Sketch Map Ratings

The mean sketch map rating for the passive haptics group was 3.6 ($\sigma = 1.1$). The mean sketch map rating for the non-passive haptics group was 3.7 ($\sigma = 0.8$). No significant differences between the passive haptics group and the non-passive-haptics group were found ($p > 0.89$). Neither gender ($p = 0.11$) nor scores on the Guilford-Zimmerman Spatial Orientation test ($p = 0.76$) produced significant results when added to the model with passive haptics.

Effects of Passive Haptics on Virtual Object Height Estimation

Participants were asked the heights of the four color-coded objects after their virtual environment session; 30 sets of measurements were collected. The heights of the objects were as follows: yellow, 24 inches; red, 36 inches; green, 48 inches; blue, 60 inches. Figure 3-9. compares the mean estimates from the group trained without passive haptics, the group trained with passive haptics, and the actual heights.

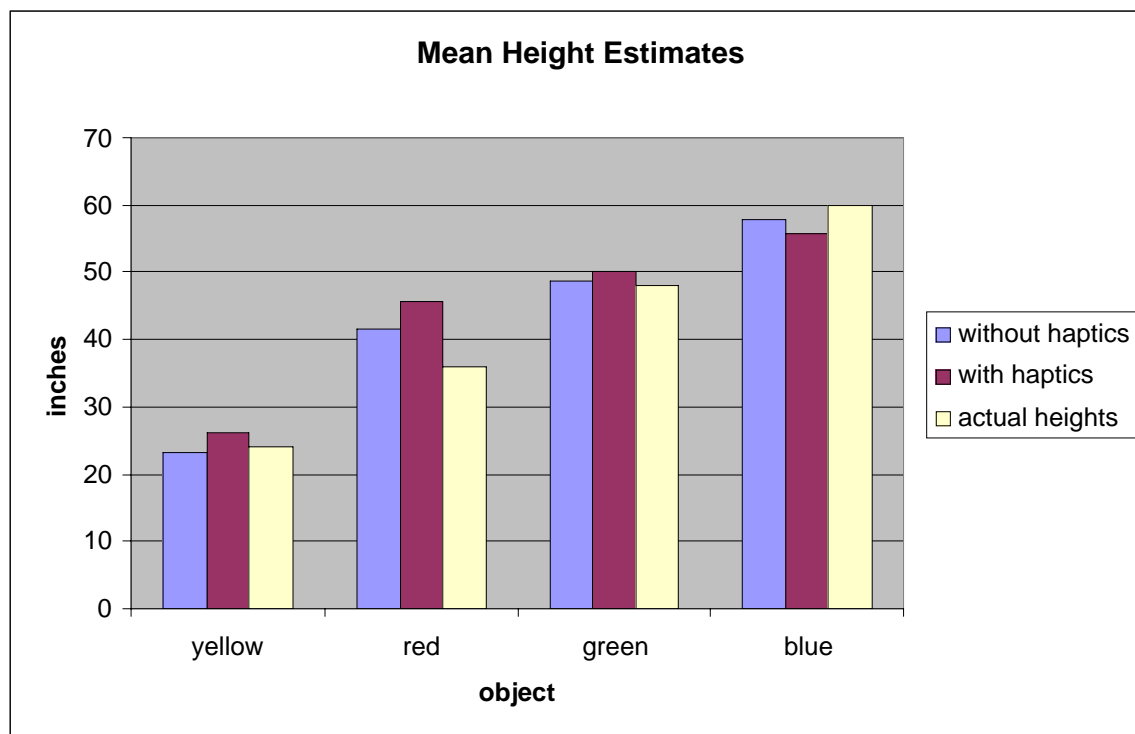


Figure 3-9. Real and Mean Estimated Heights

An ANOVA showed that none of the measured variables had any significant effects on the height estimates of any of the objects as is shown in Table 3-1.

		Independent Variable		
		Passive Haptics	Gender	Spatial Orientation Score
Object	Yellow (24 inches)	0.61	0.26	0.71
	Red (36 inches)	0.29	0.16	0.94
	Green (48 inches)	0.79	0.53	0.22
	Blue (60 inches)	0.95	0.61	0.39

Table 3-1. Significance values (p -values) from ANOVA

Effects of Passive Haptics on Interobject Distance Estimation

Participants were asked to estimate the width between the blue object and the inner gray wall after their virtual environment session. Only 29 measurements were collected for the width estimates, due to a city-wide power failure during one participant's session. The actual width was 28.5 inches.

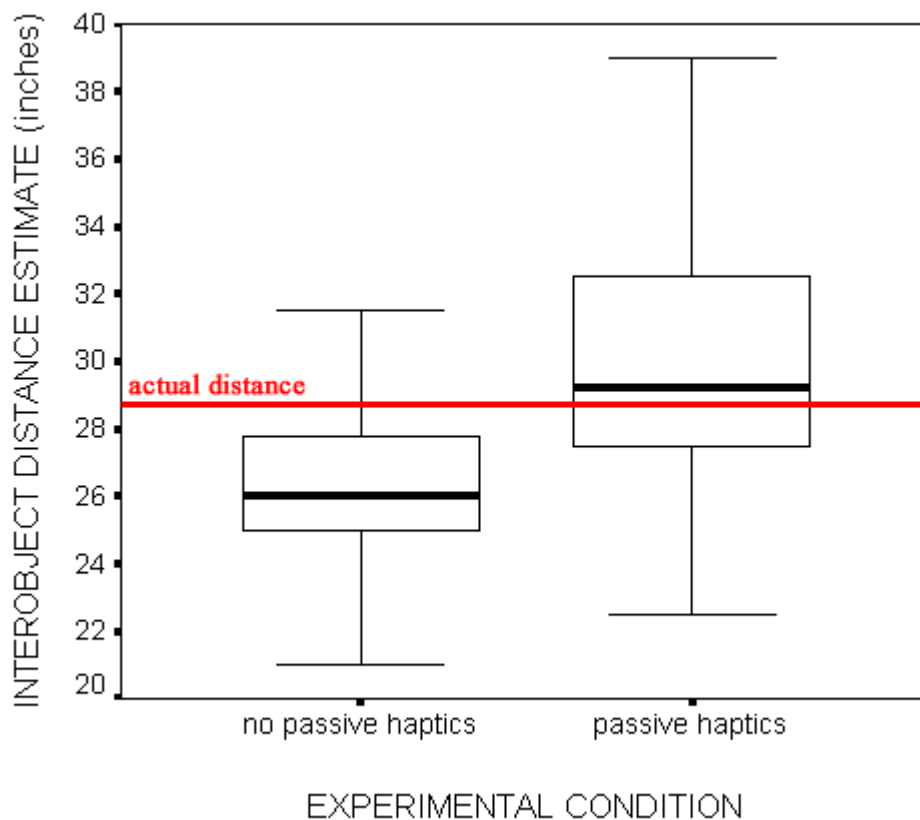


Figure 3-10. Interobject Distance Estimates

The mean interobject distance estimate for the passive haptics group was 30.4 inches ($\sigma = 6.5$ in). The mean sketch map rating for the non-passive haptics group was 26.0 inches ($\sigma = 4.4$ in). Passive haptics accounted for 15% of the variance in the interobject distance estimates. The model fit was significant ($p < 0.05$); the statistics are: $R^2 = 0.15$, $F(1,27) = 4.6$, $p = 0.040$.

Partial p-values were calculated for the covariates, gender ($p = 0.16$) and spatial orientation score ($p = 0.34$). Neither value is significant, so neither is added to the final model.

Exploratory results

Wrong Turns

Data were collected on the location and direction of wrong turns made by the participants. The data showed that a large number of participants trained without passive haptics made a wrong turn at the same location when tested in the real environment, Figures 3-11 and 3-12, so a formal analysis was done. Data from all 30 participants are included.

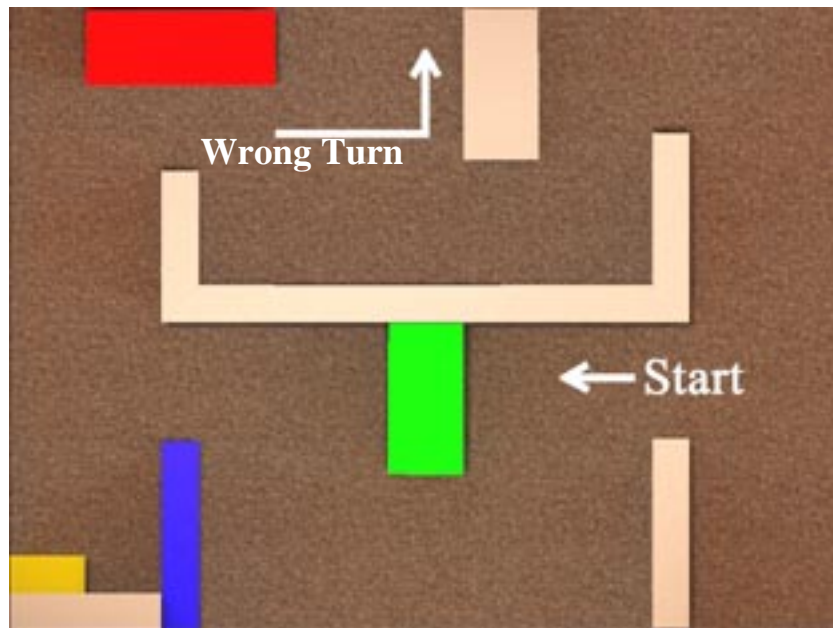


Figure 3-11. Location of the Wrong Turn in the Environment



Figure 3-12. Video frame of participant making the wrong turn during testing.

11 of 15 participants trained without passive haptics made the wrong turn while only two of 15 participants trained with passive haptics made the same wrong turn. Analysis shows that passive haptics accounts for 22% of the variance in the wrong turn data. The model fit was significant ($p < 0.01$); the statistics are: $R^2 = 0.22$, $F(1,28) = 7.8$, $p = 0.009$.

The partial p-values were calculated for the covariates, spatial orientation score ($p = 0.82$) and gender ($p = 0.96$). Neither value is significant, so neither is added to the final model.

Presence

All 30 participants' scores on the Witmer and Singer Presence Questionnaire were used in the analysis. Figure 3-13 shows the boxplot of the data.

