Passive Haptics Significantly Enhances Virtual Environments

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ABSTRACT

One of the worst virtual environment experiences is to virtually contact something and feel nothing. Visual-haptic sensory conflicts are normally dominated by visual perception. Therefore, augmenting a high-fidelity visual virtual environment with low-fidelity haptic objects, called *passive haptics*, should markedly improve both sense of presence and task training effectiveness.

Testing these hypotheses, we found adding a 1.5 inch physical ledge to a visual-cliff virtual environment increased participants sense of presence as measured by subjective questionnaires, observed participant behaviors, and physiological responses.

We next examined memory model creation and training effectiveness for a navigation task in a virtual environment with and without passive haptics. No significant differences were found in memory model creation. When navigating an identical real environment while blindfolded, those trained in a virtual environment augmented with passive haptics performed significantly faster and with fewer collisions than those trained in a non-augmented virtual environment. More participants who trained without passive haptics unexpectedly navigated incorrectly about the same obstacle.

CR Categories and Subject Descriptors: I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism —*Virtual Reality*; I.3.6 [Computer Graphics]: Methodology and Techniques —*Interaction techniques*; H.5.2 [Information Interfaces]: User Interfaces — *Evaluation/Methodology*.

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1. INTRODUCTION

Head-tracked, head-mounted display systems allow people to train for real world tasks in 3D virtual environments (VEs) [Bliss 1997]. Unlike the real world, these virtual environments only provide input sight, sometimes sound, and sometimes platform motion. One of the most disconcertingly unnatural properties of such VEs is the ability to pass through objects in the environment. Users expect the virtual environment to obey the real laws of physics [Slater 1992], namely that one can run into walls and bump into objects. This discrepancy causes a *break in presence (BIP)* in users, a reminder that the perceived environment is not real. If we can eliminate this BIP, will the VE be better , e.g. feel more real, induce more presence, or provide increased training effectiveness?

The most successful VEs, namely flight, ship and automobile simulators, physically replicate anything that the user can reach, from steering mechanisms to dials and buttons. This is feasible in such simulators because the user is stationary within a vehicle while the virtual environment passes by outside the vehicle.

However, in a wide-area, real-walking virtual environment such as a VE architectural walkthrough, physically replicating the detail of every virtual object would be costly and time consuming; indeed it would obviate most of the advantages that a VE offers.

We hypothesize that augmenting a high-fidelity visual virtual environment with low-fidelity haptic objects, called *passive haptics*, should markedly improve both sense of presence and task training effectiveness. The low-resolution physical model is constructed from cheap, easy-to-assemble materials such as styrofoam, plywood, and particle board. We studied the following:

- Presence in a fear-inducing environment with and without passive haptics. We measured physiological, behavioral, and subjective presence as subjects performed a task in an environment with a visual cliff.
- Cognitive mapping in a virtual environment with and without passive haptics. Does haptic information provided by the physical augmentation lead to better cognitive mapping of the environment?
- Navigation training in a virtual environment. Does the addition of haptic cues in a virtual training environment lead to better performance in a real-world navigation task?

2. PREVIOUS WORK

Prior research suggests that there are benefits to physical augmentation of immersive virtual environments. A study on using exact physical replication of objects, called *tactile augmentation*, performed at the University of Washington s HIT Lab [Hoffman 1996] had users actually touch real objects while wearing a head-mounted display. Subjects grasped the actual objects on which the corresponding virtual model was based. The actual object was tracked so that the visual representation moved with the haptic representation. Actually touching the real object significantly increased the sense of realism of both the objects that were touched and those not touched. Users were stationary and interacted with few objects.

