Evaluating the Importance of Multi-sensory Input on Memory and the Sense of Presence in Virtual Environments

Huong Q. Dinh, Neff Walker, Chang Song, Akira Kobayashi, and Larry F. Hodges
Graphics, Visualization & Usability Center
Georgia Institute of Technology (*Georgia Tech*)
Atlanta, Georgia 30332 USA
+1 404 894-8787
hodges@cc.gatech.edu

Abstract

322 subjects participated in an experimental study to investigate the effects of tactile, olfactory, audio and visual sensory cues on a participant's sense of presence in a virtual environment and on their memory for the environment and the objects in that environment. Results strongly indicate that increasing the modalities of sensory input in a virtual environment can increase both the sense of presence and memory for objects in the environment. In particular, the addition of tactile, olfactory and auditory cues to a virtual environment increased the user's sense of presence and memory of the environment. Surprisingly, increasing the level of visual detail did not result in an increase in the user's sense of presence or memory of the environment.

1. Introduction

In the early sixties, Morton Heilig built and patented the Sensorama Simulator. Now acknowledged as one of the first virtual environments, Sensorama provided the user with a multi-sensory experience. A simulated motorcycle ride through New York included color 3D visual stimuli, stereo sound, aromas, and tactile (wind from fans, and a seat that vibrated) cues [6].

Thirty-five years later, most virtual environments fall short of the prototype created by Heilig. Sensory cues for virtual environments usually consist primarily of visual stimuli, often but not always, accompanied with audio stimuli, and, even less often, haptic stimuli. Other sensory cues are usually not present or are present in contradiction to the virtual environment being presented. For example, a participant in a virtual environment may visually see himself in an open, sunny outdoor setting while the temperature and olfactory cues he perceives are consistent with being in an air conditioned, enclosed computer lab.

In this work we created a multimodal virtual environment that can provide the user with visual, auditory, tactile and olfactory sensory cues. Motivated by a suggestion by Fontaine [4] that access to a broader range of sensory cues promotes a greater sense of presence, we have experimentally investigated the use of tactile, olfactory, and auditory sensory modalities with different levels of visual information on a user's sense of presence and on his memory of details of the virtual experience.

2. Background

In recent years researchers have primarily investigated the effects of visual display parameters on a person's sense of presence. Visual display parameters manipulated may include level of visual detail (texture and number of polygons), field of view, stereoscopic versus bioptic, headtracked versus nonheadtracked displays, and frame rate. In general the research has found that the greater the level of visual realism, the greater the sense of presence [1,5]. The fact that increased visual realism increases the sense of presence is interesting, but not surprising. In addition, increasing visual realism is not without its costs. Increasing level of visual detail can be computationally intensive. As the designer increases visual detail, system responsiveness (frame rate) decreases. This, in turn, may reduce a person's sense of presence in the virtual environment. Apart from pure computational considerations, visual display systems, especially head-mounted displays, can only display a limited amount of visual detail. This limit, especially for moderately priced displays, is usually something much less than normal visual (20/20) acuity and field of view.

Recently, there has been some work on the use of supplemental auditory cues as a means to increase the sense of presence in a virtual environment [7].

Auditory cues have the positive benefit of having lower computational costs. Therefore they could be used to increase the sense of presence without introducing lag into the system. The initial findings on the use of auditory cues suggest that they can be used to increase the sense of presence even when the level of visual detail is low.

Olfaction plays an important role in our experience of the physical world. However, with the exception of Cater [3], almost no work has been reported in the literature on the use of olfaction in virtual environments or the development of olfactory displays for virtual environments. Barfield and Danas [2] have reviewed the physiological and psychological aspect of olfaction and discuss the potential of olfactory displays in VR. Krueger points out that surgical training systems, potentially one of the most important developing applications of VR, will be incomplete unless odors are present [9].

Reports on the use of tactile cues in virtual environments have been limited primarily to tactile feedback to the hand. Examples include pin arrays that vibrate [8] or that move up and down [11]. Ogi and Hirose [10] used air flow magnitude and direction generated by small fans blowing on the user's hand to represent vector information in a scientific visualization system. The University of Virginia's Virtual Reality Group used a heat lamp in conjunction with a virtual fire-breathing dragon in a demonstration at SIGGRAPH'97. The use of heat lamps, fans and other simple props to produce accurate simulation of skin sensations in a virtual environment, however, have not been evaluated in the VR literature.