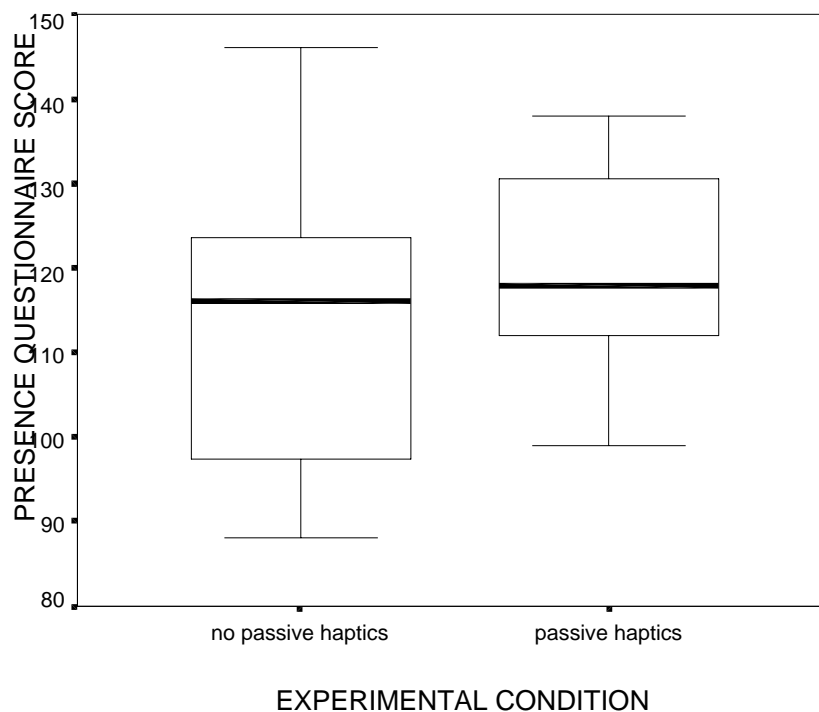


Figure 3-13. Witmer and Singer Presence Questionnaire scores.

Although the group who trained with passive haptics had a higher mean presence score, 120.2 (SD = 12.1), than the mean score of the group who trained in a non-augmented VE, 112.2 (SD = 17.4), the difference caused by passive haptics was not significant ($p = 0.16$). Neither gender ($p = 0.33$) nor spatial orientation score ($p = 0.67$) by themselves yielded significant results either.

Simulator Sickness

Participants answered the Simulator Sickness Questionnaire before and after each experiment session. The first administration was only to verify that the participant was not sick before starting the study and was not included in the analysis. Serious sickness was not seen in any of the first SSQ tests; in most cases no more than four symptoms, all “slight” were reported. 29 participants’ data were analyzed; one was lost due to procedure failure.

Table 3-2 shows the results from ANOVA for each of the dependent variables predicting each of the SSQ factors. The only significant result found was that participants’ scores on

the Guilford-Zimmerman Spatial Orientation test did indeed predict their level of disorientation. The higher the participant scored on the pre-test, the less disorientation he reported on the post-experiment SSQ. The model fit was significant ($p < 0.05$); the statistics are: $R^2 = 0.16$, $F(1,27) = 5.2$, $p = 0.031$.

		Independent Variables		
		Passive Haptics	Gender	Spatial Orientation Score
SSQ Factors	Nausea	0.82	0.33	0.39
	Oculomotor Discomfort	0.37	0.08	0.58
	Disorientation	0.91	0.22	0.03
	Total Severity	0.81	0.12	0.19

Table 3-2. p-values across all participants.

Table 3-3 shows summary statistics of post-exposure sickness scores over the entire experiment. These values give an overall indication of the “healthiness” of our VR system.

Score	Mean	Standard Deviation	Low	High	Highest Possible Score
Total severity	14.6	13.8	0	48.6	235.6
Nausea	10.9	13.9	0	38.2	200.3
Oculomotor Discomfort	12.0	11.7	0	37.9	159.2
Disorientation	16.3	18.3	0	69.6	292.3

Table 3-3. Sickness score statistics across all participants.

The following figures 3-14 and 3-15 compare the results of our system, with our exposure lengths, to others previously reported. There is large variation in the experimental conditions across these data points. Arthur (2000) is the most similar study to our conditions.

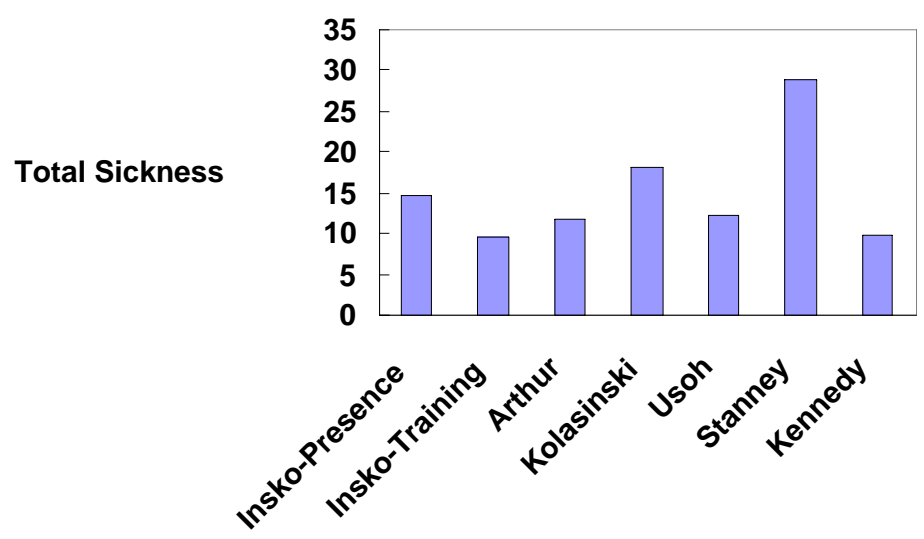


Figure 3-14. Total severity comparison of seven reports of sickness.

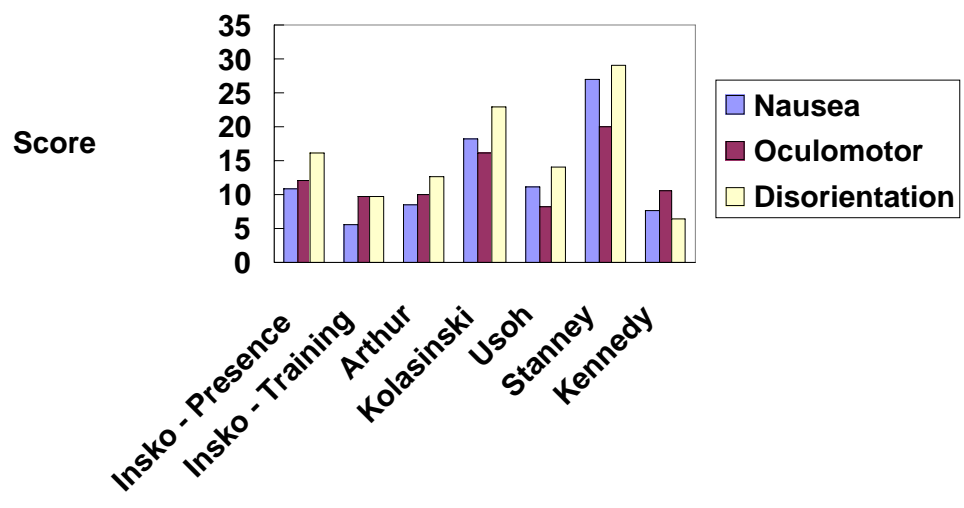


Figure 3-15. Profile comparison of seven reports of sickness.

3.5 Discussion

Both navigation time and the number of collisions support the hypothesis that spatial knowledge transfer was greater in a VE augmented by passive haptics than in a virtual environment without passive haptics.

The sketch map data and height estimates were not found to support the hypothesis that the participants trained with passive haptics form better cognitive maps than those trained without passive haptics. However when navigating in a real environment while blindfolded, a person's cognitive map is the primary source of information. And since those trained in the passive haptics VE performed better than those trained without passive haptics, it stands to reason that their cognitive maps were better too. One possible explanation for the sketch maps not supporting the hypothesis is that nearly all of the sketch maps from both groups scored three or four out of five. The environment may not have been complicated enough for participants to produce differences in sketch map performance. When participants were asked to mark the heights of objects, a few got confused as to which object was which color. This could have masked out any potential significant results. Also participants were not specifically instructed to remember the heights of objects, only to learn as much as possible about the environment.

The interobject distance estimation was significantly different between the passive-haptics and no-passive-haptics groups. Those trained with passive haptics on average overestimated the distance between objects (6.7%) and those trained without passive haptics on average underestimated the distance (-8.8%). However, neither was significantly different from the actual distance. These percentages are within the range of values found in the Waller (1998) study, though larger than the averages he found in his immersive condition. This could be caused by participants not directly being told that they would be asked the distances between objects before the VE session. In the Waller study, there were only two objects in the environment and the participants were only asked the distances between them.

In this study, no significant difference in presence between the passive-haptics and no-passive-haptics groups was found. There was no hypothesis about presence in this study and

there was no effort to prevent breaks in presence by not talking to the subjects. Another possible reason for no significant differences being found is that the environment does not evoke a large enough range of presence for us to find results. The virtual room was boring; it contained nothing such as a virtual pit that would grab the participant's attention. Moreover, the Witmer and Singer Presence Questionnaire is a general-purpose questionnaire and may not be specific enough to detect differences in this study.

No results were expected or found to show that passive haptics had any effect on reported simulator sickness. Overall simulator sickness was slightly higher in this experiment than in the presence experiment, Figure 3-15. The HiBall tracker used in this experiment has been observed to have slightly more noise in its readings than the tracker used in the presence experiment, though no formal testing has been performed. More noise in the head-tracking leads to more jitter in the views displayed to the participant, which could cause more simulator sickness.

Chapter 4

Previous Work, Costs, and Future Work

The studies reported here show that augmenting virtual environments with passive haptics increases presence in a stress-inducing environment, and increases spatial knowledge transfer. How do the methods and results in these studies relate to previous work done in the field? What are the costs of augmenting virtual environments with passive haptics? What don't we know about such a use of passive haptics?

4.1 Relation of Current Studies to Previous Work

This work builds upon several previous studies. This section details how the methods in the current studies were drawn from prior work, and relates the current findings to previous results.

4.1.1 Methods

The first study examined increasing a participant's sense of presence in a virtual pit environment using passive haptics. The visual environment used in this study was derived from Slater (1995) and most recently Usoh (1999). The Usoh study showed that in this environment, presence increased as the method of locomotion was changed from (1) flying by pushing a joystick button, (2) to walking in place, (3) to really walking around a physical area. In the present study, we augmented the real-walking space to include physical objects in the locations of some of the virtual objects.