We may be able to employ only an approximate haptic model, even though it introduces a sensory conflict between vision and touch. When the visual and haptic/proprioceptive senses conflict, vision dominates the haptic sense in most circumstances, such as perception of size, length, shape of objects [Rock 1967], and spatial location [Smothergill 1973]. In fact, several studies show that the touch experience itself can undergo a change when in conflict with the visual sense [Rock 1964; Lobb 1970; Welch 1978]. These studies suggest that when a visual virtual environment is augmented by an approximate physical model, the user will not become disoriented or confused by the sensory conflict, but rather the haptic sense will augment the dominant visual sense.

3. HYPOTHESES AND RESULTS

Hypothesis 1: Participants experience a greater sense of presence when the virtual environment is augmented with passive haptics.

Result 1: Participants in the augmented VE experienced a significantly greater sense of presence as measured by subjective questionnaires, observed participant behaviors, and physiological responses.

Hypothesis 2: Participants form a better cognitive map of the virtual environment when the VE is augmented with passive haptics.

Result 2: No significant differences were found.

Hypothesis 3: Participants perform better in a real world navigation task when trained in a VE augmented with passive haptics, than when trained in a VE without.

Result 3: Participants trained in an augmented VE performed significantly faster and with fewer errors in the real world navigation task.

Details of the measures, the studies, and the results are sketched in following sections and given in full at our web address:

http://www.cs.unc.edu/~eve/passive_haptics.html

4. COMMON ELEMENTS OF STUDIES

The experiments used one graphics pipe of a Silicon Graphics Reality Monster. The scene was rendered with custom software using OpenGL; the system maintained a frame rate between 20 and 30Hz stereo. A Virtual Research V8 head mounted display with true VGA resolution of (640x3) x 480 pixels per eye was used. This display consists of two 1.3 inch active matrix LCDs with a field of view of 60 degrees diagonal at 100% overlap and aspect ratio 4:3.

Head tracking was performed by a 3rdTech HiBall optical tracker [Ward, 1992; Welch 1997]. This tracker works over a range of 10m by 4m with millimeter precision. It updates position and orientation at approximately 1.5kHz. These reports are fed to the application at 70Hz. We set tracker filtering to result in tracker latency of 25ms. Total latency, taking into account network and graphics delays, was approximately 100ms.

Users hands and, in the Presence study, legs were tracked using a Polhemus FastTrak magnetic tracker. The input device for the presence study was a tracked joystick with four buttons; the experiment used one button. For the Memory/Training study fingerless tracked gloves were used.

Allowing participants to walk freely around a large area required care so participants would not snag or trip on cables. One of the experimenters walked behind the user silently handling cables.

5. INCREASED PRESENCE STUDY

The goal of this study was to show that participants would experience a greater sense of presence in a visual cliff environment if a slight physical ledge were added.

5.1 Methods

Model. The virtual environment consisted of the Training Room and the Pit Room. The Pit Room consisted of a 2-foot wide virtual ledge above a 20-foot (virtual) drop to a room below containing living room furniture (**Figure 1**). There was also a chair on the wooden ledge on the far side of the room. This environment is a derivative of Usoh [1999].

Figure 1. Virtual Environment with Visual Pit.

Task. While wearing the head-mounted display in the Training Room, participants were trained to pick up and move objects. After training, participants were instructed to carry a virtual book into the virtual Pit Room through a previously closed door, carry it to the other side of the room, and place it on the chair. During one of the participants two sessions, a 1.5-inch real precipice augmented the 20-foot virtual pit. While exploring the edge of the virtual pit, subjects were able to feel the real 1.5-inch ledge, (**Figure 2**). The task took no more than 5 minutes.

Design. The experiment was within subject. The independent variable was passive haptics; the dependent variable was presence. We controlled the independent variable by either including or excluding passive haptics (the 1.5-inch wooden ledge). We controlled for order bias by randomly assigning the participants into two groups. One group was exposed first to the environment with passive haptics; the other group was exposed first without.

Figure 2: Testing Edge of Physical Precipice.