3. METHOD

3.1 Participants

The participants in the experiment were 322 students at the Georgia Institute of Technology. The students were recruited from undergraduate classes. Students were given partial course credit for participation in the study. All participants had no or limited experience (one time) with a virtual environment.

3.2 Design

The study utilized a level of visual detail (2) by olfactory stimulation (2) by ambient auditory stimulation (2) by tactile stimulation (2) between-subjects factorial design. Visual detail was varied such that there was a high fidelity and low fidelity version of the environment. The other three factors were either present or absent in the environment. This design yielded 16 experimental conditions, with 18 subjects per condition. Data from some participants had to be eliminated from the analyses due to experimental error (i.e., conditions such as the subject did not complete the questionnaires or equipment malfunctioned). In all conditions of the experiment there were complete data sets from at least 15 participants. There were four primary dependent variables: one question on the overall rating of presence (range from 0 to 100), a longer 13 item presence questionnaire; a four item questionnaire on spatial layout; and, a five item questionnaire on object location.

3.3 Environment

The virtual environment for this experiment consisted of a corporate office suite which included a reception area, hallway, bathroom, small office, copier room, large office, and balcony (see figures 1-5). The environment could be represented to the user not only with visual cues, but with audio, tactile, and olfactory cues. There were two possible levels of realism for each sensory cue - two levels of visual detail, absence or presence of ambient sounds, absence or presence of specific tactile cues, and absence or presence of coffee aroma near the coffee pot. Each tactile, olfactory, and auditory cue was associated with specific visual cues when possible.

The virtual environment was modeled using the Alias Wavefront modeling package and was rendered by an application built using the Simple Virtual Environment (SVE) toolkit (http://www.cc.gatech.edu/gvu/virtual/SVE/). Texture maps were used for pictures on the walls, furniture material, and an outdoor city view. High visual detail was provided in the office model by applying local light sources and high resolution texture maps. A degraded fidelity visual model was created by using only ambient illumination and by reducing the texture resolutions to 25% of the high resolution textures. Frame rate for both high and low visual fidelity representations was fixed at twenty frames per second. Figures 5 and 6 show side by side views of the large office in both representations.

