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Visual Touch In Virtual Environments:

An Exploratory Study of Presence, Multimodal Interfaces, and Cross-Modal Sensory Illusions

Abstract

How do users generate an illusion of presence in a rich and consistent virtual environment from an impoverished, incomplete, and often inconsistent set of sensory cues? We conducted an experiment to explore how multimodal perceptual cues are integrated into a coherent experience of virtual objects and spaces. Specifically, we explored whether intermodal integration contributes to generating the illusion of presence in virtual environments.

To discover whether intermodal integration might play a role in presence, we looked for evidence of intermodal integration in the form of cross-modal interactions—perceptual illusions in which users use sensory cues in one modality to "fill in" the "missing" components of perceptual experience. One form of cross-modal interaction, a cross-modal transfer, is defined as a form of synesthesia, that is, a perceptual illusion in which stimulation to a sensory modality connected to the interface (such as the visual modality) is accompanied by perceived stimulation to an unconnected sensory modality that receives no apparent stimulation from the virtual environment (such as the haptic modality). Users of our experimental virtual environment who manipulated the visual analog of a physical force, a virtual spring, reported haptic sensations of "physical resistance," even though the interface included no haptic displays. A path model of the data suggested that this cross-modal illusion was correlated with and dependent upon the sensation of spatial and sensory presence.

We conclude that this is evidence that presence may derive from the process of multimodal integration and, therefore, may be associated with other illusions, such as cross-modal transfers, that result from the process of creating a coherent mental model of the space. Finally, we suggest that this perceptual phenomenon might be used to improve user experiences with multimodal interfaces, specifically by supporting limited sensory displays (such as haptic displays) with appropriate synesthetic stimulation to other sensory modalities (such as visual and auditory analogs of haptic forces).

1 Introduction

The design of virtual environments relies on the quality and experience of intersensory illusions. Therefore, the National Research Council panel on virtual environment design recommended the study of these illusions:

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> VEs themselves can be regarded as integrated sets of illusions. Detailed study of both intrasensory illusions and intersensory illusions is important, because, in many cases, the existence of illusions enables VE system design to be simplified and, therefore, to increase its cost-effectiveness. (Durlach & Mavor, 1994, p. 94)

We report a preliminary study that suggests the existence of a relationship between the illusion of presence and cross-modal illusions: specifically, that visual cues alone can generate significant cross-modal haptic illusions in the absence of haptic displays.

2 Does Cross-Modal Sensory Integration Play a Role in the Illusion of Presence?

It is widely reported that users of virtual environment systems experience varying levels of presence within the virtual environments. (For reviews, see Barfield, Zeltzer, Sheridan, and Slater (1995), Lombard and Ditton (1997), and Stanney (1998).) Users experience relatively coherent and consistent virtual environments. The phenomenon of presence raises an interesting question regarding cross-modal sensory integration, namely, how do users generate a sense of presence in a rich and consistent virtual environment from an impoverished, incomplete, and often inconsistent set of sensory cues?

First, consider how virtual environments provide incomplete or impoverished sensory cues when compared to the physical environment. For example, most interfaces engage only a fraction of human sensory bandwidth (Barfield, Hendrix, Bjorneseth, Kaczmarek, & Lotens, 1995; Biocca, 2000). Often, the displays of the virtual environment provide no direct stimulation to several sensory channels (such as haptic, proprioceptive, and olfactory). Within each stimulated sensory channel (such as visual and aural), the displays may not support many sensory cues (such as dynamic shadows) or they may provide inconsistent cues (such as depth information from ocular convergence) (Durlach & Mavor, 1994).

Secondly, consider how often sensory cues from the virtual environment are inconsistent across sensory modalities or are in conflict with other cues provided by the physical environment. Because the virtual and physical environments are often inconsistent world models, sensory stimuli to different sensory modalities from the physical and virtual environments are often inconsistent, providing conflicting models of the world (for example, gravity and motion cues). Users may experience sensorimotor conflict from the inconsistent or altered mappings of sensory stimuli to motor actions (Biocca, 1992; Kennedy, Hettinger, & Lilienthal, 1987; Kolasinski, 1995; Stanney, 1998; Welch & Warren, 1986). For example, the virtual image of the hand may be in a different spatial location than the felt proprioceptive location of the hand. Such conflicts can trigger disturbing examples of perceptual adaptation, such as significant rearrangements of hand-eye coordination (Biocca & Rolland, 1998).

Nonetheless, even under conditions in which many sensory cues are missing, impoverished, or in conflict, users may report high levels of presence and a coherent experience of another space. This suggests that when users integrate the sensory stimuli they must somehow construct a more-to-less consistent mental model of the virtual environment. Does this process of constructing a coherent mental model contribute to a sense of presence? The ability of users to feel "present" suggests a pair of key research questions explored in this study:

- Does the process of reconciling incomplete or inconsistent multimodal cues during cross-modal sensory integration contribute to presence?
- Do users who experience higher levels of presence integrate or fill in more sensory details to generate a coherent mental model of the virtual environment?

Answering these questions might give us a better grasp of multimodal interaction and the psychological causes and correlates of the illusion of presence.

3 Multimodal Interactions in Virtual Environments

The illusion of a virtual environment involves constructing a mental model of the perceptual world from the interaction of multimodal cues from the visual, aural, and tactile displays. (See discussions of intersensory coordination in Begault (1994), and Durlach and Mavor (1994).) Considered broadly, cross-modal interactions in virtual environments include various intended and unintended interactions among the sensory and motor channels. Table 1 is a typology of different kinds of cross modal interactions in virtual reality systems. Some of these are intentionally designed, for example, the cross-modal mappings of cues from one sensory channel to another. Some are unintentional or unwanted, such as the intersensory conflict contributing to simulation sickness and perceptual adaptation (Biocca, 1992; Kolasinski, 1995; Stanney, 1998). The design and coordination of multimodal cues and the user's perceptual integration of those cues are particularly critical when users must perform frequent and precise motor movements such as reaching, manipulating, and placing objects (Biocca & Rolland, 1998; Welch, 1998).