Measures and Data Collection. A tracking system recorded the locations of the participant s feet, hands, and head approximately 70 times per second. Task completion time and button press events were recorded. Presence was measured in three components: subjective presence, observed behavioral presence, and physiological presence. Subjective presence was measured by the UCL Presence Questionnaire [Usoh 1999]. This questionnaire assesses three factors: subjective behavioral presence, reported presence, and ease of locomotion. Observed behavioral presence was measured by scoring key 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. Additionally, finger skin temperature, electrodermal response (galvanic skin response), and heart rate (via a three electrode electrocardiography) were measured non-invasively from the fingers of one hand using ProComp+ tethered telemetry system at a rate of 32 times per second.

We also used a simulator sickness questionnaire [Kennedy 1993], a fear of heights assessment questionnaire [Cohen 1977], an oral debriefing sheet, a participant health assessment form, an informed consent form, and an instruction form.

5.2 Procedures

Participants. 60 participants took part. Data lost due to equipment and procedure failures resulted in 52 participants data included in the analysis; 36 were male, 16 were female. All were ambulatory and had use of both hands and both legs. Participants were paid.

Schedule. Each participant visited the lab twice, once for each experimental condition. Each session, including the task, questionnaires, and debriefing, lasted approximately 1 hour. Except for the inclusion of passive haptics, everything was identical during the two sessions, including number and type of tasks.

5.3 Results

A repeated-measures analysis [Kleinbaum 1998] of subjective presence produced results trending toward higher presence with the wooden ledge than without it ($p = 0.06$).

Those who experienced passive haptics exhibited significantly more behaviors associated with pit avoidance than participants who did not experience passive haptics, ($p < 0.001$).

Physiological measures showed significantly higher changes in heart rate ($p < 0.05$) and skin conductivity ($p < 0.05$), with skin temperature also trending higher ($p < 0.10$), with the wooden ledge than without it.

Order effects were not significant for any measure.

6. MENTAL MODEL & TRAINING STUDY

This study had two goals. First, to show whether participants form better cognitive maps of the virtual environment when the VE is augmented with passive haptics. Cognitive mapping is defined by Downs and Stea [Downs 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.

The second goal was to show whether participants perform a real-world navigation task better after training in a VE augmented with passive haptics than after training in a purely visual VE.

6.1 Methods

Model. The virtual environment used in this experiment was constructed from rectangular solids of various sizes. Objects were colored gray, red, green, blue, and yellow. To prevent participants from getting information about object size from textures, no textures were used on the objects. Patterned textures were used on the walls, floor and ceiling to prevent disorientation, (**Figure 3**).

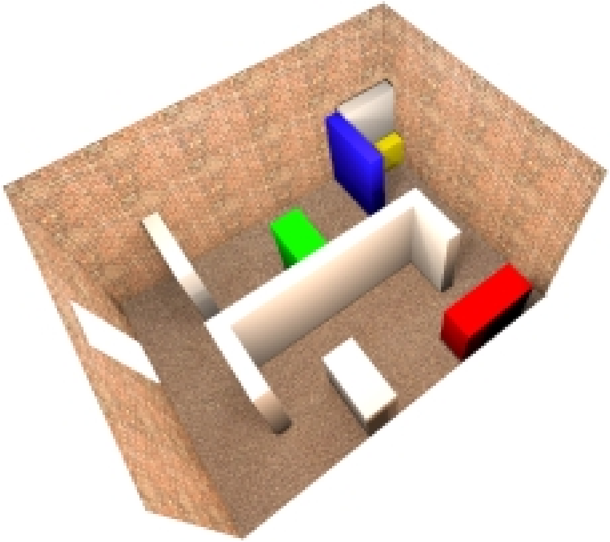

Figure 3. View of Virtual Training Environment

Task. The task was to gain as much information about the layout of the environment as possible. Participants knew before the VE session that their training would be tested by navigating an identical real environment blindfolded. Participants walked three laps around the environment and were instructed to touch the various objects in the room.