The more a person feels present in a virtual environment, the more he will react both behaviorally and physiologically as if the environment is real. Several papers have recommended using external behaviors as a measure of presence (Barfield et al., 1995). One reaction of interest is reflexive response (Held & Durlach, 1987; Loomis, 1992). If a virtual

object is thrown at a person, does he duck? It would seem the more present a person feels in the virtual environment the more likely it is that he will subconsciously respond to such stimuli. A case often cited in UNC Chapel Hill Computer Science department occurred when a professor was viewing a virtual kitchen in an HMD. He bent over to look along the top of a virtual counter and remarked that no one would ever be convinced that it was real. He then proceeded to reach out to use the virtual counter to balance himself as he came up, a reflexive response.

The complete measure of behavioral presence used in the Usoh (1999) study not only asked participants about their behaviors while in the virtual environment, but also included a component that recorded whether or not the participant took a path to the chair that led over the virtual pit. The premise was if a participant took a path directly over the pit, he is not convinced that the pit is real and therefore is less present than a person who avoids the pit. For the current study, a list of common behaviors associated with pit avoidance was constructed from behaviors exhibited by participants in demonstrations of the system and pilot studies of the current experiment, Appendix A.7.

Participants may also exhibit physiological reactions to stimuli in the virtual environment. In the present study, a stress-inducing virtual environment was used. When exposed to fear-inducing stimuli, the body undergoes physiological changes. Breathing, sweating, and heart rate increase, while the skin temperature decreases as the body concentrates heat in its core (Schwartz, 1995). The current study's use of measures of these reactions is taken from Weiderhold et al. (1998). That study examined the use of virtual reality in the treatment of the fear of flying. Physiological measures used in the Wiederhold study include: skin resistance – which changes in relation to change in sweat gland activity (as sweat gland activity increases, skin resistance decreases), heart rate – measured by an electrocardiograph, peripheral skin temperature – measured with a thermistor, and respiration rate – measured with a pneumograph. Participants included one with a phobia of flying. Participants were exposed to the virtual flight simulator using a desktop monitor for one session and an HMD for the other. It was predicted that the more immersive condition, the HMD, would yield more presence and thus more physical arousal. Skin resistance was shown to be the most

responsive measure, changing significantly from the baseline, for all participants while heart rate, skin temperature and respiration did not significantly change during the VR exposure. The phobic demonstrated greater change in skin conductivity than the non-phobics.

The most common method for assessing the participant's sense of presence is the post-session questionnaire. Most presence studies have used custom questionnaires developed specifically for the virtual environment and hardware used (Dinh et al., 1999; Hendrix & Barfield, 1996). The Witmer and Singer Presence Questionnaire was an attempt at creating a common questionnaire (Witmer & Singer, 1993); it was used in the spatial knowledge transfer study. This questionnaire attempts to measure presence by examining factors thought to underlie a person's sense of presence.

These factors are grouped into four categories: Control Factors, Sensory Factors, Distraction Factors, and Realism Factors. The control factors examined included the ability to control the relation of sensors to the environment, the speed at which the system reacts to changes caused by the user, the amount to which a user can anticipate what can happen next in the environment, the "naturalness" of control over the environment, and the ability to modify the physical environment. Sensory factors examine the amounts, coherence, and consistency of information arriving from different senses, the ability to perceive self-movement through the environment and the ability to search the environment actively. Distraction Factors measure the possible distractions a person may experience in a virtual environment, such as awareness of the real environment, devices used to transmit the virtual environment to the user, and the observer's willingness to focus on the VE stimuli presented. Realism factors measure factors such as environment realism and meaningfulness, as well as disorientation when returning to the real world.

It is important to note that this questionnaire reports the user's perception of these factors. For example, one question asks, "How much were you able to control events?" The problem is that two people may have different responses in the same environment although the system control parameters are the same (Slater (1999) argues strongly that this questionnaire measures the user's perception of system properties, rather than psychological presence).

The Witmer and Singer Presence Questionnaire was used in the Training Transfer study. For the presence study, the UCL Presence Questionnaire, developed over a number of studies involving the visual pit (Slater et al., 1995; Usoh et al., 1999), was used.

The Acrophobia Questionnaire (Cohen, 1977) was used to control for the differences between participants' reactions to the virtual pit environment. Previous work in acrophobia desensitization using virtual reality at the Georgia Institute of Technology has used this questionnaire to gauge participants' fear of heights (Hodges et al., 1995; Rothbaum et al., 1995). These studies took participants on virtual elevator rides or on walks across high, narrow bridges to desensitize them to situations involving heights. This questionnaire showed that participants' self-reported anxiety over fear of heights decreased after VR desensitization.

I also studied the use of passive haptics in virtual environments to increase spatial knowledge transfer to the real world. The current study was modeled after Waller (1998) and used a similar maze-like environment. Waller et al. (1998) compared the spatial knowledge training transfer from six different training methods: no training, real world training, training with a map, VE training using a desktop, VE training using an HMD for two minutes, and VE training using an HMD for five minutes. 125 students participated in the experiment at the University of Washington. The environment was a maze, the virtual environment had red arrows indicating the correct path. VE movement was accomplished with a joystick. Those participants training in the real world and with a map were given a one-minute exposure, whereas the short VE session was two minutes. The Guilford-Zimmerman spatial orientation test (discussed in Chapter 3) was administered to all participants before the VE session. The Waller study utilized blindfolded navigation in a real environment as the testing method and the time to complete the maze and the number of collisions with maze walls as the measures of spatial knowledge transfer.

For testing, Waller's participants were blindfolded and instructed to navigate a real-world maze constructed from seven-foot tall curtains. The participants' time to complete the maze, and the number of collisions with the maze were recorded. Each participant completed six

trials; each trial consisted of a training session and testing session. After the first trial, participants trained in the real world performed better than those trained with a map. Those in turn performed better than either group trained in the VE, although not significantly better. By the sixth trial, the real world training group and the five-minute-VE-trained group performed significantly better than the two-minute-VE-trained group and the desktop-trained group.

In order for spatial knowledge transfer to occur, participants must develop a cognitive map of the virtual environment. Cognitive mapping is defined by Downs and Stea (1973) as:

"a process composed of a series of psychological transformations by which an individual acquires, codes, stores, recalls and decodes information about the relative locations and attributes of phenomena in their everyday spatial environment."

Furthermore,

"An individual's cognitive map is an active information-seeking structure of which spatial imagery is but one aspect. Cognitive maps are also made up of memories of objects and kinesthetic, visual and auditory cues (Billingshurst & Weghorst, 1995)."

Cognitive maps answer the questions: Where is that? How do I get there from here? A person's ability to move through an environment is dependent on the accuracy and completeness of his cognitive map of the environment.

Cognitive maps are created from information provided by an individual's senses, from maps or other symbolic representations, and from ideas about the environment inferred from experiences in other similar spatial locations (Briggs et al., 1973). Golledge (1976) discusses four distinct categories of methods for extracting cognitive map information from subjects: experimenter observation of subject behavior, historical reconstruction, analysis of external representations (such as drawings), and indirect judgment tasks.

I chose methods from two of these categories, external representation via sketch maps of the environment, and indirect judgment through estimating the heights and interobject distances in the environment. Billinghamurst and Weghorst (1995) studied the use of sketch maps to measure participants' cognitive maps of the virtual environment. This study, conducted at the University of Washington, included 84 participants. Three different virtual environments were used, each containing a different density of objects: Virtual Valley was a dense world with objects placed in a logical manner; Cloudland was sparse, with a ground plane and unrelated objects clustered above in cloud groups; Neighborhood was a cluttered world containing clusters of nearly indistinguishable buildings and other related objects. The sketch maps were analyzed on a 3-point goodness scale by two researchers blind to subject identity. The maps were ranked on their usefulness as navigational tools. The maps were also scored for completeness by assessing the number of different types of objects included on the map. Two object-positioning scores were also used, one in which all objects were scored by comparing their reported location to the actual location in the VE, and one which scored the five most commonly drawn objects for each world. These scores from the sketch map were then correlated with participant's self-reported knowledge of world orientation, and where things are in the world. For the two dense environments, map goodness significantly correlated with the participants' reported sense of orientation in the virtual environment. Map goodness also significantly correlated with participants' knowledge of where everything is.

Interobject distances have been used as a spatial knowledge metric in other VR studies (Waller 1999). In the present study, after the VE session, participants were instructed to draw a horizontal line at the height of each object, as they remembered them, on a sheet of paper mounted on a wall. I hypothesized that more accurate estimates of height would be gained from muscle memory after physically touching the tops of the objects (Brooks, 1999).

I administered the Guilford-Zimmerman Spatial Orientation test to participants as a method of factoring out individual differences in spatial orientation ability. Prior studies have used this test in the same manner (Satalich 1995; Waller 1998).

4.1.2 Results

Results from the current studies agree with a growing literature showing the value of adding passive haptic feedback to objects in immersive virtual environments. Hunter Hoffman (1998) studied the impact of physically touching a virtual object on how realistic the VE seems to the user. The virtual objects were modeled based on real objects such as a dinner plate and a butter knife. The real object, a kitchen plate, was tracked such that it moved with its virtual counterpart. Users who placed the real plate on the real table would see the virtual plate rest on the virtual countertop. Nineteen participants were split into two groups, the "see only" group who would only experience the virtual environment, and the "see and touch" group who would see the VE and touch the real dinner plate. During the VR session, participants would pick up the dinner plate, either virtually with a joystick, or using the hand on the real plate.

After the VR session, participants were asked to make predictions about the solidity and weight of virtual objects in the environment that they had not touched. They used scales from one (only visual, no solidity / weight) to seven (as solid / heavy as real object). Statistical analysis revealed a significant difference between the two conditions, with the "see and touch" group predicting more solidity and weight for the objects in the environment that they had not touched.

Hinckley et al. (1994) at the University of Virginia studied the use of handheld props as a human-computer interface device for specifying spatial relations in neurosurgical planning. Magnetic Resonance Imaging (MRI) data of the patient's head provided a 3D volume of information. The two tracked props, a doll's head and a Plexiglas rectangle, were used to assist surgeons in visualizing this data. The plane was used to represent a 2D cutting plane through a patient's head. The surgeon could position the plane in relation to the doll's head to indicate the 2D slice of information he wanted displayed on the monitor.

