Physiological Measures of Presence in Virtual Environments

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Abstract

Virtual environments (VEs) are one of the most advanced human-computer interfaces to date. A common measure of the quality or effectiveness of a VE is the amount of *presence* it evokes in users. Presence is commonly defined as the sense of *being there* in a VE.

In order to study the effect that technological improvements such as higher frame rate, more visual realism, and lower latency have on presence, we must be able to measure it. There has been much debate about the best way to measure presence, and we, as presence researchers, need and have sought a measure that is **Reliable, Valid, Sensitive, and Objective**.

We hypothesize that to the degree that a VE seems real, it will evoke physiological responses similar to those evoked by the corresponding real environment, and that greater presence will evoke a greater response. We conducted three experiments the results of which support the use of physiological reaction as a reliable, valid, sensitive, and objective measure of presence. In the experiments, we compared participants' physiological reactions to a non-threatening virtual room and to their reactions to a room that presented a stressful virtual height situation. We found that change in heart rate satisfied our requirements for a measure of presence, change in skin conductance did also, but to a lesser extent, and that change in skin temperature did not. Moreover, the results showed that inclusion of a passive haptic element in the virtual environment significantly increased presence and that, in this predominantly static environment, a graphics frame update rate of either 20 or 30 FPS evokes significantly higher presence than does an update rate of 15 FPS and that, although not statistically significant, 30 FPS evokes higher presence than 20FPS.

Whereas our experiments were run as between-subject, we additionally analyzed the data using only the first exposure of each subject and found some support for the use of change in heart rate as a between-subject measure.

1. Introduction

Virtual environments (VEs) are the most sophisticated human-computer interfaces yet developed. The effectiveness of a VE might be defined in terms of enhancement of task performance, effectiveness for training, improvement of data comprehension, etc. A common metric of VE quality is the degree to which the VE creates in the user the subjective illusion of presence – a sense of being in the virtual, as opposed to the real, environment. Since presence is a subjective condition, it has most commonly been measured by self-reporting, either during the VE experience or immediately afterwards by questionnaires. There has been vigorous debate as to how to best measure presence [Barfield, 1995; Ellis, 1996; Freeman, 1998; IJsselsteijn, 1998; Lombard, 1997; Regenbrecht, 1997; Schubert, 1999; Sheridan, 1996; Slater, 1999; Witmer, 1998].

In order to study the effectiveness of a virtual environment in evoking presence, researchers need a well-designed and verified measure of the phenomena. This paper reports our evaluation of three physiological measures – heart rate, skin conductance, and skin temperature – as alternate operational measures for presence. Since the concept and idea of measuring it are heavily debated, finding a measure that could find wide acceptance would be ideal. In that hope, we investigated the reliability, validity, sensitivity, and objectivity of each physiological measure.

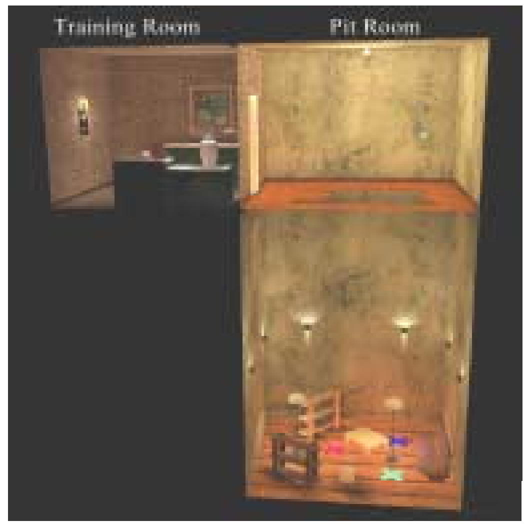

Figure 1. Side view of the virtual environment. Subjects start in the Training Room and later enter the Pit Room.

2. Physiological Reaction as a Surrogate Measure of Presence

As VE system and technology designers, we have sought for a presence measure that is

Reliable – produces repeatable results, both from trial to trial on the same subject and across subjects,

Valid – measures subjective presence, or at least correlates with well-established subjective presence measures,

Sensitive – discriminates among multiple levels of presence, and

Objective – well shielded from both subject and experimenter bias.

We hypothesize that to the degree that a VE seems real, it will evoke physiological responses similar to those evoked by the corresponding real environment, and that greater presence will evoke a greater response. If so, these responses can serve as objective surrogate measures of subjective presence.

2.1. Our Environment and Measures

We use a derivative of the compelling VE reported by Usoh *et al*. [Usoh, 1999]. Figure 1 shows the environment: a Training Room, quite ordinary, and an adjacent Pit Room, with an unguarded hole in the floor leading to a room 20 ft. below. On the upper level the Pit Room is bordered with a 2-foot wide walkway. The 18x32 foot, 2-room virtual space fits entirely within the working space of our lab's wide-area ceiling tracker. Users, equipped with a head-tracked stereoscopic head-mounted display, practice walking about and picking up and placing objects in the Training Room. Then they are told to carry an object into the next room and place it at a designated spot. The door opens, and they walk through it to an unexpected hazard, a virtual drop of 20 ft. if they move off the walkway. Below is a furnished Living Room (Figure 2).

Users report feeling frightened. Some report vertigo. Some will not walk out on the ledge and ask to stop the experiment or demo at the doorway. A few boldly walk out over the hole, as if there were a solid glass floor. For most of us, doing that, if we can, requires conscious mustering of will.

This environment, with its ability to elicit a fear reaction in users, enables investigation of physiological reaction as a measure of presence. If so strong a stress-inducing VE does not produce significant physiological reactions, a less stressful VE won't. This investigation is a first step. Follow-on research should investigate whether less stressful environments also elicit statistically significant physiological reactions.