Researchers are most aware of the effects of multimodal interactions when integration fails in an interface and it produces unwanted effects. For example, Biocca and Rolland (1998) found that an augmented-reality visual display that displaced the phenomenal location of the eyes by a few millimeters led to decrements in hand-eye coordination in an object manipulation task, followed by adaptation, and finally to significant aftereffects. Users left the system with noticeable discoordination in rapid hand-eye movements. In an effort to integrate what started out as discrepant multisensory cues, the user's visual motor system adapted and adjusted the processing of visual inputs and haptic outputs. This resulted in a user who was temporarily adapted to the new, altered sensory order of the augmented-reality environment, but was significantly discoordinated when exiting the system to manipulate objects in the physical environment.

4 Intermodal Integration and Cross-Modal Transfer in Virtual Environments

The human sensorimotor system is designed to experience the world as a whole, merging and synthesizing input from different sensory modalities in an ongoing and dynamic fashion. Each sensory system appears quite independent. However, research on intermodal integration suggests that this impression of sensory independence is "more illusory than real" (Stein, Wallace, & Meredith, 1995, p. 683).

Illusions in virtual environment systems may be greatly assisted by the process of intermodal integration and the "assumption of unity" (Welch & Warren, 1980). Users of virtual environments may have an assumption that multimodal stimuli emanate from a single focal object or event, because objects or events in the physical world have redundant cross-modal cues.

Information from one modality (such as visual) can interact with information from other modalities (such as aural or haptic) to enhance the properties of the illusion in an interacting modality, "fill in" information or disambiguate information in another modality, or drive attention to a location, object, or event (Stein et al., 1995; Stein & Meredith, 1993; Welch & Warren, 1986). For example, in table 1 we listed one type of cross-modal interaction that involves the perceived enhancement or decrement of unimodal cues. This involves perceptions of an object or event in which the property of a stimulus in one sensory modality alters the experience of stimulus properties that are presented in another sensory modality. Numerous studies in various aspects of human perception indicate that stimuli in one modality can alter experience in another. (See reviews Cytowic (1989), Marks (1978), Stein and Meredith (1993), Welch (1978), and Welch and Warren, (1986).) Although intersensory interactions vary, the visual sensory channel is more likely to skew the interpretation of information processed by the other senses, a phenomenon sometimes referred to as "visual capture." (See the review by Welch and Warren (1980).) Next, we briefly consider how the visual sense sometimes dominates in visual-to-haptic and visual-to-aural intersensory biases and cross-modal interactions.

4.1 Visual-to-Haptic Intersensory Biases and Cross-Modal Interactions

A classic example of visual-to-haptic intersensory interaction is the size-weight illusion (Cross & Rotkin,

Table 1. *A Taxonomy of Different Kinds of Cross-Modal Sensory Interactions in Virtual Environments*

Cross-modal sensory interactions in VEs	Descriptions	Examples
Amodal mapping	Use of VE or other representational system to map abstract or amodal information (e.g., time, amount, etc.) to some continuous or discrete sensory cue (e.g., color, size, depth, etc.).	The use of color mapping and relative size in graphics and scientific visualization to represent money, time, etc.
Cross-modal mapping	Use of a VE to map one or more dimensions of a sensory stimulus to another sensory channel. Typical mappings are auditory-to-visual, visual-to-haptic. The mapped cues may be simultaneous and redundant (e.g., beeping sound and flashing light) or a replacement (e.g., sound source, such as a beep, mapped and experienced as a visual analog, such as a flashing light).	An oscilloscope. Auditory stimuli are transformed to oscillations of a line. The user benefits from the analytical and pattern-perception capabilities of the visual system to analyze the properties of sound.
Intersensory biases and adaptations	Stimuli from two or more sensory channels may represent discrepant/conflicting information about a virtual object, e.g., its spatial location. As the users attempt to perceptually integrate the discrepant information, they may experience immediately (1) sensorimotor illusions usually biased towards one sensory modality, e.g., incorrect distance judgments; or, over time, (2) simulation sickness or other discomfort, and/or (3) adaptation/recalibration of a sensory or motor modality.	"Ventriloquism effect" when spatially discrepant audio and visual cues are experienced as colocalized with the visual cue. In immersive VR systems, lag in visual update rate may be experienced as a potentially nauseating conflict between the visual and proprioceptive systems (i.e., the world appears to "swim" back-and-forth around the head).
Cross-modal enhancement or modification	Stimuli from one sensory channel enhances or alters the perceptual interpretation of stimulation from another sensory channel. Interactions might include changes in detectability, perceived intensity, perceived fidelity, or some other perceptual quality of the stimuli from another sensory channel.	Increased perceived visual fidelity of display as a result of increased auditory fidelity. Changes in the perceived location or intensity of a haptic force based on changes in visual cues. Increased ability to hear and process speech as result of seeing synchronized lip movement.
Cross-modal transfers or illusions (synesthesia)	Broadly, all environments: Stimulation in one sensory channel leads to the illusion of stimulation in another sensory channel. Narrowly, virtual environments: Stimulation from one sensory display, leads to the illusion of stimulation in a sensory channel not connected to a display.	Experience of visual sensations (e.g., colored or pulsating lights) when hearing sounds. Illusion of haptic sensations from a visual cue.

1975). Lifting two objects of equal weight but different volumes, participants perceive the larger volume to be lighter than the smaller volume. Although both haptic and visual cues contribute to this illusion (Ellis & Lederman, 1993), visual cues alone are sufficient. So perceived weight—or, more generally, the perception of inertial forces—may be an interaction of visual and haptic cues.

A recent experiment demonstrated how visual and haptic cues might interact in the perception of a virtual environment. Lecuyer and his colleagues (Lecuyer, Coquillart, & Kheddar, 2000) found that the perceived resistance of an isotonic haptic force on a spaceball was influenced by the visual cue (the degree to which a virtual spring was visually compressed).

In virtual environments, it is not uncommon for the felt and visual location of the hand to be misaligned and discrepant. Numerous studies show that, when visual and proprioceptive cues of the location of the hand are discrepant, the perceived location of the hand or a haptic stimulus to the hand will be strongly influenced by visual cues. (See, recently, Pavani, Spence, and Driver (2000), and the review by Welch and Warren (1980).)

4.2 Visual-to-Aural Intersensory Biases and Cross-Modal Interactions

A classic example of a visual-to-aural intersensory interaction is the ventriloquism effect (Howard & Templeton, 1966). In the ventriloquism effect, the spatial cues from the visual sense dominate over the spatial cues of the aural senses to distort the perceived location of a sound. The sound is experienced as colocalized with the visual cue. Because the audio speakers in film, television, and computer systems are rarely positioned in the same location as the images of the sources of sound, this intersensory interaction makes the integration of the visual and aural coherent and consistent, the experience satisfactory, and the limitations of the technology acceptable.