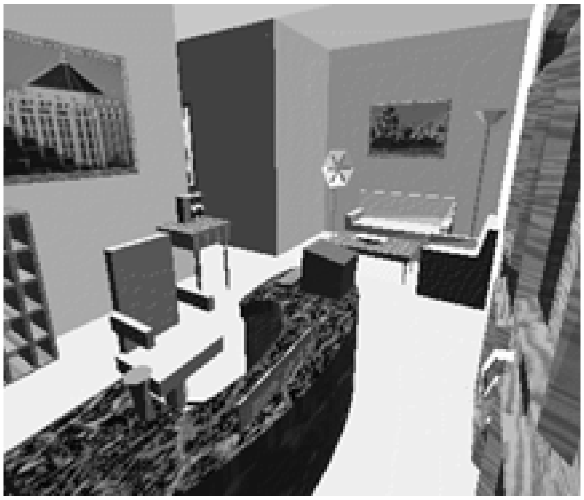

Figure 1. Reception Area

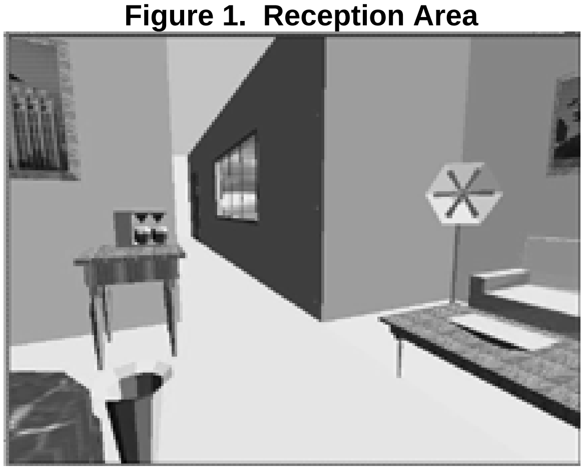

Figure 2. Hallway leading off of reception area

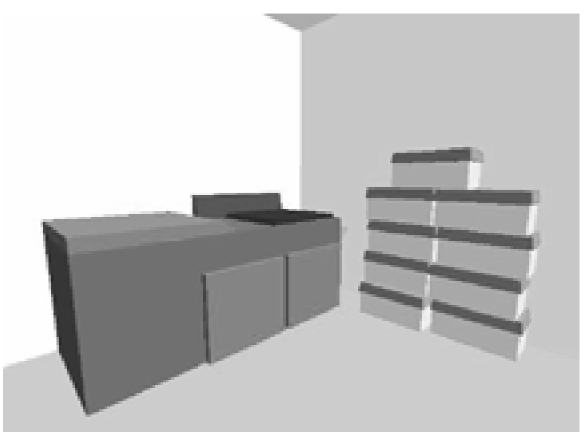

Figure 3. Copy Room

Figure 4. Balcony

Audio sensory cues included stereo sounds of a fan in the reception area, a toilet flushing as you pass the bathroom door, the sound of a copier in the copy room, and city noise on the balcony. The volume of the different sounds were varied according to the user's location in the environment. As the participant approaches the copier room, the volume level of the copier increases. Three different volumes for this sound were used, with the highest volume occurring within the copier room itself. Other sounds - such as the fan, the toilet, and the city noise - were enabled and disabled immediately as the subject passes a specific navigation point. For example the city noise is switched on and off as the balcony door opens and closes.

Two specific tactile cues were provided to augment the other sensory cues presented by the environment. As the user moves through the reception area she passes a fan that is obviously turned on (cued by the visual cue of the fan blades turning and audio cue of a fan running). As the user passed in front of the fan in the virtual environment, a real fan was automatically switched on to blow on the user. Later in the environment, the user goes through a door onto an outside balcony on an obviously sunny day (cued by bright illumination and sharp shadows). At this point a heat lamp is automatically switched on by the application. The heat lamp is positioned at an angle consistent with the shadows in the virtual environment. The heat lamp gives a tactile impression to the user that she is standing in the sunshine on a warm day. (See figure 7).

The scent of coffee was the olfactory cue, delivered to the test subject via a small oxygen mask connected to a canister of coffee grounds and a small pump. The coffee smell is provided in the reception area where a coffee maker can be seen. The relay switch described above was used to enable/disable the coffee pump. Another pump supplies constant fresh air to disperse the coffee scent once the subject leaves the reception area.

3.4 Questionnaires

The first questionnaire had 14 questions that related to the sense of presence. The questions of primary interest were: a rating question on overall presence where 100 signified highest presence "I felt I was actually in the office" and 0 signified no sense of presence "I felt like I was looking at pictures of the office." The next 13 questions were adapted from two presence questionnaires that have appeared in the literature [4,7].

Figure 5. Large office in high detail

The subjects were also asked to answer 14 questions that asked about the location of items in the office (e.g., in what room was the coffee pot located) and questions about the general layout of the office space (e.g., what room was closest to the reception area). Of the 14 questions, five were filler/catch items. The remaining nine could be broken into two types or subscales: four spatial layout questions and five object location questions. For all of these questions the participant answered by selecting from a list of eight choices, which included all the rooms in the environment, "Nowhere" and "Do not remember".

3.5 Procedures

The participants in the experiment were asked to evaluate a virtual environment system that could be used by real estate brokers. The idea was that a customer looking for office space to rent could tour the virtual offices and then make a decision about what office space to rent, or at least to decide what offices to see in person. Each subject was given a sheet explaining this scenario and told that they would be looking at one such office and then be asked to evaluate the effectiveness of the system. Participants were also told that the virtual environment could present multiple sensory cues: odors, ambient sounds, heat, wind. However, it was stressed that some participants would get none of these cues or a subset of the cues.

Prior to the office tour, participants started in a training room which contained various objects, such as books on the floor directly in front, a table and vase in the rear, and a speaker above. This training room allowed the subjects, who were not familiar with virtual environments, to become accustomed to maneuvering

Figure 6. Large office in low detail

in virtual space. To ensure that the subjects were comfortable in a virtual environment, the participants were asked to find each of five objects that were scattered throughout the practice virtual environment.