Below, we discuss the physiological measures we tested and the reported measures we used to evaluate validity

2.1.1. The Physiological Measures

As stated above, we investigated three physiological metrics that measure stress in real environments [Andreassi, 1995; Guyton, 1986; Weiderhold, 1998]:

Change in heart rate (Δ Heart Rate). The heart beats faster in stress.

Change in skin conductance (Δ Skin Conductance Level). The skin of the palm sweats more in stress, independently of temperature, so its conductance rises.

Change in skin temperature (Δ Skin Temperature). Circulation slows in the extremities in stress, causing skin temperature to drop.

Each of these measures was constructed to increase when the physiological reaction to the Pit Room was greater.

Δ Heart Rate = mean $HR_{\text{Pit Room}}$ – mean $HR_{\text{Training Room}}$.
Δ Skin Conductance = mean $SC_{\text{Pit Room}}$ – mean $SC_{\text{Training Room}}$
Δ Skin Temperature = mean $ST_{\text{Training Room}}$ – mean $ST_{\text{Pit Room}}$

We measured heart rate with a chest-attached three-electrode electrocardiography (ECG). This gave a good signal. Skin conductivity and skin temperature were successfully measured on the fingers. Once connected, users reported forgetting about the physiological sensors – they did not cause breaks in presence during the experiments. Figure 4 shows a subject wearing the physiological monitoring equipment.

Figure 2. View of the 20' pit from the diving board.

2.1.2. The Reported Measures

We used the University College London (UCL) questionnaire [Slater, 1995; Usoh, 1999]. The UCL questionnaire contains seven questions that measure presence (Reported Presence), three questions that measure behavioral presence (Reported Behavioral Presence) – does the user act as if in a similar real environment – and three that measure ease of locomotion (Ease of Locomotion). Responses for each question are on a scale of 1 to 7. Reported Ease of Locomotion was administered for consistency with earlier experiments, but we do not report on it in this paper.

2.2. The Three Experiments

Multiple Exposures: 10 subjects (average age 24.4; $\sigma = 8.2$; 7 female, 3 male) were trained to pick up books and move about in the Training Room – at which time a physiological baseline was taken. Subjects then carried a virtual book from the Training Room and placed it on a virtual chair on the far side of the Pit Room. After that, they returned to the Training Room. The subjects performed this task three times per day on four separate days. We investigated whether the presence-evoking power of a VE declines with multiple exposures. Heart Rate was not successfully measured in this study due to problems with the sensor.

Passive Haptics: 52 subjects (average age 21.4; $\sigma = 4.3$; 16 female, 36 male) reported on two days. On one day, a subject experienced the VE with the 1.5-inch wooden ledge. The 1.5-inch height was selected so that the edge-probing foot did not normally contact the real laboratory floor where the virtual pit was. On the other day, he experienced the VE without the ledge. Subjects were counterbalanced as to the order of presentation of the ledge. Subjects performed all exposures to the VE wearing only thin sock-like slippers (Figure 3). The task was the same as in the Multiple Exposures study except subjects were instructed to walk to the edge of the wooden platform, place their toes over the edge, and count to ten before they proceeded to the chair on the far side of the room to drop the book. We investigated whether the 1.5-inch wooden ledge increased the presence-evoking power of the VE.

Figure 3. Subject in slippers with toes over 1.5-inch ledge.

Frame Rate: 33 participants (average age 22.3; $\sigma = 3.6$; 8 female, 25 male). Subjects entered the VE four times on one day and were presented the same VE with a different frame rate each time. The four frame rates were 10, 15, 20, and 30 frames-per-second (FPS). Subjects were counterbalanced as to the order of presentation of the four frame rates. Subjects were trained to pick up and drop blocks in the Training Room and then carried a red block to the Pit Room and dropped it on a red X-target on the floor of the Living Room, a procedural improvement that forced subjects to look down into the pit. They then plucked from the air two colored blocks floating in the Pit Room and dropped each on the correspondingly-colored Xs on the floor of the Living Room. The X-targets and the green and blue blocks are visible in Figure 1. In this study, we investigated the effect of multiple frame rates on presence and hypothesized that the higher the frame rate, the greater the presence evoked.

Figure 4. Subject wearing HMD and physiological monitoring equipment in the "Pit Room".

3. Summary and discussion

For a full discussion of the results please see [Meehan, 2001; Meehan 2002]. Of the three physiological measures in our studies, Δ Heart Rate performs best. It consistently differentiates among conditions with more sensitivity and more statistical power than the other physiological measures, and more than most of the self-reported measures. It also best correlates with the reported measures.

Δ Skin Temperature is less sensitive, less powerful, and slower responding than Δ Heart Rate, although its response curves are similar. It also correlates with reported measures. Our results and the literature on skin temperature reactions suggest that Δ Skin Temperature would differentiate among conditions better if the exposures to the stimulus were at least 2 minutes [McMurray, 1999; Slonim, 1974]. Ours averaged 1.5 minutes in each experiment.

ΔSkin Conductance Level yielded significant differentiation in some experiments but was not so consistent as ΔHeart Rate. More investigation is needed to establish whether it can reliably differentiate among multiple levels of presence.

Although, ΔHeart Rate satisfied the requirements for a presence measure for our VE, which evokes a strong reaction, it may not for les stressful VEs. To determine whether physiological reaction can more generally measure presence, a wider range of VEs must be tested, including less stressful, non-stressful, and relaxing environments. Investigation is currently under way to look at physiological reaction in relaxing 3D Television environments [Dillon, 2001].

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