Although the visual channel can be dominant in intersensory interactions, auditory stimuli can also affect perceived properties of visual stimuli. For example, some studies report that increasing audio fidelity can enhance the perceived fidelity of the video monitor (Neuman, Crigler, & Bove, 1991; Reeves, Detember, & Steuer, 1993; Reeves & Nass, 1996). The interactions between visual and auditory stimuli in the perception of the quality of audiovisual systems are systematic (Hollier, Rimell, Hands, & Voelcker, 1999).

5 Cross-Modal Transfers from One Sensory Channel to Another: Synesthesia

An extreme case of cross-modal interaction involves experience in which sensory stimulation of one sensory channel produces experiences in another unstimulated sensory channel. One form of this is the controversial phenomenon commonly referred to as synesthesia (Baron-Cohen, Wyke, & Binnie, 1996; Cytowic, 1989, 1995; Marks, 1978; Watkins, 1997). Synesthesia can be defined as follows:

> Synesthesia is an involuntary joining of the senses in which the real information of one sense is accompanied by a (virtual) perception in another sense. In addition to being involuntary, this additional perception is regarded by the synesthete as real, often outside the body, instead of imagined in the mind's eye. (Cytowic, 1989, p. 3)

Although synesthesia can be dramatic, it may be just a subclass of a much broader class of cross-modal interactions. Synesthesia may be "natural," because the phenomenal intuition of the separation of the senses in any perceptual act is illusory, as the senses are fundamentally integrated and cross-modal (Marks, 1978; Stein & Meredith, 1993).

How common are synesthetic experiences in physical environments? Some researchers suggest that synesthesia may be common and normal in the early stages of development (Baron-Cohen et al., 1996). Although adults differ greatly in the intensity, consistency, and reliability of synesthetic experiences, reports of cross-modal transfer and phenomena suggest that synesthetic experience can be found in the general population (Cytowic, 1995). Some of these experiences may be little more than cross-modal associations, but others appear to be durable, vivid, and reproducible.

Might the experience of cross-modal transfers (synesthesis) be more frequent in virtual environments than in physical environments? Reports of synesthesia in physical environments are often of cross-modal illusions that are not normally associated with the originating stimuli. A common report is the experience of colored lights with specific sounds. This coupling does not reflect typical couplings in the physical environments, as everyday experience of a sound does not suggest that it should be associated and consistently trigger the experience of colored lights. In most other physical stimuli, the sensory cues are normally consistent and copresent: an object such as a face may emit visual, aural, and haptic stimuli.

In virtual environments, stimuli that would normally be coupled to other sensory stimuli are often artificially decoupled. Surfaces appear solid and textured, but they provide no haptic sensation when touched. This suggests the following theoretical proposition:

> Theoretical Proposition 1: Although in physical environments synesthesia is often an abnormal coupling of sensory experiences, in virtual environments synesthesis might involve the coupling of normally linked sensations. Therefore, reports of cross-modal illusions should be more frequent in virtual environments than in physical environments, because users may automatically infer normally coupled sensations during intersensory integration.

To put this proposition another way, the absence of so many "missing" sensory cues in virtual environments may invite some users to "fill in" the missing sensations. In environments impoverished in stimuli in which the user must act, the user may need to interpolate sensory stimuli to create a functional spatial mental model.

5.1 Can Virtual Environments Be Designed to Induce Cross-Modal Sensations?

Inducing synesthetic experiences might be useful in improving the quality and texture of experience in virtual environments and, possibly, enhancing the sense of presence.

In physical environments, synesthesia can be experienced in nonsynesthetes if "properly catalyzed" (Marks, 1978). There are a number of reports of cross-modal illusions and synesthesia in individuals catalyzed by direct brain stimulation and some drug reactions (Cytowic, 1989). In the last century, a number of multimedia performances (for example, sound and light shows) intended to stimulate synesthetic experiences (Cytowic, 1989). If synesthesia may be commonly experienced in the newborn, it might be induced in the adult brain (Baron-Cohen et al., 1996).

We previously noted that, in virtual environments, sensory cues are artificially decoupled and missing. Therefore, it may be possible to induce the synesthesis of what in the physical environment would be a naturally coupled sensory cue. Inducing synesthesia in a virtual environment would involve the design of stimuli that elicit the naturally coupled cue.

A dramatic example of how normally coupled sensations can produce strong visual-to-haptic cross-modal transfers from visual stimuli is provided by the reports of sensations from individuals with amputated arms (Ramachandran & Rogers-Ramachandran, 1996; Ramachandran, Rogers-Ramachandran, & Cobb, 1995). When shown a moving image of their intact arm reflected in a mirror so that it appeared in the location of the lost arm, patients reported "feeling" their missing limb. The point here is that synesthesia of a normally coupled sensation was induced by a visual illusion, in this case a virtual image of a moving limb.

Work on intermodal integration, therefore, suggests that appropriately designed virtual environments may induce two types of intermodal interactions in virtual environments: cross-modal enhancement and decrement, and cross-modal transfer (synesthesia). In the experiment that follows, we attempted to find evidence of the less common effect: cross-modal transfer or synesthesia.

6 Hypotheses

To manipulate objects and move around a virtual environment, users must construct some spatial mental model of the virtual environment. In immersive virtual environments, users use this model to guide action, but the stimuli used to construct this model often involve information in only one channel and weak cues. The neuroscience literature on cross-modal interaction suggests that weak signals sometimes produce big effects: multisensory cells work nonadditively but multiplicatively, with multiplicative factors highest when signals are lowest and smallest when signals are high (Stein et al., 1995). In virtual environments, normally coupled sensations are absent, such as the visual and haptic sensations of a manipulated object. In the process of creating and acting on the spatial mental model, some users of virtual environments may "fill in" other sensory attributes to create a mental model of the virtual world that is consistent with multisensory experiences of physical environments.

> Hypothesis 1: When building a spatial mental model of the virtual environment, users of immersive virtual reality systems sometimes experience a form of cross-modal transfer or synesthesia.

Because most virtual environments focus on the visual modality, the first hypothesis can be extended more precisely:

> Hypothesis 2: Users of virtual environments sometimes experience visual-to-haptic cross modal transfers (synesthesia) when manipulating objects.