After completion of the training procedure, participants were placed in the experimental virtual environment. The tour of the virtual office space required approximately 5 minutes. During the experimental virtual office tour, all subjects wore both the face mask for smells and the head phones for sounds. During the actual tour, subjects were moved into a room in the office. They were then told (via the headphones) the name of the room and asked to look around. In all rooms the participants were moved to two different locations. On entering each room they were told, for example, "This is the reception area. Please look around the room". Participants could not control their location except for head movements. At the completion of the virtual office tour, the participant was asked to fill out the two sets of questionnaires described previously.

Figure 7. VR Setup

4. Results

The results of this study will be presented in two sections. In the first section we will present analyses that test the effects of visual, tactile, auditory, and olfactory cues on the subjects' subjective sense of realism or presence of the environment. In the second section we will present results that investigate the effects that these cues have on the subjects memory for the environment and the objects in that environment.

4.1 Subjective Measures of Presence and Realism

As described in section 3.4 there were two primary measures of realism and presence: the first measure was the 100 point rating scale for the overall sense of presence; the second measure was the 13-item questionnaire on presence (see APPENDIX).

Initially we performed a 2 (level of visual detail) by 2 (olfactory information) by 2 (auditory information) by 2 (tactile information) analysis of variance on the 100 point scale of presence. This analysis revealed significant main effects of auditory cues [$F(1,263) = 8.24$, $p < .01$] and tactile cues [$F(1,263) = 5.81$, $p < .02$]. As expected, overall sense of presence was higher when ambient sounds were added to the environment and when tactile cues were presented in the environment. There was also a non-significant trend for olfactory cues [$F(1,263) = 2.53$, $p < .11$]. Again, adding an olfactory cue tended to make the rating of presence higher. Of interest is the failure of the level of visual cues to have an effect on the perceived sense of presence. Also the analysis revealed no significant interaction effects.

Table 1
Means and Standard Deviations of Presence Rating and Presence Questionnaire by Cue Type

Measure	100 Point Rating		13-Item Questionnaire	
Condition	Mean	s.d.	Mean	s.d.
Visual-High	66.2	18.1	43.1	9.0
Visual-Low	66.4	17.2	43.1	9.2
Tactile-Yes	68.9	16.9	45.3	8.7
Tactile-No	63.9	18.1	40.7	9.0
Auditory-Yes	69.3	16.1	46.0	8.7
Auditory-No	63.4	18.6	39.2	8.2
Olfactory-Yes	68.1	17.1	44.8	9.4
Olfactory-No	64.7	18.1	41.8	8.7

The same 4-way analysis of variance was also performed on the total score of the 13-item questionnaire on sense of presence. This analysis revealed the same general pattern of results. There were significant main effects of tactile cues [$F(1,233) = 18.30$, $p < .001$] and auditory cues [$F(1,233) = 36.66$, $p < .001$]. There was a greater sense of presence with the addition of ambient sounds and tactile cues. Again, there was a trend for olfactory cue [$F(1,233) = 2.401$, $p < .12$]. As in the previous analysis, there were no significant interaction effects.

4.2 Memory Measures

The questions on the memory test can be broken into two types: 4 questions that tested memory for the spatial layout of the office (e.g., "The bathroom was closest to what room?"); and 5 questions that tested memory for the location of specific items in the environment (e.g., "The fan was located in what room?"). As with the measures of presence, the analyses for each of these measures will be presented separately.

4.2.1 Spatial layout. Initially we performed a 2 (level of visual detail) by 2 (olfactory information) by 2 (auditory information) by 2 (tactile information) analysis of variance on spatial layout. This analysis revealed no significant main effects or interactions. The overall recall for all conditions was 2.15 questions correct.

Of the four questions on spatial layout there was one question that was tied directly to an ambient sound. When subjects passed the bathroom in the ambient sounds condition they heard a toilet flush. Therefore we could compare memory for the location of the bathroom for the subjects who had the ambient sounds to those that did not. This analysis revealed that more subjects recalled the location of the bathroom with the auditory cue (mean = 69.7%) than when there was no auditory cue (mean = 58.7%).