Hinckley's informal study found that neurosurgeons were quickly able to pick up the props and use them with little instruction. People are familiar with picking up objects and holding them in different relations to one another. The props provided real-world feedback to the

user on the position of the head and cutting plane as well as a natural method of rotating and orienting the props. Although this study did not use a virtual environment, it did show the benefits of using props as a human-computer interaction device for specifying spatial relations.

Lindeman (1999) studied the use of a tracked, handheld paddle as a user interface prop in an immersive virtual environment. This paddle held in one hand corresponded to a 2D window which contained user interface widgets. The user would use the tracked index finger of his other hand to point, click or draw objects on the 2D window. Two tasks were examined, a docking task where the user slid a 2D shape into the outline of that shape, and a shape-selection task where a 2D shape was shown in the virtual environment and the user selected the corresponding shape on the paddle. Participants performed significantly faster in both tasks when using a real paddle which augmented the virtual paddle rather than using the virtual paddle alone. For the docking tasks, participants were also significantly more accurate in the placement of the shape when using the real paddle in the VE.

The Hinckley and Lindeman studies described above both showed benefits in using handheld passive-haptic devices as aids to user interfaces. Dinh et al. (1999) at the Georgia Institute of Technology examined the effects of haptic cues on spatial memory in virtual environments. The hypothesis was that increasing the number of sensory modalities in a virtual environment would increase sense of presence, spatial layout recall, and object location recall. 322 students participated in the experiment. The environment was a seven-room office building. Various sensory cues were provided: coffee smells, sounds of a toilet flushing and haptic cues from a heat lamp representing sunlight and a blowing fan. This study also compared a high-fidelity visual environment, which used local light sources and high-resolution textures, and a low-fidelity visual environment, which used ambient-only lighting and reduced the resolution of the high-resolution textures to 25% of their original. This study examined the effects of these cues on presence, spatial layout recall, and object location recall.

Results showed significant increases in presence with the addition of haptic and auditory cues. Object location recall also increased with haptic and olfactory cues. Spatial layout

recall was not significantly effected by any cues. They found no significant differences between the visual quality levels on any measure. Participants were teleported between two places in each room, though head-controlled movements were allowed. All haptic cues were exterosensory, in other words, participants did not come into direct contact with the haptic stimulus. The current study addresses the sensory inconsistency that arises when users come into direct contact with a virtual object; they should physically feel something.

4.2 Costs

Although one would expect passive haptics augmentation of a virtual environment to be costly, we have not found it so, and this has surprised us. Making low-fidelity physical models is often much less effort than making the corresponding high-fidelity visual models.

The first augmented model constructed was a kitchen with six counter-cabinets. Cutting and assembling the styrofoam blocks and particle-board countertops took only 25 person-hours. The visual model took far longer. Informal observations and subject self-reports indicate that passive haptics augmentation radically enhanced presence.

We do not have effort data for making the plywood ledge for the Pit Room. Our impression is that it took more effort than making the visual model of the ledge, but far less than making the whole visual model of the VE. Because the ledge had to be much sturdier to be safe to walk on, it was made from a less tractable material, wood, which increased the effort and time involved in construction. However, more time and effort went into the construction of the entire computer model of the virtual pit environment than the construction of the corresponding physical model.

For the navigation training experiment, the passive haptics model took only seven person hours, versus about 20 for the very simple visual model. However, it should be noted that this virtual environment was designed around the physical materials at hand.

4.3 Future Work

4.3.1 Registration of the Passive Haptics Model

The present studies registered the passive haptics model to within half an inch of the virtual model. But how close must the haptics model be registered with the virtual model to prevent degradation of the virtual experience? Based on the work done while fine-tuning these studies, I believe that if the haptics model is uniformly misregistered, then participants could become accustomed to the disparity and perhaps tolerate misregistration of two to three inches in a task and environment similar to those used in these studies. There were as many as 13 coordinate system transforms used to draw the virtual objects and the user's avatar in the right places. Each of the transforms used in the VR system contains deviations from the actual transforms arising from sources such as the HMD and tracking gloves fitting each user differently and differences in each user's interpupillary distance. Techniques for isolating and reducing these deviations should be investigated.

4.3.2 Passive Haptics with lower visual quality VEs

In the current studies, a high quality visual virtual environment system was used. If a VR designer had a low-quality visual environment and some small extra resources, would it be better to invest those resources in higher quality visuals, or in adding passive haptics? I believe that augmenting a low quality visual virtual environment with passive haptics would show similar effects to the current studies' findings. I believe these effects would be more than those found when moving from low-quality visuals to high quality visuals. It would be interesting to investigate this trade-off.

4.3.3 Passive Haptics + Virtual Environment versus Real Environment

The training transfer study compared the transfer of spatial knowledge from virtual environments with and without passive haptics to blindfolded navigation in an identical real environment. An extension of this study would train some participants in the real environment and then test them blindfolded in that environment as before. I would expect better spatial knowledge transfer in real world training than in the virtual environment or virtual environment plus passive haptics cases, as was shown in Waller et al. (1998). That study showed participants trained in the real world performed better in a blindfolded navigation task than those trained in a virtual world (through desktop or HMD). It would be

exciting to find that the augmented VE approached the real world in training effectiveness. It would also be valuable to run the presence study in a real pit environment, with a safety harness, to get a baseline of human responses with which to compare our findings in the virtual environment.

4.3.4 Task Performance

I have so far studied effects on presence, cognitive map formation, and spatial knowledge training transfer, but not task performance. Can passive haptics enhance task performance, such as design, design validation, and design modification, in a virtual environment?

4.3.5 Training for hazardous work

Augmenting virtual environments with passive haptics could prove beneficial in training for low-visibility real world situations such as nighttime hostage rescue or fighting fires. These situations are analogous to the blindfolded testing conducted in the training transfer study.

Although passive haptics is not appropriate for all virtual environments, the low added costs combined with demonstrated presence and training transfer increase suggest that passive haptics be used as a practical technique for enhancing the effectiveness of VEs.

Appendix A

Documents – Presence Study

A.1 Consent form

Effects of Static Haptics on Presence in Virtual Environments

Introduction and purpose of the study:

We are inviting you to participate in a study of effect in virtual environment (VE) systems. The purpose of this research is to measure how presence in (or believability of) VEs changes with the addition of static haptics. We hope to learn things that will help VE researchers and practitioners using VEs to treat people.

The principle investigators are Michael Meehan and Brent Insko (UNC Chapel Hill, Department of Computer Science, 039 Sitterson Hall, 962-1979, email: meehan@cs.unc.edu, UNC Chapel Hill, Department of Computer Science, 386 Sitterson Hall, 962-1850, email: insko@cs.unc.edu). The Faculty advisor is Dr. Fredrick Brooks, Jr. (UNC Chapel Hill, Department of Computer Science, 216 Sitterson Hall, 962-1931, email: brooks@cs.unc.edu).

What will happen during the study:

We will ask you to come to the laboratory for two sessions, each on a different day, with each session lasting approximately one hour. During the sessions, you will perform a few simple tasks within the VE. You will also be given questionnaires asking about your perceptions and feelings during and after the VE experience. Approximately 10 people will take part in this study. We will use computers to record your hand, head, and body motion during the VE experience. We will use a finger sensors to record heart rate and other physiological measures. We will also make video and audio recordings of the sessions.

Protecting your privacy:

We will make every effort to protect your privacy. We will not use your name in any of the data recording or in any research reports. We will use a code number rather than your name. No images from the videotapes in which you are personally recognizable will be used in any presentation of the results.

Risks and discomforts:

While using the virtual environment systems, some people experience slight symptoms of disorientation, nausea, or dizziness. These can be similar to "motion sickness" or to feelings experienced in wide-screen movies and theme park rides. We do not expect these effects to be strong or to last after you leave the laboratory. If at any time during the study you feel uncomfortable and wish to stop the experiment you are free to do so.

Your rights:

You have the right to decide whether or not to participate in this study, and to withdraw from the study at any time without penalty. We will pay you \$6 per hour you spend participating in the study.

Institutional Review Board approval:

The Academic Affairs Institutional Review Board (AA-IRB) of the University of North Carolina at Chapel Hill has approved this study. If you have any concerns about your rights in this study you may contact the Chair of the AA-IRB, David A. Eckerman, at CB#4100, 201 Bynum Hall, UNC-CH, Chapel Hill, NC 27599-4100, (919) 962-7761, or email: aa-irb@unc.edu.

Summary:

I understand that this is a research study to measure the change in presence (or believability) over subsequent exposures to a virtual environment.

I understand that if I agree to be in this study:

- I will visit the laboratory two times for sessions lasting approximately one hour.
- I will wear a virtual environment headset to perform tasks, and my movements, physiological signals (via sensors on my fingers), and behavior will be recorded by computer and on videotape, and I will respond to questionnaires between and after the sessions.
- I may experience slight feelings of disorientation, nausea, or dizziness during or shortly after the VE experiences.

I certify that I am at least 18 years of age.

I have had a chance to ask any questions I have about this study and those questions have been answered for me.

I have read the information in this consent form, and I agree to be in the study. I understand that I will get a copy of this consent form after I sign it.

Signature of Participant

Date

A.2 Participant information sheet

Effect of Static Haptics on Presence in Virtual Environments

Participant Instructions

As a participant in the study "Effect of Static Haptics on Presence in Virtual Environments" you will do several things. This document describes what you will be doing and gives you instructions. The investigators will elaborate on the instructions and answer any questions you have.

Part I: Preliminaries (Conference Room)

1. We will ask you again if you meet all the qualifications to be a participant in this study.
2. We will explain the entire experiment to you by going through these instructions and answering any questions that you have.
3. We will show you the equipment we will use, the head-mounted display (HMD) and a hand-held joystick and answer any questions you have about them.
4. We will give you a consent form that describes aspects of the study not included in these instructions. You'll read this form and be asked if you have any more questions about the study.
5. After all your questions are answered, we will ask you if you are willing to sign the form agreeing to be a participant in this experiment.

Once you have signed the consent form, you are officially a participant in this experiment and you are entitled to payment.

Part II: First Questionnaire Session

The two questionnaires you'll fill out at the beginning of each session investigate symptoms of illness sometimes induced by virtual environment (VE) systems. The first is a very short questionnaire asking about the general state of your health. The second asks how you feel in 17 different categories, e.g. dizziness. Please answer the questions thoughtfully; your answers are a key element in making our study produce meaningful and useful results.

When you've finished the questionnaires, we will again review the instructions for the VE part of the experiment, and we'll move into the laboratory.