As we noted above, the visual sensory channel tends to be dominant in many cross-modal interactions, producing what is commonly called "visual capture" (Pavani et al. (2000), Welch (1999); for related reviews, see Welch and Warren (1986). During the planning of motor actions, multisensory neurons may play an important role in the creation of egocentric spatial models, and they may play a role in attention and orientation. Attention to objects in a virtual space prior to and during their manipulation may require that users carefully construct a spatial model. So attention to the objects and visual cues of physical resistance may induce users to experience visual-to-haptic synesthesia when attending to and manipulating virtual objects.

> Hypothesis 3: Users of immersive virtual environments sometimes experience visual-to-aural cross modal transfers (synesthesia) when manipulating objects.

Objects in the physical world often make some sound when manipulated. Virtual environments can sometimes be silent, so that objects make no noise at all when manipulated. In physical environments, visual stimuli are often coupled to predictable sounds, such as moving mouths and vocalizations, hands clapping and the associated sound. In some cases visual cues during virtual object manipulation may induce some users to "fill in" expected sounds and experience visual-to-aural synesthesia.

6.1 Intermodal Integration and Presence

Spatial cognition is fundamentally intermodal and multisensory (Anderson, Snyder, Bradley, & Xing, 1997; Bryant, 1992; Foreman & Gillet, 1997, 1998; Paillard, 1991). In immersive virtual environments, inputs from the visual, auditory, and somatosensory systems contribute to a coherent spatial mental model. Intermodal integration constructs the spatial mental model of the virtual environment.

It is possible that, during the process of intermodal integration, some users may generate synesthetic illusions during the filling-in process of building a coherent spatial mental model of the environment. We hypothesize that the richer the mental model of the virtual environment the greater the level of presence. Evidence of this richer mental model may be the accompanying experience of presence. Both presence and synesthesia may be phenomenal byproducts of the same intermodal integration process, the building of a rich spatial mental model of the environment. If both presence and cross-modal illusions are the result of intermodal integration, then they should be correlated. This suggests the following theoretical proposition:

> Theoretical Proposition 2: In conditions of higher presence, the stimulation of one sensory channel may induce "virtual" sensation in the normally coupled sensory channel.

If this were the case, we would expect individuals who are more likely to experience presence to be prone to synesthesia in these environments.

Therefore, we hypothesize that the experience of induced synesthesia and presence in virtual environments are correlated, and that users who experience higher levels of presence may also experience higher incidences of cross-modal illusions.

Hypothesis 4: Users experiencing higher levels of presence are more likely to experience cross-modal illusions (synesthesia) in virtual environments.

7 Method

Our exploratory study of synesthesia was part of a larger experiment on presence in narrative virtual environments. The details of the narrative theory and hypotheses of the main experiment are reported elsewhere (Biocca, Kim, & Brady, 2000). For the purposes of this exploratory part of the study, it is important to note that participants entered one of two virtual environments: a medical anatomy simulation called the Hands-on Virtual Cadaver (Tang, Maslowski, & Biocca, 2000) or a similar control environment made up of geometric primitives (see section 7.2).

7.1 Participants

A convenience sample of eighty students from a large midwestern university participated in the study for extra credit. (Students were also given the choice of an alternative extra-credit activity other than participation in the study.) Participants were randomly assigned to experimental conditions.

7.2 Stimulus Materials

7.2.1 Immersive Virtual Reality System. Participants were exposed to a 3-D stimulus environment using an immersive virtual reality system. The hardware platform was the SGI Onyx Reality Engine with two graphics pipes. Multigen Smart Scene software was used to create the 3-D virtual environments. The environments were displayed to the participants through a V8 Virtual Research, stereoscopic, head-mounted display. A Polhemus magnetic tracker measured the position of the participants' head and hands, and the position data were used to move the participants' viewpoints in the virtual environment and to display a 3-D cursor (a blue transparent sphere with embedded tubular cross) for each of their hands. Fakespace pinch gloves allowed participants to grab and move objects by pinching their fingers together. Because of the nature of this study, it is important to underline the fact that the virtual reality system did not include any tactile or force-feedback displays. The virtual environment included no sounds, and participants did not wear headphones during the study.

7.2.2 Virtual Hands-On Cadaver Environment. Forty-nine (66.2%) participants were exposed to the Virtual Hands-on Cadaver Environment that was developed by Media Interface & Network Design (M.I.N.D.) Lab (Tang et al., 2000). See figure 1. The environment was composed of a 3-D room that resembles a doctor's examining room. The room included an examining table with a cadaver and medical charts on the wall. The cadaver was a realistic skeleton with eight complete organs inside its ribcage. The ribcage and organs could be grasped by the participant and removed in the immersive virtual reality system.

7.2.3 Control Virtual Environment. The control virtual environment was similar in size and shape to the test virtual environment, but, instead of the virtual cadaver, participants saw a collection of simple symmetrical polygonal shapes (cubes, cones, and spheres) that matched the number of objects in the virtual cadaver environment and occupied the same area and location. Twenty-five participants (33.8%) interacted with this environment.

7.3 Measures

7.3.1 Presence. A set of scales were used to measure the participants' level of presence, often described as the sense of "being there" in the virtual envi-