Table 2
Means and Standard Deviations of Number of Correct Responses on Tests of Spatial Layout and Object Location by Cue Type.

Measure	Spatial Layout		Object Location	
Condition	Mean	s.d.	Mean	s.d.
Visual-High	2.13	0.8	2.57	1.0
Visual-Low	2.17	0.8	2.63	0.9
Tactile-Yes	2.02	0.7	2.76	0.9
Tactile-No	2.26	0.8	2.43	1.0
Auditory-Yes	2.19	0.7	2.51	1.0
Auditory-No	2.10	0.8	2.67	0.9
Olfactory-Yes	2.14	0.7	2.78	0.9
Olfactory-No	2.15	0.8	2.40	1.0

4.2.2 Object Location. We next performed the same 4-way analysis of variance on the total score of the 5 questions of memory for the location of objects. This analysis revealed a significant main effect of olfactory cue [$F(1,272) = 11.52$, $p < .001$] and of tactile cues [$F(1,272) = 8.46$, $p < .01$]. Recall was higher for the subjects who had tactile cues and for subjects who had an olfactory cue in their environment. Neither the remaining two main effects or the interaction effects reached significance.

To determine what caused the increase in recall of the location of objects, we compared the percentage of participants who recalled specific objects when they had or did not have additional sensory cues. Due to the nature of the cues we provided for ambient sounds, we did not have a specific question that related directly to that cue. However, we did have a question that directly related to one tactile cue (wind associated with the fan) and one olfactory cue (the smell of coffee with the coffee pot). In this comparison we found that more subjects recalled the fan's location when there was a tactile cue (mean = 86.7%) than when there was no tactile cue provided with the fan (mean = 62.7%). We also compared recall of the location of the coffee pot for subjects who received the olfactory cue with those who did not. Again, we found that providing the addition cue increased performance, as 95.1% of the people recall the coffee pot's location when the olfactory cue was provided, while only 59.4% of the people who did not receive the olfactory cue recalled its location.

5. Discussion

The findings of this study suggest that additional sensory input can increase both the sense of presence in a virtual environment and memory for the objects in the environment. Overall sense of presence increased with the addition of tactile and auditory cues. There was also a trend for olfactory cues. Based on our failure to find significant interactions, it appears that the additional sensory cues work in a simple additive fashion on one's sense of presence. The more sensory cues that are added, the greater the sense of presence.

One surprising finding of our study was that, while adding auditory, tactile and olfactory cues increased the user's sense of presence, increasing the level of visual fidelity did not. While this finding may at first seem counter-intuitive, we would argue that it is not. Overall, visual displays are the core of any virtual environment. This is true even in the low level of visual fidelity condition. In this experiment we were manipulating the relative quality of the visual display. In the lower quality visual display condition visual cues were present, they were just not as good as the visual cues in the high fidelity visual condition. For the other sensory modalities, the cues either existed, or they did not. Therefore there was a stronger test of the other sensory modalities. In addition, if we think about the quality and amount of visual cues that are present in the real world (say one was looking at the actual office space) then the relative difference between the two levels of visual fidelity used in our experiment both represent minor changes at the lower end of the visual quality spectrum. *This is still significant, however, since the difference in computational resources required to provide the higher level of visual fidelity is considerable, while the addition of the other sensory cues required relatively little extra computation.*

The results suggest that the addition of sensory cues other than visual may be an effective way to manage the level of detail and frame rate tradeoff that exists in virtual environments. As we briefly outlined in the introduction, we know that presence (and performance in most tasks) increases with increased levels of visual detail and realism. However, as visual detail increases, system responsiveness (e.g., frame rate) goes down, due to the computational cost of rendering a more complex visual scene. This lower level of system responsiveness decreases the sense of presence and performance in a virtual environment [12].

Our non-visual sensory cues required little computation, therefore we were able to increase the sense of presence without lowering system responsiveness. In fact, if we had not fixed an upper limit for the frame rate in the low visual condition to control for that effect, the average frame rate would have been almost twice as fast as in the high visual condition. Our work suggests that a designer of a virtual environment could increase the sense of presence and memory for an environment with the use of additional non-visual sensory cues. This augmentation yields an increased sense of presence with no decrease in system responsiveness.