Part III: The VE Session

A. Training

1. You will wear a VE headset and hold a joystick during your VE session. We will show you how to use the joystick and its buttons. You will need to try to hold the joystick somewhat vertically so that the tracker will work properly.
2. We'll put you in the HMD and adjust it so that it fits snugly and comfortably.
3. When you put the HMD on, you'll find yourself in a virtual room with several pieces of furniture, some boxes on chairs, and a closed door in one wall. There is another room through the door that we'll use later in the experiment.
4. We'll help you adjust the HMD so that you can see the images properly and in stereo. We'll hand you the joystick. We'll start a timer each time you put the HMD on, and, even if you have not finished the experiment, we will stop the session after 15 minutes. You can ask to discontinue to experiment at any time.
5. You, represented by a model of a person, are part of the virtual environment. We'll ask you if you can see feet and an arm and hand. The entire virtual environment you will visit fits inside the open

- space of the laboratory we will be in. You won't be able to see the real laboratory once you put the HMD on, so one of the investigators will stay near you all the times to be sure that you don't trip on or bump into anything.
6. Next we will train you in how to move in the virtual environment. Your walking in the virtual environment exactly corresponds to your walking within the real environment. When you take a step in the real world, you move the length of that step in the virtual environment. When you stop walking, your virtual body in the virtual environment also stops walking.
 7. Now we will train you how to pick up, carry, and put down objects. You pick up objects by moving your hand near (or into) them and pushing the button on the joystick. (We showed you the button earlier before you had the helmet on.) As long as you hold the button down, you will continue "holding" the object in your hand. When you release the button, the object will fall.
 8. You can stay in the training room until you're comfortable moving around in the virtual environment and you are comfortable picking up and putting down objects. Take as long as you need, up to the maximum session length of 15 minutes.
 9. After we start the experiment we will try not to interact with you at all; we will tug on your cables, speak to you, or touch you gently on the shoulder *only* if we must help you stay in the proper part of our laboratory.

B. Task in the virtual environment

1. Your task in the virtual environment is to pick up the box from the chair in the room you are in, carry it through the virtual door and put it on the virtual chair on the far side of the new virtual room.
2. When you've put the box on the chair, you're done. We will ask you to return to the first room where we will take the joystick from you and help you take the HMD off.
3. After completing the task, you will be asked to fill out one short questionnaire.
4. You will repeat the task 4 times.
5. After the 4 tasks, we will return to the conference room to do the post-experience questionnaires and debrief.

Part IV: Second Questionnaire Session

You'll fill out two questionnaires after the VR session. Please answer the questions thoughtfully; your answers are a key element in making our study produce meaningful and useful results.

1. We'll ask you to fill out the questionnaire asking about how you are feeling again.
2. We'll ask you to fill out a somewhat longer questionnaire asking other questions about the VE experience.

Part V: Debrief session

When you've finished the questionnaires, the investigator will ask you if you have any other comments about the experience or questions that you'd like to ask.

A.3 Pre-session health questionnaire

This questionnaire was administered using an HTML form. Below is a reproduction of the information on that form.

Participant Health Information

Subject ID: _____

1. Are you in your usual state of good fitness (health)?

Yes

No (please explain)

2. In the past 24 hours which, if any, of the following substances have you used?
(Check all that apply)

None

Sedatives or Tranquilizers

Decongestants

Anti-histamines

Alcohol (three drinks or more)

Other (please explain)

A.4 Simulator Sickness Questionnaire

This questionnaire was administered using an HTML or paper form. Below is a reproduction of the information on that form.

Simulator Sickness Questionnaire

For each of the following conditions, please indicate how you are feeling *right now*, on the scale of “none” through “severe”.

1. General discomfort	None	Slight	Moderate	Severe
2. Fatigue	None	Slight	Moderate	Severe
3. Headache	None	Slight	Moderate	Severe
4. Eye Strain	None	Slight	Moderate	Severe
5. Difficulty Focusing	None	Slight	Moderate	Severe
6. Increased Salivation	None	Slight	Moderate	Severe
7. Sweating	None	Slight	Moderate	Severe
8. Nausea	None	Slight	Moderate	Severe
9. Difficulty Concentrating	None	Slight	Moderate	Severe
10. Fullness of Head	None	Slight	Moderate	Severe
11. Blurred Vision	None	Slight	Moderate	Severe
12. Dizzy (Eyes Open)	None	Slight	Moderate	Severe
13. Dizzy (Eyes Closed)	None	Slight	Moderate	Severe
14. Vertigo	None	Slight	Moderate	Severe
15. Stomach Awareness	None	Slight	Moderate	Severe
16. Burping	None	Slight	Moderate	Severe

The following information was available through a hypertext link or separate sheet:

Explanation of Conditions

General Discomfort	
Fatigue	weariness or exhaustion of the body
Headache	
Eye Strain	weariness or soreness of the eyes
Difficulty Focusing	
Increased Salivation	
Sweating	
Nausea	stomach distress
Difficulty Concentrating	
Fullness of Head	
Blurred Vision	
Dizzy (with your eyes open)	
Dizzy (with your eyes closed)	
Vertigo	surroundings seem to swirl
Stomach Awareness	a feeling just short of nausea
Burping	

Scoring

For each question, a score of 0 (none), 1 (slight), 2 (moderate), or 3 (severe) is assigned. The scores are then combined as follows (Kennedy et al., 1993). (See also Table 5-1.)

COLUMN 1 = SUM (1, 6, 7, 8, 9, 15, 16)

COLUMN 2 = SUM (1, 2, 3, 4, 5, 9, 11)

COLUMN 3 = SUM (5, 8, 10, 11, 12, 13, 14)

NAUSEA = COLUMN 1 \times 9.54

OCULOMOTOR DISCOMFORT = COLUMN 2 \times 7.58

DISORIENTATION = COLUMN 3 \times 13.92

TOTAL SEVERITY = (COLUMN 1 + COLUMN 2 + COLUMN 3) \times 3.74

A.5 Acrophobia Questionnaire

Height Questionnaire - Anxiety

Below we have compiled a list of situations involving height. We are interested to know how anxious (tense, uncomfortable) you would feel in each situation nowadays. Please indicate how you would feel by choosing one of the following numbers (0, 1, 2, 3, 4, 5, 6) in the space to the left of each item:

- 0 Not at all anxious; calm and relaxed
- 1
- 2 Slightly anxious
- 3
- 4 Moderately anxious
- 5
- 6 Extremely anxious

1. Diving off the low board at a swimming pool.

(Not at all anxious) 0 1 2 3 4 5 6 (Extremely Anxious)

2. Stepping over rocks crossing a stream.

(Not at all anxious) 0 1 2 3 4 5 6 (Extremely Anxious)

3. Looking down a circular stairway from several flights up.

(Not at all anxious) 0 1 2 3 4 5 6 (Extremely Anxious)

4. Standing on a ladder leaning against a house, second story.

(Not at all anxious) 0 1 2 3 4 5 6 (Extremely Anxious)

5. Sitting in the front of an upper balcony of a theater.

(Not at all anxious) 0 1 2 3 4 5 6 (Extremely Anxious)

6. Riding a ferris wheel.

(Not at all anxious) 0 1 2 3 4 5 6 (Extremely Anxious)

7. Walking up a steep incline in country hiking.

(Not at all anxious) 0 1 2 3 4 5 6 (Extremely Anxious)

8. Airplane trip (to San Fransisco).

(Not at all anxious) 0 1 2 3 4 5 6 (Extremely Anxious)

9. Standing next to an open window on the third floor.

(Not at all anxious) 0 1 2 3 4 5 6 (Extremely Anxious)

10. Walking on a footbridge over a highway.

(Not at all anxious) 0 1 2 3 4 5 6 (Extremely Anxious)

11. Driving over a large bridge (Golden Gate, George Washington).

(Not at all anxious) 0 1 2 3 4 5 6 (Extremely Anxious)

12. Being away from window in an office on the 15th floor of a building.

(Not at all anxious) 0 1 2 3 4 5 6 (Extremely Anxious)

13. Seeing window washers 10 flights up on a scaffold.
(Not at all anxious) 0 1 2 3 4 5 6 (Extremely Anxious)
14. Walking over a sidewalk grating.
(Not at all anxious) 0 1 2 3 4 5 6 (Extremely Anxious)
15. Standing on the edge of a subway platform.
(Not at all anxious) 0 1 2 3 4 5 6 (Extremely Anxious)
16. Climbing a fire escape to the 3rd floor landing.
(Not at all anxious) 0 1 2 3 4 5 6 (Extremely Anxious)
17. On the roof of a 10 story apartment building.
(Not at all anxious) 0 1 2 3 4 5 6 (Extremely Anxious)
18. Riding the elevator to the 50th floor.
(Not at all anxious) 0 1 2 3 4 5 6 (Extremely Anxious)
19. Standing on a chair to get something off a shelf.
(Not at all anxious) 0 1 2 3 4 5 6 (Extremely Anxious)
20. Walking up the gangplank of an ocean liner.
(Not at all anxious) 0 1 2 3 4 5 6 (Extremely Anxious)

Height Questionnaire - Avoidance

Now that you have rated each item according to anxiety, we would like you to rate them as to avoidance. Indicate in the space to the left of the items below how much you now avoid the situation, if it arose.

- 0 Would not avoid doing it
- 1 Would try to avoid doing it
- 2 Would not do it under any circumstances

1. Diving off the low board at a swimming pool.
(Would not avoid it) 0 1 2 (Would not do it under any circumstances)
2. Stepping over rocks crossing a stream.
(Would not avoid it) 0 1 2 (Would not do it under any circumstances)
3. Looking down a circular stairway from several flights up.
(Would not avoid it) 0 1 2 (Would not do it under any circumstances)
4. Standing on a ladder leaning against a house, second story.
(Would not avoid it) 0 1 2 (Would not do it under any circumstances)
5. Sitting in the front of an upper balcony of a theater.
(Would not avoid it) 0 1 2 (Would not do it under any circumstances)
6. Riding a ferris wheel.
(Would not avoid it) 0 1 2 (Would not do it under any circumstances)
7. Walking up a steep incline in country hiking.
(Would not avoid it) 0 1 2 (Would not do it under any circumstances)

8. Airplane trip (to San Fransisco).
(Would not avoid it) 0 1 2 (Would not do it under any circumstances)
9. Standing next to an open window on the third floor.
(Would not avoid it) 0 1 2 (Would not do it under any circumstances)
10. Walking on a footbridge over a highway.
(Would not avoid it) 0 1 2 (Would not do it under any circumstances)
11. Driving over a large bridge (Golden Gate, George Washington).
(Would not avoid it) 0 1 2 (Would not do it under any circumstances)
12. Being away from window in an office on the 15th floor of a building.
(Would not avoid it) 0 1 2 (Would not do it under any circumstances)
13. Seeing window washers 10 flights up on a scaffold.
(Would not avoid it) 0 1 2 (Would not do it under any circumstances)
14. Walking over a sidewalk grating.
(Would not avoid it) 0 1 2 (Would not do it under any circumstances)
15. Standing on the edge of a subway platform.
(Would not avoid it) 0 1 2 (Would not do it under any circumstances)
16. Climbing a fire escape to the 3rd floor landing.
(Would not avoid it) 0 1 2 (Would not do it under any circumstances)
17. On the roof of a 10 story apartment building.
(Would not avoid it) 0 1 2 (Would not do it under any circumstances)
18. Riding the elevator to the 50th floor.
(Would not avoid it) 0 1 2 (Would not do it under any circumstances)
19. Standing on a chair to get something off a shelf.
(Would not avoid it) 0 1 2 (Would not do it under any circumstances)
20. Walking up the gangplank of an ocean liner.
(Would not avoid it) 0 1 2 (Would not do it under any circumstances)

Scoring

The Anxiety and Avoidance scores are calculated simply by adding together the values entered by the participant. The Anxiety score ranges from 0 to 120, the Avoidance score ranges from 0 to 40.