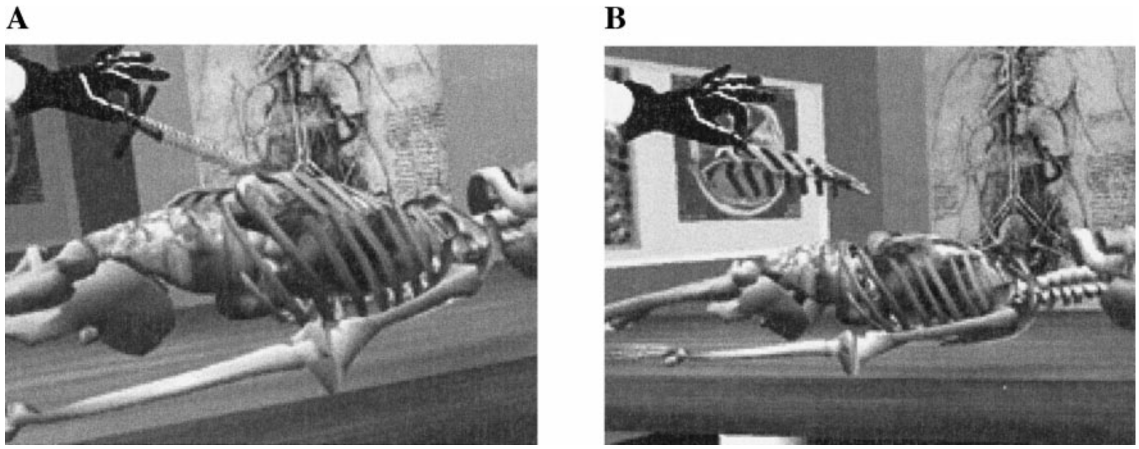

Figure 1. *The test environments contained either a "medical office room" with a table on which there was a skeleton with removable internal organs, or a matching, more semantically neutral "geometric primitives room" similar to the medical room. The geometric primitives room had a crate on the table that contained removable geometric primitives matching the size and location of the virtual cadaver. In both rooms, users could grasp selected objects in their hands with a finger-to-thumb pinch gesture. A spring indicated that an object was being pulled away from its "snap" location (figure A). When the user pulled on the object a sufficient distance the spring was retracted and the object "popped" into their hand (figure B). (The Fakespace pinch glove is made visible here for purposes of this illustration).*

ronment (Barfield et al., 1995; Held & Durlach, 1992; Steuer, 1995; Witmer & Singer, 1994). This scale was modified from the scales collected by Lombard and Ditton (1999). See appendix A.

7.3.2 Synesthesia. Two items were used to measure the degree of reported synesthesia. One item measured the degree to which the participants felt "physical force" and the other the degree to which the participants "heard a sound" when manipulating the objects in the virtual environment. (The exact wording of the questions was: "How often did you feel physical resistance such as gravity and inertia from the objects that you tried to move?" and "How often did you hear sounds made by the objects that you tried to move?")

7.3.3 Other Measures. A number of other measures not reported here were collected, including mood (Lang, Greenwald, Bradley, & Hamm, 1993; Lang & Greenwald, 1985), recognition memory, need for cognition (Cacioppo & Petty, 1982; Cacioppo, Petty, & Kao, 1984), time perception (Fraisse, 1963, 1984), demographics, and levels of computer experience. (See Biocca et al. (2000) for more detail.)

7.4 Procedure

Participants were greeted and completed a set of questionnaires in the following order: demographics, media experience, and need for cognition. Participants were then led into the virtual reality lab where they were introduced to the immersive virtual reality system. They listened to audio instructions about their task. Participants then completed the two self-reported mood measures while the experimenter timed their work. The participants then were asked to estimate the time they spent working on the two mood forms.

A brief recorded training session gave the participant basic instructions in how to navigate the environment and manipulate objects. Participants were then led to the virtual reality system where they put on the head-mounted display and gloves. They then entered a training environment, an open city space. At this point, the experimenter started timing the amount of time the participant was in the virtual environment. When participants felt comfortable with the training environment, they were transferred to a test virtual environment. Inside the Hands-on Virtual Cadaver virtual environment, all participants completed the task of removing all the organs of the virtual cadaver. In the control condition, the participants removed the same number of objects shaped in combinations of 3-D primitives (such as simple cones, cubes, and spheres).

After the participants completed the task of removing all the objects, they removed the virtual reality equipment. Participants were then asked to estimate the time that they spent inside the virtual reality system. After this, the participants completed the two mood measures, again before leaving the experimental room.

They then immediately completed a self-report measure of presence including the items on synesthesia and the recognition memory task; finally, they typed a description of their experience in the virtual environment (verbal retrospective protocol).

8 Results

Data from three participants were dropped from the analysis because of equipment failures that interrupted data collection; therefore, the analysis was conducted with data from 77 participants.

8.1 Factor Analysis of the Presence Scales

To construct reliable scales, the presence items were submitted to two-factor analytic procedures (Kim & Mueller, 1978; Long, 1983). First, an exploratory factor analysis with varimax rotation was conducted to extract the principal components. Five components were extracted. Using the eigenvalues, theoretical importance, and logical coherence of the items, the first three components were retained (components 1, 2, and 3). These were interpreted to be:

- spatial presence (items included "being really THERE," "inside another environment," "visited another place")
- tactile engagement (items included "want to touch," and "try to touch" virtual objects)
- sensory presence (items included "look like" and "feel like" the real world).

A determination of face validity was made on the basis of existing theory, logical judgment, and internal consistency for the items. Each factor was judged to measure a distinct and meaningful construct. These three components explained 49% of the total variance and were retained for further analysis. (See appendix A.)

For the items designed to measure each construct to be meaningful, the items should represent alternative measures of the same underlying factor (Hunter & Gerbing, 1982). Therefore, all scales used in the research, including the dependent measures and the intermediary variables, were tested and optimized for face validity, internal consistency, and parallelism using confirmatory factor analysis and tested for reliability using coefficient alpha. The determination of face validity was made on the basis of existing theory, judgment of logical coherence, and internal consistency. Parallelism tests were conducted by comparing the obtained value with the predicted value of the correlation coefficients of each item. The items with relatively large error sizes (obtained value subtracted by predicted value) were dropped from each scale. The reliabilities (coefficient alpha) for the three variables ranged from 0.51 to 0.87.

8.2 Analysis of the Experimentally Manipulated Variable

An analysis of variance indicated that the experimentally manipulated variable, the effect of meaningful narrative, did not have a significant effect on the two dependent variables of interest to this exploratory study: the self-reports of a visual-to-haptic illusion ($F(2, 73) = 0.531$, $p = 0.59$) and of a visual-to-aural intersensory illusion ($F(2, 73) = 0.165$, $p = 0.89$). Therefore, data from the two conditions were collapsed into one group

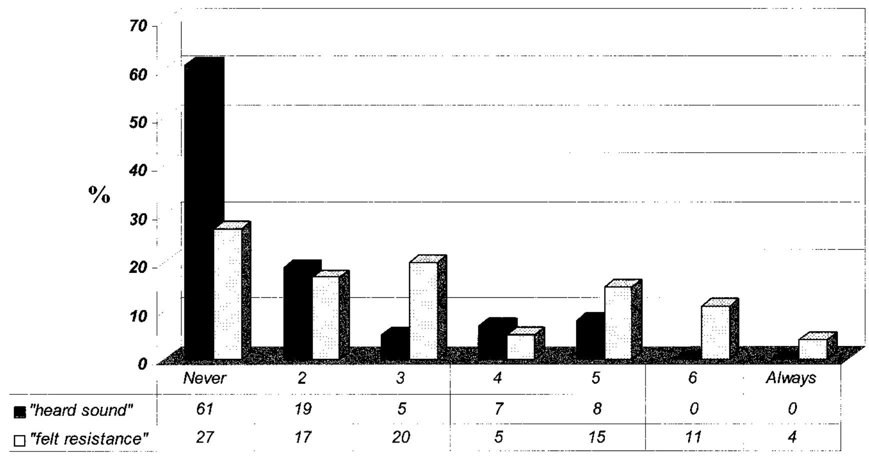

Figure 2. *Distribution of responses to questions as to whether users "heard sounds" or "felt physical resistance" when moving virtual objects that provided no haptic or aural feedback.*

for the following analyses testing the hypotheses of this exploratory study.