6. Acknowledgments

We would like to thank Aileen Worden, Ben Watson, Donita Phipps, and Randy Carpenter for their help in getting this research done. Special thanks to Jarrell Pair for creating and mixing the audio files. Thanks to Doug Bowman and several anonymous reviewers for reading and commenting on an earlier version of the paper. This work was funded, in part, by a seed grant from the Graphics, Visualization & Usability Center and a grant from the Office of Naval Research.

7. References

1. Barfield, W. and Hendrix, C. The effect of update rate on the sense of presence in virtual environments. *Virtual Reality: Research, Development, Applications*, 1,1 (1995), 3-15.

2. Barfield, W. and Danas, E. . Comments on the use of olfactory displays for virtual environments. *Presence: Teleoperators and Virtual Environments*, 5,1, (1996), 109-121.

3. Cater, J.P. (1992). The nose have it! *Presence: Teleoperators and Virtual Environments*, 1,4, pp. 493-494.

4. Fontaine, G. The experience of a sense of presence in intercultural and international encounters. *Presence: Teleoperators and Virtual Environments*, 1,4 (1992).

4. Hendrix, C. and Barfield, W. Presence within virtual environments as a function of visual display parameters. *Presence: Teleoperators and Virtual Environments*, 5, 3, (1996), 274-289.,

5. Heilig, Morton (1962). U.S. Patent #3,050,870.

6. Hendrix, C. and Barfield, W. , The sense of presence with auditory virtual environments. *Presence: Teleoperators and Virtual Environments 5,3* (1996), 290-301.

7. Ikei, Y,, Wakamatsu, K,, and Fukuda, S. Texture presentation by vibratory tactile display. *Proceedings of the IEEE 1997 Virtual Reality Annual International Symposium* (1997) 199-205.

8. Krueger, M. Reality stinks and so should virtual reality. Keynote address at *VRMM96* in Gifu, Japan (1996).

9. Ogi, T. and Hirose, M. . Multi-sensory data sensualizaton based on human perception. *Proceedings of the IEEE 1996 Virtual Reality Annual International Symposium (1996)*, 66-70.

10. Shimojo, M., Shinohara, M. and Fukui, Y. Shape identification performance and pin-matrix density in a 3 dimensional tactile display. *Proceedings of the IEEE 1997 Virtual Reality Annual International Symposium* (1997), 180-187.

12. Watson, B., Walker, N., Ribarsky, W. & Spaulding, V. The effects of mean and variation of system responsiveness on performance in virtual environments. GVU Technical Report, Georgia Institute of Technology, (1997) to appear in *Human Factors*.

APPENDIX

The Rating Question. If your level of presence in the real world is "100" and your level of presence is "1"' if you lack presence, rate your level of presence in this virtual world (presence is a "feeling of being there"). Enter a number 1-100.

The 13 Other Presence Questions. Subjects were asked to rate each question on scale of 1-5 where 1=poor, 2=fair, 3=good, 4=very good, and 5=excellent.

1. How strong was your sense of presence in the virtual environment?
2. How strong was your sense of "being there" in the virtual environment?
3. How strong was your sense of inclusion in the virtual environment?
4. How aware were you of the real world surroundings while moving through the virtual world (i.e., sounds, room temperature, other people, etc.)?
5. In general, how realistic did the virtual world appear to you?
6. How realistically were you moved through the virtual world?
7. With what degree of ease were you able to look around the virtual environment?
8. Do you feel that you could have reached into the virtual world and grasped an object?
9. What was your overall comfort level in this environment?

10. What was your overall enjoyment level in the virtual environment?
11. Please rate your sense of being there in the computer generated world.
12. To what extent were there times during the experience when the computer-generated world became the reality for you, and you almost forgot about the "real world" outside?
13. What was the quality of the visual display?

The 14 Location Questions. Subjects were asked to circle one or more of: balcony, copy room, smaller private office, bathroom, larger private office, reception area, nowhere, don't remember.

1. Where were the flowers located?
2. Where was the fan located?
3. Which area was visited before the copy room?
4. What area is located furthest from the reception area?
5. What area is located closest to the reception area?
6. Where is the coffee pot located?
7. Which area was the warmest?
8. What area is visited immediately before the balcony is visited?
9. Where is the green couch located?