A.6 UCL Presence questionnaire

Questionnaire

The following questions relate to your experience...

1. Please rate the extent to which you were aware of background sounds in the real laboratory in which this experience was actually taking place. Rate this on the scale from 1 to 7 (where for example 1 means that you were hardly aware at all of the background sounds):

While in the virtual reality I was aware of background sounds from the laboratory:

(Not at all) 1 2 3 4 5 6 7 (Very much)

2. Please rate your sense of being in the room that has the window on the following scale from 1 to 7, where 7 represents your normal experience of being in a place.

I had a sense of being in the room containing the counters and the radio:

(Not at all) 1 2 3 4 5 6 7 (Very much)

3. Gender, Age, and Race/ Ethnicity:

Male _____
 Female _____
 Age _____

Race/ Ethnicity:

American Indian or Alaskan Native _____
 Asian or Pacific Islander _____
 Black, not of Hispanic Origin _____
 Hispanic _____
 White, not of Hispanic Origin _____
 Other _____

4. Did you find it relatively simple or relatively complicated to move through the computer generated world?

To move through the computer generated world was...

(Very complicated) 1 2 3 4 5 6 7 (Very simple)

5. To what extent were there times during the experience when the virtual rooms you were in became the "reality" for you, and you almost forgot about the "real world" of the laboratory in which the whole experience was really taking place?

There were times during the experience when the virtual rooms became more real for me compared to the "real world"...

(At no time) 1 2 3 4 5 6 7 (Almost all of the time)

6. How difficult or straightforward was it for you to get from place to place?

To get from place to place was...

(Very difficult) 1 2 3 4 5 6 7 (Very straightforward)

7. To what extent did you associate with the computer generated limbs and body as being "your body" while in the virtual reality?

I associated with the computer generated body...

(Not at all) 1 2 3 4 5 6 7 (Very much)

8. To what extent was your reaction when looking down into the pit in the virtual reality the same as it would have been in a similar situation in real life?

Compared to real life my reaction was...

(Not at all similar) 1 2 3 4 5 6 7 (Very similar)

9. The act of moving from place to place in the computer generated world can seem to be relatively natural or relatively unnatural. Please rate your experience of this.

The act of moving from place to place seemed to be...

(Very unnatural) 1 2 3 4 5 6 7 (Very natural)

10. Please rate any sense of fear of falling you experienced when looking down over the virtual precipice.

The sense of fear of falling I experienced was...

(Not at all) 1 2 3 4 5 6 7 (Very much)

11. What is your University status?

My status is as follows:

Undergraduate student	_____
Graduate student	_____
Research Associate	_____
Staff member - systems/technical staff	_____
Faculty	_____
Administrative staff	_____
Other (please write in)...	_____

12. When you think back to your experience, do you think of the virtual rooms more as images that you saw, or more as somewhere that you visited?

The virtual rooms seem to me to be more like...

(Images that I saw) 1 2 3 4 5 6 7 (Somewhere that I visited)

13. Have you experienced virtual reality before?

I have experienced virtual reality...

(Never before) 1 2 3 4 5 6 7 (A great deal)

14. During the time of the experience, which was stronger on the whole, your sense of being in the virtual rooms, or of being in the real world of the laboratory?

I had a stronger sense of being in...

**(The real world
of the laboratory) 1 2 3 4 5 6 7 (The virtual world)**

15. Consider your memory of being in the virtual rooms. How similar in terms of the structure of the memory is this to the structure of the memory of other places you have been today? By "structure of the memory" consider things like the extent to which you have a visual memory of the virtual rooms, whether that memory is in color, the extent to which the memory seems vivid or realistic, its size, location in your imagination, the extent to which it is panoramic in your imagination, and other such structural elements.

I think of the virtual rooms as a place in a way similar to other places that I've been today...

(Not at all) 1 2 3 4 5 6 7 (Very much)

16. To what extent do you use a computer in your daily activities?

I use a computer...

(Not at all) 1 2 3 4 5 6 7 (Very much)

17. Please rate your sense of being in the room with the pit on the following scale from 1 to 7, where 7 represents your normal experience of being in a place.

I had a sense of being in the room with the pit:

(Not at all) 1 2 3 4 5 6 7 (Very much)

18. During the time of the experience, did you often think to yourself that you were actually just standing in a laboratory wearing a helmet or really in the virtual rooms?

During the experience I often thought that I was really standing in the lab wearing a helmet...

**(Most of the
time I realized I
was in the lab) 1 2 3 4 5 6 7 (Never because I believed
I was in the virtual
environment)**

20. To what extent do you play computer games?

I play computer games...

(Not at all) 1 2 3 4 5 6 7 (Very much)

21. How many hour per week do you exercise?

During an average week, I exercise...

Less than 0.5 hours

0.5 hours

1 hour

1.5 hours

2 hours

2.5 hours

3 or more hours

Further Comments

Please write down any further comments that you wish to make about your experience. In particular, what things helped to give you a sense of "really being" in the virtual rooms, and what things acted to "pull you out" and make you more aware of "reality"?

Reminder - all answers will be treated entirely confidentially.

Thank you once again for participating in this study and helping with our research. Please do not discuss this with anyone until the end of the semester. This is because the study is continuing, and you may happen to speak to someone who may be taking part.

Scoring

The UCL Questionnaire is scored by counting the number of "high" scores, in our case, five, six and seven responses. Details can be found in Meehan (2001).

A.7 Behavioral Measures Grade Sheet

Behavioral Measures Grade Sheet

Walks across ledge	going to chair (1)	coming from chair (1)
Slows motion when entering pit room	yes(1)	no (0)
Leans against wall	going to chair(1)	coming from chair(1)
Curls toes	1 2 3 4 5 6 7 8	
Tests edge with foot	1 2 3 4 5 6 7 8	
Kneels to feel ledge	1 2 3 4 5 6 7 8	
Sticks out arms for balance	1 2 3 4 5 6 7 8	
Takes baby steps	1 2 3 4 5 6 7 8	
Peers over ledge	1 2 3 4 5 6 7 8	
Number of HMD adjustments	1 2 3 4 5 6 7 8	
Change of breath pattern	1 2 3 4 5 6 7 8	
Loss of balance	1 2 3 4 5 6 7 8	
Refuses to complete experiment	yes	no
Refuses to start experiment	yes	no

Other Comments:

Scoring

The observed behaviors (except “number of HMD adjustments” and “walking over the pit”) are scored by counting the number of each behavior that the participant exhibits, and adding them together to create a subtotal. Two scores, “number of HMD adjustments” and “walking over the pit” are considered to show signs of decreased presence so these scores are subtracted from the subtotal.

Appendix B

Documents – Training Study

B.1 Consent form

Effect of Static Haptics on Training and Memory in Virtual Environments

Introduction and purpose of the study:

We are inviting you to participate in a study of effect in virtual environment (VE) systems. The purpose of this research is to measure how task performance in VEs changes with the addition of static haptics. We hope to learn things that will help VE researchers and practitioners using VEs to train people for real-world situations.

The principal investigator is Brent Insko (UNC Chapel Hill, Department of Computer Science, 268 Sitterson Hall, 962-1850, email: insko@cs.unc.edu.) The Faculty advisor is Mary Whitton (UNC Chapel Hill, Department of Computer Science, Sitterson Hall, 962-1950, email: whitton@cs.unc.edu).

What will happen during the study:

We will ask you to come to the laboratory for one session lasting approximately two hours. During the session, you will perform a few simple tasks within the VE. You will also be given questionnaires asking about your perceptions and feelings during and after the VE experience. Afterward, you will navigate a real environment on which the virtual environment is based. You will be blindfolded for the navigation. Approximately 30 people will take part in this study. We will use computers to record your hand, head, and body motion during the VE experience. We will also make video and audio recordings of the sessions.

Protecting your privacy:

We will make every effort to protect your privacy. We will not use your name in any of the data recording or in any research reports. We will use a code number rather than your name. No images from the videotapes in which you are personally recognizable will be used in any presentation of the results, without your consent.

Risks and discomforts:

While using the virtual environment systems, some people experience slight symptoms of disorientation, nausea, or dizziness. These can be similar to “motion sickness” or to feelings experienced in wide-screen movies and theme park rides.

We do not expect these effects to be strong or to last after you leave the laboratory. Also being blindfolded in the real environment can be dangerous, but an investigator will be nearby to prevent you from falling. If at any time during the study you feel uncomfortable and wish to stop the experiment you are free to do so.

Your rights:

You have the right to decide whether or not to participate in this study, and to withdraw from the study at any time without penalty. We will pay you \$10 per hour you spend participating in the study.

Institutional Review Board approval:

The Academic Affairs Institutional Review Board (AA-IRB) of the University of North Carolina at Chapel Hill has approved this study. If you have any concerns about your rights in this study you may contact the Chair of the AA-IRB, David A. Eckerman, at CB#4100, 201 Bynum Hall, UNC-CH, Chapel Hill, NC 27599-4100, (919) 962-7761, or email: aa-irb@unc.edu.

Summary:

I understand that this is a research study to measure the effects of static haptics on training in virtual environments.