8.2.1 Hypotheses 1 and 2. Participants responded on a seven-point scale (never–always) to the question "How often did you feel physical resistance (e.g., gravity, inertia) from the objects you tried to move?" Because the interface contained no haptic displays and therefore the environment provided no direct stimulation to the haptic channel, we would expect the great majority of the responses to the "feel physical resistance" question would be "never." This was not the case.

The mean response to the "haptic question" was $M = 3.1$, $SD = 1.9$. Twenty-seven percent (27%) reported "never" (=1) feeling physical resistance. Almost 15% of the participants reported feeling "physical resistance" either "always" (=7) or almost always (=6). Another 15% appear to have felt physical resistance at least some of the time (=5). Hypothesis 1 and 2 are supported. (See figure 2.)

Hypothesis 1: When building a spatial mental model of the virtual environment, users of immersive virtual reality systems sometimes experience a form of cross-modal transfer or synesthesia.

Hypothesis 2: Users of virtual environments sometimes experience visual-to-haptic cross modal transfers (synesthesia) when manipulating objects.

8.2.2 Hypothesis 3. Participants responded on a seven-point scale (i.e., never–always) to the question "How often did you hear sounds that were made by the objects that you tried to move?" Because they did not have any auditory display and, therefore, there was no direct stimulation from the virtual environment to the aural sensory channel, we would expect the great majority of the responses to the "hear sounds" from the objects to be "never." (See figure 2.)

The mean response to the "hear sounds" question was $M = 1.8$, $SD = 1.3$. The reports of this illusion appears to have been far less frequent than the haptic illusion with the majority: 61% reporting "never" (=1), and only 8% reporting "sometime" (=5), and none reporting "always" (=7) or "almost always" (=6). Because the majority report "never" feeling the sensation, Hypothesis 3 is not supported.

Hypothesis 3: Users of immersive virtual environments sometimes experience visual-to-aural cross modal transfers (synesthesia) when manipulating objects.

8.2.3 Hypothesis 4. Table 2 reports the pattern of correlations among the variables of interest. It ap-

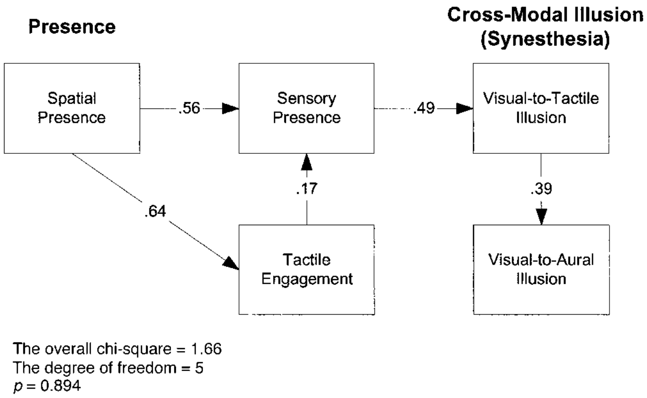

Figure 3. *Path analysis indicating a relationship between presence and cross-modal illusions.*

pears that Hypothesis 4 is supported. There is a correlation between sensory presence and visual-to-haptic illusions ($r = 0.36$, $p < 0.01$).

Hypothesis 4: Users experiencing higher levels of presence are more likely to report cross-modal illusions (synesthesia) in virtual environments.

Formal path analysis was conducted using five variables based on the correlations in table 2. The overall chi-square goodness of fit test yielded a nonsignificant chi-square value for the model in figure 3, which suggested that the model is consistent with the data. Additionally, individual link analysis showed that none of the errors due to the missing links was statistically significant. These results indicate that the error generated by the path model was not substantial.

9 Discussion

This study has two key findings: (1) evidence that some participants report haptic illusions in the absence of stimulation of this sensory channel by the interface, and (2) the apparent connection of these cross-modal interactions, specifically cross-modal transfers, and the experience of presence. We discuss these in the following sections.

9.1 Some Users May Experience Cross-Modal Transfers (Synesthetic Cross-Modal Interactions) from Visual Displays

The study found evidence of cross-modal visual-to-haptic transfers. Therefore, we are presented with a nonintuitive finding that users of immersive virtual reality systems may sometimes experience haptic illusions when no haptic stimuli are presented. This may be evidence of cross-modal transfers, or synesthesia, as predicted above. It should be recalled that no haptic display or feedback was provided by the interface. Therefore, the expected response would be that all or most of the participants would report that they never experienced physical resistance. But we observed that 15% of the participants reported feeling physical resistance either “always” or “almost always”. Another 14.9% appeared to have felt physical resistance at least some of the time, and a majority, over 73%, reported some level of sensation other than “never.”

Reports of the aural illusion of a “pop” or “snap” when the spring was released were far less common. The majority of respondents (61%) indicated that they never experienced the illusion, and only 8% reported experiencing the illusion at most “sometimes.” The path analysis (see figure 3) suggests that the aural illusion may be dependent on the user’s experience of the haptic illusion.

9.2 What Variables in the Virtual Environment Contribute to Inducing a Virtual-to-Haptic or Virtual-to-Aural Cross-Modal Transfer (Synesthesia)?

What design element in this virtual environment contributed to the inducement of cross-modal illusions or transfers? We assume that virtual environments are not equal in their ability to induce cross-modal illusions. Because reports of cross-modal illusions are not common in the presence and virtual environment literature, it suggests that something in these two environments provided an above-average cue to induce these self-reports.