Variables. This experiment was between subjects. The independent variable was the presence or absence of the Styrofoam mockup of the environment during training, (**Figure 4**). The dependent variables were cognitive mapping and training effectiveness.

Figure 4. Real Training Environment with Passive Haptics

Measures and Data Collection. Sketch maps were used to assess the participants ability to encode, store and decode cognitive mapping information as in [Billinghurst 1994]. Participants also marked the heights of the objects on a 7ft sheet of paper attached to a wall and the width between two obstacles on a 6ft piece of paper on a table. The expectation was the act of marking heights and widths in this manner would stimulate muscle memory and help participants remember the heights of the objects [Brooks 1999]. At the end of the experiment, participants navigated, while blindfolded, a real environment identical to the virtual environment. The participant s time to complete the navigation, the number of times he bumped into objects, and the number of wrong turns were recorded.

6.2 Procedures

Participants. 33 college student volunteers took part in the experiment, 17 females and 16 males. 3 participants data are not included in the analysis because their virtual experience was monoscopic due to procedure failure. All participants had full color vision, as well as stereo depth vision. Participants were paid.

Schedule. Each participant made one two-hour visit to the lab. The experiment began with a simulator sickness questionnaire, followed by a spatial orientation test [Guilford 1948]. Next, participants were trained in the virtual environment followed by another simulator sickness questionnaire. Participants sketched maps of the virtual environment they had just experienced. Participants were asked to mark the heights of the four colored virtual objects and the width of a passageway on strips of paper. Then participants were tested by navigating an identical real environment while blindfolded. An oral debriefing followed.

The virtual training session consisted of participants navigating a virtual environment while touching the objects in the environment. In the VE augmented with passive haptics, participants would reach out and really feel the objects. In the non-augmented VE there were no real objects to touch; participants could pass through the objects. However, to provide additional feedback when a user touched an object, the avatar s hand would turn from gray to red and the user would hear a hand-specific sound in the HMD.

6.3 Results

A MANOVA [Kleinbaum 1998] revealed a statistically significant difference ($p < 0.05$) in the time to complete the blindfolded navigation between the group trained in an augmented VE (Mean = 64.6 seconds) and the group trained in a non-augmented VE (Mean = 100.8 seconds). Analysis also showed that the group that trained with passive haptics navigated with fewer collisions with objects, ($p < 0.05$).

No significant differences were found in accuracy of the sketch maps or the reported heights of objects.

Unexpected Result. When subjects navigated the virtual environment, the main obstacles were colored red, green, and blue. The next-to-last obstacle in the virtual environment was colored gray like the interior wall of the room. 11 of 15 participants trained without passive haptics bumped into this obstacle in the testing session and moreover turned the wrong direction to navigate around it. Only 2 of 15 participants trained with passive haptics made the same navigation error. This is a statistically significant difference, ($p < 0.01$). It was unexpected that such a dramatic difference would occur in the same place in the environment.

7. COSTS

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

Our first augmented model 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. Anecdotally, we observed passive haptics augmentation to radically enhance 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. This haptics model is higher fidelity than our others, for it has to be safe to walk on.

For the navigation training experiment, the passive haptics model took only 7 person hours, versus about 20 for the visual model. However, it should be noted that this virtual environment was designed around the materials at hand.

8. FUTURE WORK

We have shown how passive haptics can be used to increase presence and improve training effectiveness in VEs. Augmenting virtual environments with passive haptics could prove beneficial in training for low-visibility real world situations such as hostage rescue or fighting fires. Although passive haptics is not appropriate for all virtual environments, the low added costs combined with demonstrated training enhancement suggest that passive haptics may prove to be a practical technique.

Other issues are worth exploring:

- How does training in a virtual environment augmented with passive haptics compare to training in an identical real-world environment?
- Can passive haptics enhance task performance, such as design, validation, and modification, in a virtual environment? We have so far studied effects on presence, cognitive map formation, and training effectiveness, but not performance.

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