I understand that if I agree to be in this study:

- I will visit the laboratory one time for sessions lasting approximately one hour.
- I will wear a virtual environment headset to perform tasks, and my movements and behavior will be recorded by computer and on videotape, and I will respond to questionnaires between and after the sessions.
- I may experience slight feelings of disorientation, nausea, or dizziness during or shortly after the VE experiences.
- I will navigate in a real environment while blindfolded.

I certify that I am at least 18 years of age.

I have had a chance to ask any questions I have about this study and those questions have been answered for me.

I have read the information in this consent form, and I agree to be in the study. I understand that I will get a copy of this consent form after I sign it.

Signature of Participant

Date

I am willing for videotapes showing me performing the experiment to be included in presentations of the research. Yes No

B.2 Participant information sheet

Effect of Static Haptics on Training and Memory in Virtual Environments.

Participant Instructions

As a participant in the study "Effect of Static Haptics on Training and Memory in Virtual Environments" you will do several things. This document describes what you will be doing and gives you instructions. The investigators will elaborate on the instructions and answer any questions you have.

Part I: Preliminaries (Conference Room)

1. We will ask you again if you meet all the qualifications to be a participant in this study.
 2. We will explain the entire experiment to you by going through these instructions and answering any questions that you have.
 3. We will show you the equipment we will use, the head-mounted display (HMD) and tracking gloves and answer any questions you have about them.
 4. We will give you a consent form that describes aspects of the study not included in these instructions. You'll read this form and be asked if you have any more questions about the study.
 5. After all your questions are answered, we will ask you if you are willing to sign the form agreeing to be a participant in this experiment.
- Once you have signed the consent form, you are officially a participant in this experiment and you are entitled to payment.

Part II: First Questionnaire Session

The questionnaire you'll fill out at the beginning of the training session investigates symptoms of illness sometimes induced by virtual environment (VE) systems. The first is a very a short questionnaire asking about the general state of your health. The second asks how you feel in 17 different categories, e.g. dizziness. Please answer the questions thoughtfully; your answers are a key element in making our study produce meaningful and useful results.

When you've finished the questionnaires, we will again review the instructions for the VE part of the experiment, and we'll move into the laboratory.

Part III: The VE Session

A. Orientation

1. You will wear a VE headset and two tracking gloves during your VE session.
2. We'll help you place a backpack on. This backpack contains tracking equipment.
3. We'll help you place the tracking gloves on your hands.

4. We'll put you in the HMD and adjust it so that it fits snugly and comfortably.
5. When you put the HMD on, you'll find yourself in a virtual kitchen.
6. We'll help you adjust the HMD so that you can see the images properly and in stereo. We'll start a timer each time you put the HMD on, and, even if you have not finished the experiment, we will stop the session after 15 minutes. You can ask to discontinue the experiment at any time.
7. You, represented by a model of a person, are part of the virtual environment. We'll ask you if you can see feet, arms, and hands. The entire virtual environment you will visit fits inside the laboratory we will be in. You won't be able to see the real laboratory once you put the HMD on, so one of the investigators will stay near you all the times to be sure that you don't trip on or bump into anything.
8. Next we will train you in how to move in the virtual environment. Your walking in the virtual environment exactly corresponds to your walking within the real environment. When you take a step in the real world, you move the length of that step in the virtual environment. When you stop walking, your virtual body in the virtual environment also stops walking.
9. Once you have become accustomed to the virtual environment, we will begin the training. Take as long as you need, up to the maximum session length of 15 minutes.
10. After we start the experiment we will try to minimize interaction with you to only giving you directions. However, we will tug on your cables, speak to you, or touch you gently on the shoulder *only* if we must help you stay in the proper part of our laboratory.

B. Training in the virtual environment

11. Your task in the virtual environment will be to navigate the virtual kitchen and perform various tasks within the kitchen.
12. When you've completed the last task in the sequence you're done. We will take the gloves from you and help you take the HMD off.
13. After completing the task, you will be asked to fill out a short questionnaire and be debriefed.

Part IV: Second Questionnaire Session

You'll fill out two questionnaires after the VR session. Please answer the questions thoughtfully; your answers are a key element in making our study produce meaningful and useful results.

14. We'll ask you to fill out the questionnaire asking about how you are feeling again.
15. We'll ask you to fill out a somewhat longer questionnaire asking other questions about the VE experience.

Part V: Debrief session

When you've finished the questionnaires, the investigator will ask you if you have any other comments about the experience or questions that you'd like to ask.

B.3 Pre-session health questionnaire

Same as Appendix A.3

B.4 Simulator Sickness Questionnaire

Same as Appendix A.4

B.5 Witmer & Singer Presence questionnaire

The presence questionnaire I used was modified from that of Witmer and Singer (1998). The questionnaire is scored as follows (from the original questionnaire):

“Simply score the boxes for each question from left to right beginning with one and increasing in value to the box the subject has marked, and the number of that box becomes the score. Some of the questions have reversed response anchors, and are scored so the left-most box receives a seven and the rest decrease in value. The subscale scores are the sum of the scores for each subscale item. There is no weighting of items or subscales. The questionnaire total and subscales are comprised as follows:

PRESENCE QUESTIONNAIRE

Total: Items 1, 2, 3, 4, 6, 7, 8, 9, 10, 14, 15, 16, 18, 19+, 20, 21, 22+, 23+, 24.

PQ-Involved/Control: Items 1, 2, 4, 7, 9, 10, 14, 18, 19+, 20, & 21.

PQ-Natural: Items 3, 6, & 8.

PQ-Interface Quality: Items 22+, 23+, & 24.

PQ-Auditory*: Items 5, 11, 12.

PQ-Haptic*: Items 13 & 17.

PQ-Resolution*: Items 15 & 16.

The last three subscales listed for the PQ are marked with an asterisk (*) because they have yet to be used in analyses, but are being retained on a theoretical basis. Since there have been no haptic or auditory interfaces, nor any differences in resolution to judge, those items have been scored as zero. Items marked with a plus (+) have to be reverse scored (see above) in order to contribute to the subscale and overall totals.”

Because our system did not use audio or haptics across all participants, I removed questions that contributed to those subscores and to no others. The original questionnaire also contains experimental questions numbered 25 through 32, which the authors have not yet used for computing any scores. I removed those questions as well. I added a question for general comments (33). The full questionnaire that I used is as follows.

PRESENCE QUESTIONNAIRE

Characterize your experience in the environment, by marking an "X" *inside* the appropriate box of the 7-point scale, in accordance with the question content and descriptive labels. Please consider the entire scale when making your responses, as the intermediate levels may apply. Answer the questions independently in the order that they appear. Do not skip questions or return to a previous question to change your answer.

WITH REGARD TO THE VIRTUAL ENVIRONMENTS THAT YOU EXPERIENCED TODAY

1. How much were you able to control events?

NOT AT ALL	SOMEWHAT		COMPLETELY

2. How responsive was the environment to actions that you initiated (or performed)?

NOT RESPONSIVE	MODERATELY RESPONSIVE		COMPLETELY RESPONSIVE

3. How natural did your interactions with the environment seem?

EXTREMELY ARTIFICIAL	BORDERLINE		COMPLETELY NATURAL

4. How much did the visual aspects of the environment involve you?

NOT AT ALL	SOMEWHAT		COMPLETELY

6. How natural was the mechanism which controlled movement through the environment?

EXTREMELY ARTIFICIAL	BORDERLINE		COMPLETELY NATURAL

7. How compelling was your sense of objects moving through space?

_____	_____	_____	_____	_____	_____
NOT AT ALL		MODERATELY COMPELLING		VERY COMPELLING	

8. How much did your experiences in the virtual environment seem consistent with your real world experiences?

_____	_____	_____	_____	_____	_____
NOT CONSISTENT		MODERATELY CONSISTENT		VERY CONSISTENT	

9. Were you able to anticipate what would happen next in response to the actions that you performed?

_____	_____	_____	_____	_____	_____
NOT AT ALL		SOMEWHAT		COMPLETELY	

10. How completely were you able to actively survey or search the environment using vision?

_____	_____	_____	_____	_____	_____
NOT AT ALL		SOMEWHAT		COMPLETELY	

14. How compelling was your sense of moving around inside the virtual environment?

_____	_____	_____	_____	_____	_____
NOT COMPELLING		MODERATELY COMPELLING		VERY COMPELLING	

15. How closely were you able to examine objects?

_____	_____	_____	_____	_____	_____
NOT AT ALL		PRETTY CLOSELY		VERY CLOSELY	

16. How well could you examine objects from multiple viewpoints?

_____	_____	_____	_____	_____	_____
NOT AT ALL		SOMEWHAT		EXTENSIVELY	

18. How involved were you in the virtual environment experience?

_____	_____	_____	_____	_____	_____	_____
NOT INVOLVED			MILDLY INVOLVED			COMPLETELY ENGROSSED

19. How much delay did you experience between your actions and expected outcomes?

_____	_____	_____	_____	_____	_____	_____
NO DELAYS			MODERATE DELAYS			LONG DELAYS

20. How quickly did you adjust to the virtual environment experience?

_____	_____	_____	_____	_____	_____	_____
NOT AT ALL			SLOWLY			LESS THAN ONE MINUTE

21. How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?

_____	_____	_____	_____	_____	_____	_____
NOT PROFICIENT			REASONABLY PROFICIENT			VERY PROFICIENT

22. How much did the visual display quality interfere or distract you from performing assigned tasks or required activities?

_____	_____	_____	_____	_____	_____	_____
NOT AT ALL			INTERFERED SOMEWHAT			PREVENTED TASK PERFORMANCE

23. How much did the control devices interfere with the performance of assigned tasks or with other activities?

_____	_____	_____	_____	_____	_____	_____
NOT AT ALL			INTERFERED SOMEWHAT			INTERFERED GREATLY

24. How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?

_____	_____	_____	_____	_____	_____	_____
NOT AT ALL			SOMEWHAT			COMPLETELY

Appendix C

Data

The following tables contain raw data from the two studies with the outliers removed.