Table 2. *Correlations between Presence and Synesthesia*

	Spatial presence	Sensory presence	Tactile engagement	Visual-to-haptic illusion	Visual-to-aural illusion
Spatial presence	*1.00*	0.67	0.64	0.14	0.05
Sensory presence	0.45**	*1.00*	0.53	0.49	0.21
Tactile engagement	0.49**	0.32**	*1.00*	0.24	0.15
Visual-to-haptic transfer	0.13	0.35**	0.20	*1.00*	0.39
Visual-to-aural transfer	0.05	0.15	0.13	0.39**	*1.00*

** Correlation is significant at the 0.01 level (two-tailed).
The lower triangle includes uncorrected correlations. The top triangle includes the correlations corrected for attenuation due to measurement error.

A distinctive feature of these environments and participants' anecdotal reports suggests that the visual cue of physical resistance, the virtual spring, may have helped induce the cross-modal visual-to-haptic illusion. The virtual spring was a dynamic visualization of the existence of a physical force. The participants pulled on the spring and observed the spring expanding and growing taut before it finally "released" the virtual object, which "snapped" into the hand.

The possibility that the spring contributed to the cross-modal illusion is supported by a more controlled, experimental replication of this finding conducted in our lab as this article was going to press (Biocca, Polinsky, Inoue, & Lee, 2001). The replication of the findings came from an experiment that used a simple environment with basic polygonal objects. The two-factor experiment included conditions in which a visual spring and auditory stimuli were present or absent. The experiment replicated the findings of this study and determined that the visual spring was causally related to reports of haptic illusions. The presence of the virtual spring, a visual analog of haptic forces, significantly increased reports of cross-modal haptic illusions.

Evidence that the virtual spring contributed to the illusion in this study is further supported by findings from a experiment by Lecuyer and his colleagues (Lecuyer et al., 2000). In that study, the perception of a "pseudo haptic" isotonic force varied with the amount of displacement of a virtual spring. In their experiment, a visual cue (the amount of displacement of a visual spring) created what we have labeled a *cross-modal enhancement* (see table 1) of a tactile cue, an isotonic force.

Therefore, the users' reports may be an example of cross-modal illusions or synesthesia. The visual experience of a dynamically stretched spring may have been enough to sometimes induce the haptic illusion of physical resistance in a majority of the users.

Although there was no haptic display, this does not mean that there are absolutely no haptic or proprioceptive forces to help anchor the illusion. It is possible that the isometric haptic feedback from pinching two fingers together, moving the arm through space, or even the light resistance of the gloves' cables contributed to the cross-modal illusion. But these are very weak cues and are unlikely to create a haptic illusion in the absence of a visual cue. Rather, it is likely that the cross-modal integration of the strong visual cue, the dynamic spring, with an interpretation of very weak proprioceptive cues, a moving hand, generates the illusion. This is confirmed by our controlled replication of this study (Biocca et al., 2001). In the replication, the weak haptic forces provided by the gloves and cables were the same across all conditions. Adding or subtracting the visual spring was significantly related to differences in reports of haptic illusions. Our results here and in the replication of this study, combined with those of Lecuyer and his colleagues (Lecuyer et al., 2000), suggests that the visualization of physical forces, in both cases a virtual spring, can enhance haptic force based on either fixed weight, an isotonic force, or a purely proprioceptive force involving no more than the weight of a moving arm.

9.3 Presence and the Mental Models of Multimodal Virtual Worlds

The data from this exploratory study are consistent with a view that intermodal integration may be related to—and maybe even give rise to—the sensation of presence. Presence was correlated with participants' reports that they experienced cross-modal illusions.

The need to integrate spatial location during object manipulation (Graziano, 1999) may provide an explanation for the pattern of the findings. Looking at the path analysis in figure 3 suggests that spatial presence, the sense of being there, may be primary in the sense of presence. The path model suggests that spatial presence may contribute to sensations of sensory presence, the sensory vividness of the environment. Tactile engagement, the sensation in people who "wanted to touch," "tried to touch," and who felt the experience was "addictive," contributed to sensory presence. Higher levels of sensory presence in turn appeared to be related to higher levels of visual-to-haptic cross-modal illusions, and through the tactile illusions to some visual-to-aural illusions as well.

The process of intermodal integration, of generating a coherent mental model of the virtual environment, may be the source of these illusions. In some cases, individuals may be using cues from the physical environment to fill in a coherent virtual environment with sensory detail that is not actually present, but that users expect would be present if the experience occurred in the physical environment. Note that people who "wanted to touch" or "tried to touch" the virtual objects felt more sensory presence, and sensory presence contributed to the tactile illusion.

9.4 There Was No Evidence That the Presence of Meaningful Content Played a Role in the Synesthetic Illusion

From the results, we can conclude that the variable we manipulated, the "meaningfulness" of the virtual environment, was not related to this cross-modal illusion. So it did not matter if the environment was composed of meaningful and vivid human organs or abstract geometric primitives. Nor did it matter whether the participant was a character in a narrative or merely completing an object-picking task in the environment. This suggests that these content variables did not play a significant role in the cross-modal illusion reported here, nor is there much evidence in the intermodal integration literature that it should.

9.5 Possible Limitations of the Study

Anecdotal reports by users led us to explore the existence of these illusions in an exploratory component of an ongoing study of narrative and presence. We were surprised by the percentage of participants who reported "always" or "almost always" experiencing the visual-to-haptic cross-modal illusion. Our interpretation that the visualization of the spring was a key cause of these findings is limited by the fact that we did not manipulate this variable. But the likelihood that the spring contributed to the illusion is consistent with other findings in virtual environments involving virtual springs (Lecuyer et al., 2000), and with evidence from physical environments showing that subjects pulling on a fixed weight on a string can experience the size-weight illusion when manipulated with a changing visual cue (Ellis & Lederman, 1993; Masin & Crestoni, 1988). We are following up with psychophysical studies of these phenomena.

We considered and rejected two possible threats to the internal validity of the self-reports. The self-reports were collected immediately after the experience. We considered whether the self-reports might have been an artifact of memory retrieval, and that the cross-modal illusions were not present at the moment the springs were manipulated. But this concern is contradicted by a number of observations. First, users in our lab prior to, during, and after the study consistently report feeling as if they are "tugging" on the spring while they are carrying out the action in the virtual environment. Secondly, the experience in the virtual environment was very brief and lasted, on average, little more than five to ten minutes. Their self-reports were collected within five-to-ten minutes immediately after they exited following the mood measure (which took approximately three minutes to complete). So their self-reports rely on short-term memory and are less likely to be the result of long-term memory confusion about the nature of the experience. Finally, there is evidence that changing visual cues interacting with a fix haptic stimulus can cause cross-modal visual-to-haptic interactions consistent with our findings both in virtual environments (Lecuyer et al., 2000) and in physical environments (Ellis & Lederman, 1993; Masin & Crestoni, 1988).

We also considered whether these responses were largely driven by the demand or suggestion of the questions to report such illusions. Patterns in the subjects' responses do not support this concern. If the demand pressures to report illusions were the principle cause of these self-reported illusions, we would expect similar patterns of response to questions posed to participants on whether they experienced tactile or aural sensations. But this is not the case. The distributions of self-reports show very different patterns of response to questions about the haptic and aural illusions. Secondly, these questions on aural and haptic sensation were buried within larger questionnaires on mood and presence, and were not the apparent focus of the experiment. Furthermore, in the replication of this study (Biocca, Polinsky, Inoue, & Lee, 2001) subjects were asked the same questions in experimental conditions that included or did not include the visual spring. In conditions with the visual spring present, there were significantly higher reports of haptic illusions. This is evidence that it is the visual experience that causes the reports of haptic illusions and not just the effect of "asking" whether the user experienced haptic illusions.

10 Some Implications for the Design of Multimodal Interfaces

This study provides evidence of the existence of cross-modal interactions in immersive virtual environments and their possible relation to desired outcomes, such as the feeling of presence. The results of this study suggest the following.

10.1 Designing for Interaction in the Perceptual Experience of Displays

Consistent with past recommendations (Durlach & Mavor, 1994), these findings indicate that the perceptual effects of displays and sensors should probably not be considered in isolation in the design of immersive interfaces. Designers might use stimulation from displays for which they have greater control of fidelity (such as visual or aural displays) to augment the experience of stimulation for which the designer might have less control or fidelity (such as haptic displays).

10.2 Dynamic Cross-Modal Analogs—Even Those That Are Not Realistic—May Enhance User Experience

If the virtual spring is a key component of the cross-modal illusion reported here, it suggests that designers might achieve these effects by creating cross-modal analogs in one sensory channel of a sensation in another sensory channel. For example, in this study, the interface significantly violated fidelity and included some unrealistic features. Dynamic virtual springs were attached to objects, and objects were not grabbed and moved directly as in the physical environment. Rather, when the user grabbed the object, a virtual spring stretched. The object appeared in the hand of the user only after the spring was stretched a distance away from the object. The visual spring may have acted as a visual analog of physical resistance, and the visual cues may have helped users "feel" physical resistance.

This suggests that exaggerating or distorting the representations of physical phenomena may create desirable cognitive effects. In a curious twist on the belief that verisimilitude and presence are linked, it appears that the very lack of verisimilitude may have contributed to the cross-modal illusion, and, possibly, to higher levels of presence.

11 Conclusions

The sensation of presence in virtual environments may be related to the mind's attempt to integrate incomplete sensory cues to form a complete spatial model of the virtual environment, especially when deriving an accurate model is needed to prepare the body for action in the environment (Anderson et al., 1997). To construct a spatial mental model of the virtual environment, users must integrate information from the visual, aural, haptic, and other sensory channels (Marks, 1978; Stein et al., 1995; Stein, 1984; Stein & Meredith, 1993). Virtual environments provide fewer sensory cues than most physical environments do, but the user must be able to use these cues to walk towards, reach out, and manipulate objects in the environment. During the process of integrating and augmenting impoverished sensory cues, information from one sensory channel may be used to augment and help disambiguate information from another sensory channel. In some cases, as in this study, the process of intermodal integration may produce perceptual illusions that enhance the perception of information in one sensory channel (that is, cross-modal enhancement) or arouse reports of sensations in senses that have not been stimulated by the interface (that is, cross-modal illusions or synesthesia).

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Appendix A: Factor-analysis of Presence Scales Used for Data Analysis

Measure of Presence and Tactile Engagement

	Factors				
	1	2	3	4	5
P15	0.801				
P7	0.788				
P9	0.786				
P16	0.745				
P17	0.731				
P8	0.683				
P4	0.629				
P12	0.614				
P10	0.565				
P13	0.492				
P18		0.827			
P14		0.717			
P19		0.703			
P1			0.787		
P2			0.652		
P3			0.594		
P11				−0.757	
P5				0.615	
P6					0.668

Extraction method: principal component analysis.
Rotation method: varimax with Kaiser normalization.

Total Variance Explained

Rotation Sums of Squared Loadings			
Factors	Total	% of Variance	Cumulative %
1	5.207	27.403	27.403
2	2.261	11.897	39.300
3	1.906	10.032	49.332
4	1.335	7.024	56.357
5	1.323	6.966	63.322

Extraction method: principal component analysis

Spatial Presence Measure (Factor 1)

P15: To what extent did you feel like you were inside the environment?

P7: How much did you feel involved in the environment?**

P9: How much did you feel as if you visited another place?

P16: To what extent did you feel immersed in the environment?

P17: To what extent did you feel surrounded by the environment?

P8: To what extent did you feel a sense of being really THERE inside the environment?

P4: How often did you feel like you were inside the environment?**

P12: How involving was the experience?

P10: How much did you feel as if you were inside the environment OBSERVING the events?

P13: How intense was the experience in the environment?**

**Indicates that these items were not retained for the final analysis due to large error of measurement.

Scale reliability: coefficient alpha = 0.87

Tactile Engagement (Factor 2)

P18: How often did you WANT TO TOUCH something inside the environment?

P14: How addictive was the experience in the environment?**

P19: How often did you TRY TO TOUCH something you saw inside the environment?

**Indicates that the item was not retained for the final analysis due to large error of measurement.

Scale reliability: coefficient alpha = 0.71

Sensory Presence (Factor 3)

P1: How much did things and people in the environment SOUND LIKE the real world?**

P2: How much did things and people in the environment LOOK LIKE the real world?

P3: How much did things and people in the environment FEEL LIKE the real world?

**Indicates that the item was not retained for the final analysis due to large error of measurement.

Scale reliability: coefficient alpha = 0.51