Appendix C.1 Presence Study Data

ID	SESSION	PASSIVE HAPTICS	PHYSIOLOGICAL MEASURES			ACROPHOBIA QUEST.		UCL QUEST.	
			HEART RATE CHANGE	SKIN CONDUCTANCE CHANGE	SKIN TEMPERATURE CHANGE	ANXIETY SCORE	AVOIDANCE SCORE	REPORTED PRESENCE	REPORTED BEHAVIORAL PRESENCE
10	1	1	4.4	4.8	2.9	31	10	7	2
10	2	0	3.1	6.6	0.4	31	10	6	2
11	1	1	8.6	6.0	1.1	3	1	5	0
11	2	0	7.5	5.3	0.8	3	1	3	1
14	1	1	12.9	7.7	0.3			5	2
14	2	0	7.7	7.2	0.4			4	1
15	1	1	2.8	7.1	0.2	18	0	5	0
15	2	0	1.8	3.8	0.5	18	0	3	2
16	1	0	7.9	7.2	0.7	47	11	6	2
16	2	1	10.3	5.8	-0.2	47	11	5	0
17	1	1	17.4	6.2	3.6	9	5	1	2
17	2	0	21.6	5.2	2.5	9	5	0	1
18	1	1		14.0		10	2	5	1
18	2	0		12.2		10	2	7	2
19	1	1	6.8	6.9	0.5	16	2	5	2
19	2	0	4.2	6.2	1.8	16	2	5	1
20	1	0	9.5	3.7	0.1	7	6	7	2
20	2	1	0.9	12.2	0.2	7	6	7	2
21	1	0	7.0			40	1	7	0
21	2	1	11.1			40	1	7	2
22	1	0	6.2	1.8	0.3	11	0	3	1
22	2	1	9.0	2.2	0.2	11	0	3	0
23	1	0	4.9	2.0	1.6	8	0	7	1
23	2	1	9.6	2.5	1.1	8	0	7	2
27	1	0	1.5	5.4	0.9	18	6	5	1
27	2	1	4.2	4.7	1.5	18	6	1	1
28	1	0	-0.3	6.4	3.4	56	2	7	2
28	2	1	5.1	5.3	0.8	56	2	5	2

29	1	0	0.5	4.0	3.3	10	0	7	1
29	2	1	0.8	6.0	3.3	10	0	7	2
30	1	0	2.9	4.2	1.1	18	2	7	2
30	2	1	8.0	4.8	1.9	18	2	6	3
31	1	1	16.7	9.1	0.8	11	2	2	2
31	2	0	7.5	7.3	0.4	11	2	0	0
33	1	0	-2.5	5.2	0.6	0	1	7	2
33	2	1	20.6	7.8	-0.2	0	1	7	2
34	1	1	1.1	5.6	1.0	8	2	7	2
34	2	0	-1.5	6.1	5.1	8	2	5	1
35	1	1	7.6	4.1	1.5	50	13	5	2
35	2	0	9.2	3.2	1.8	50	13	3	1
36	1	0	10.8	4.1	0.6	4	0	6	0
36	2	1	7.7	5.1	0.3	4	0	4	2
37	1	1	6.6	7.5	1.3	18	1	6	2
37	2	0	7.3	4.3	2.4	18	1	2	1
38	1	1	10.5	1.1	2.6	23	11	4	1
38	2	0	6.0	2.2	0.5	23	11	4	1
39	1	1	27.7	2.5	1.0	17	3	5	0
39	2	0	2.1	2.6	0.6	17	3	4	1
40	1	0	-3.1	5.6	1.3	5	0	3	0
40	2	1	-0.4	2.5	0.0	5	0	4	0
41	1	1	-5.4	4.7	0.4	38	7	5	3
41	2	0	-10.5	11.8	0.1	38	7	1	3
42	1	0		2.7	0.9	0	0	5	0
42	2	1		8.9	1.7	0	0	4	1
43	1	1	9.7	2.9	-3.6	49	15	5	2
43	2	0	0.4	1.2	0.3	49	15	7	2
44	1	1	-12.4	2.9	1.1	33		6	2
44	2	0	1.0	2.7	2.2	33		6	1
45	1	1	6.4	6.9	2.3	10	1	5	2
45	2	0	2.8	3.6	3.1	10	1	0	1

46	1	1	9.7	2.9	0.7	17	5	6	2
46	2	0	4.8	2.7	1.3	17	5	6	1
48	1	0	9.7	7.3	1.4	22	4	6	2
48	2	1	10.8	7.8	-1.1	22	4	7	2
49	1	1	9.4	1.7	2.7	37	6	2	0
49	2	0	3.9	6.2	1.0	37	6	0	1
50	1	0	8.2	2.3	0.8	17	6	4	2
50	2	1	12.0	4.3	0.3	17	6	7	2
51	1	1	13.1	2.1	2.8	47	6	6	2
51	2	0	5.9	3.2	2.2	47	6	4	0
52	1	0	7.7			12	3	6	1
52	2	1	0.5			12	3	4	1
53	1	0	5.0	1.4	0.3	73	16	6	3
53	2	1	12.4	2.4	0.3	73	16	6	3
54	1	1		5.3	1.1	11	1	6	2
54	2	0		3.0	2.1	11	1	4	0
55	1	1	12.5	6.5	3.1	35	0	6	1
55	2	0	9.0	2.3	2.2	35	0	4	0
56	1	0		5.7	0.5	5	0	3	0
56	2	1		5.0	0.6	5	0	4	2
57	1	0	4.6	1.6	1.2	12	4	7	0
57	2	1	3.2	3.9	1.8	12	4	7	2
58	1	0		4.7	1.0	4	2	6	1
58	2	1		3.5	-0.8	4	2	7	1
61	1	0	13.3	2.7	-0.3	10	1	7	1
61	2	1	9.4	2.7	-1.8	10	1	2	1
62	1	0	2.4	9.1	-0.8	18	2	4	0
62	2	1	5.7	6.1	0.7	18	2	5	3
63	1	0	-5.4	4.1	1.0	2	0	6	1
63	2	1	3.2	9.4	0.7	2	0	7	0
64	1	0	1.8	2.7	1.2	0	1	1	2
64	2	1	3.3	3.6	0.5	0	1	0	2

65	1	1	9.6	4.2	1.5	11	3	7	0
65	2	0	7.5	3.7	1.5	11	3	7	0
66	1	1	3.8	5.2	0.4	21	5	3	2
66	2	0	2.3	3.3	0.4	21	5	3	2
67	1	1		4.0	1.4	0	0	7	1
67	2	0		3.2	0.4	0	0	7	1
68	1	0	7.2	2.0	0.7	20	0	4	3
68	2	1	13.3	1.2	-2.0	20	0	6	1
69	1	1	-2.9	3.8	1.2	0	1	7	2
69	2	0	18.1	1.8	1.5	0	1	7	0
70	1	1	12.9	5.0	0.5	11	2	3	2
70	2	0	3.6	3.6	3.1	11	2	1	0

Observed Behavior Data			
ID	ORDER	BEHAVIORAL INDEX WITH HAPTICS	BEHAVIORAL INDEX WITHOUT HAPTICS
10	0	8	0
11	0	6	1
12	0	6	1
14	0	6	5
15	0	5	2
16	0	5	2
17	0	4	0
18	0	4	5
19	0	7	0
20	1	6	3
21	1	13	4
22	1	3	-1
23	1	3	1
27	1	5	5
28	1	-1	1
29	1	1	0
30	1	4	3
33	1	2	1
35	0	5	2
36	1	2	2
37	0	4	-2
38	1	2	1
40	1	11	2
41	0	0	-2
42	1	2	1
44	0	7	3
49	0	2	-1
50	0	4	0
57	1	7	1
58	1	3	0
60	0	5	2
63	1	3	2
64	1	1	0

ID	PRESENCE OF HAPTICS	SPATIAL ORIENTATION SCORE	EST. HEIGHT RED OBJECT	EST. HEIGHT GREEN OBJECT	EST. HEIGHT BLUE OBJECT	EST. HEIGHT YELLOW OBJECT	EST. WIDTH	TIME	COLLISIONS	PRESENCE SCORE	SKETCH MAP SCORE	GENDER
1	0	19.75	43.0	55.0	56.3	16.5	27.0	44.0	7	149	3	M
2	0	22.50	57.0	43.0	60.0	26.5	19.0	111.0	5	186	4	F
3	0	24.00	37.5	52.5	64.0	25.5	25.0	98.0	4	158		M
4	0	14.75	49.0	54.0	63.5	24.0	25.5	71.0	8	191	3	F
5	0	15.25	40.5	49.5	67.5	29.5	18.5	128.0	12	308	3	F
6	0	28.00	35.0	43.5	53.5	21.5	26.5	91.0	7	196	4	M
7	0	36.25	33.0	46.0	52.0	24.0	27.5	177.0	9		4	M
8	0	34.50	36.0	31.0	64.5	17.0	28.0	97.0	8		5	M
9	0	10.00	40.0	44.5	59.0	23.0	31.5	108.0	12	277	4	M
13	0	25.50	32.0	61.5	48.0	56.5	23.5	49.0	4	109	4	M
14	0	26.75	65.0	43.5	54.0	27.0	25.0		15	300	2	F
15	0	6.25	46.0	57.0	63.0	29.0	21.0	48.0	10	198	3	F
16	0	13.00	42.0	49.0	50.5	15.0	34.0	61.0	13	256	5	M
17	0	12.75	49.5	60.5	53.5	22.5	32.0	62.0	7	167	4	M
18	0	19.75	18.0	40.0	30.0	59.5	25.5	68.0	13	263	4	F
20	1	17.75	37.5	50.0	37.5	26.0	26.5	57.0	7	162	4	F
21	1	4.75	37.0	35.0	55.0	23.0	29.5	97.0	6	187	3	F
22	1	9.75	31.0	56.0	62.0	31.0	28.0	56.0	6	146	4	F
23	1	1.75	38.0	55.0	64.0	31.0	32.5	86.0	6	176	5	M
24	1	10.75	54.0	43.0	57.0	24.0	22.5	62.0	5	137	3	F
25	1	18.00	41.0	51.0	62.0	26.0		48.0	6	138	5	F
26	1	21.00	52.0	45.5	62.0	24.0	28.0	56.0	5	131	4	F
27	1	11.75	40.0	50.0	68.0	30.0	29.0	57.0	5	132	5	F
28	1	24.00	53.0	32.0	40.0	20.0	30.0	78.0	9	213	2	M
29	1	7.75	62.5	49.0	45.0	33.5	40.5	40.0	7	145	2	F
30	1	26.75	38.0	54.0	45.5	29.0	39.0	87.0	6	177	5	M
31	1	16.50	45.0	52.0	60.0	23.0	29.5	45.0	8	165	3	M
32	1	38.50	53.0	47.0	57.0	24.0	27.5	59.0	6	149	3	F
33	1	15.50	52.5	46.5	63.0	23.0	43.0	86.0	9	221	3	F
34	1	32.50	49.0	53.0	58.0	22.0	20.0	55.0	8	175	4	M

Appendix C.2 Training Transfer Study Data

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