Physiological Reaction as an Objective Measure of Presence in Virtual Environments

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ABSTRACT

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(Under the direction of Dr. Frederick P. Brooks, Jr.)

Virtual environments (VEs) are one of the most advanced human-computer interface to date. A common measure of the 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 lag 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, have yearned for a 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 well with established subjective presence measures;

Sensitive — is capable of distinguishing multiple levels of presence; and

Objective — is well shielded from both subject bias 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. Hence, these responses serve as reliable, valid, sensitive, and objective measures of presence.

We conducted three experiments that support the use of physiological reaction as a reliable, valid, sensitive, and objective measure of presence. We found that change in heart rate was the most sensitive of the physiological measures (and was more sensitive than most of the self-reported measures) and correlated best among the physiological measures with the reported presence measures. Additionally, our findings showed that passive haptics and fame rate are important for evoking presence in VEs. Inclusions of the 1.5-inch wooden ledge into the virtual environment significantly increased presence. Also, for presence evoked: 30 FPS (frames per second) > 20 FPS > 15 FPS. In conclusion, physiological reaction can be used as a reliable, valid, sensitive, and objective measure of presence in stress-inducing virtual environments.

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Chapter 1 Introduction

1.1 Presence and virtual environments

Virtual environments (VEs) are the most advanced human-computer interfaces yet developed. Researchers, by the development of new methods, theories, and technologies, have endeavored to make effective VEs. The definition of effectiveness changes based on the application of the VE. For flight simulators, training transfer is important. For architectural walkthroughs, accurate perception of space is important. For treatment of phobias and post-traumatic stress disorders, presence — evoking in patients the feeling that they are near the source of their phobia or stress — is important[Hodges, 1994]. It is on this last concept, presence, that this dissertation focuses.

Rothbaum and Hodges VE system for graded exposure treatment of acrophobia strives to bring patients near the source of their phobias [Hodges, 1994]. They state that the user s sense of presence is the defining factor in the [successful treatment of acrophobia]. We believe this is true for all phobia treatment systems: the system must evoke presence in order to work. Such systems are useful as they allow much of the effectiveness of *in vivo* exposure with the safety, convenience, and reduced cost of in-office therapy [Hodges, 1995]. To ensure the systems evoke presence in users, developers endeavor to build the best VEs possible: stereo portrayal (as opposed to mono) in the headmounted display, realistic models and lighting, low lag, high frame rate, etc.

VE developers, though, have limited time and resources, and these limitations force system design choices. When making these choices, it is important for designers to ensure that the users still have a compelling experience — that the VE still evokes a sense of presence. So they need to know what is important for evoking presence in VEs: Is increasing the frame rate more important than stereo display in the headmounted display (HMD)? Is it more important to have lower lag or a richer model? Is pixel density (resolution) more important than field-of-view? Are dynamic shadows the key to making a VE convincing?

1.1.1.2

The answers to these questions may be different for every person and even for the same person at different times. We believe, however, that a broad suite of thoughtfully constructed studies investigating the effects of varying VE system parameters (lag, frame rate, realism) on presence would reveal rules of thumb for *what evokes presence* for the general population. To find these rules, however, we need to be able to measure presence, and the measure must be reliable, valid, multi-level sensitive, and objective. This dissertation details the investigation of physiological reactions as such measures.

1.2 Measuring presence

The concept of *presence* is difficult to define, and becomes even more so when one tries. Nevertheless, we attempt to define it here, and we discuss concepts and definitions of presence from the literature in Chapter 2. We define presence as *perceiving stimuli as one would perceive stimuli from the corresponding real environment*. The stimuli that the user perceives come from the VE in our experiments. Since presence is a subjective condition, it has commonly been measured by self-reporting, either during the session or afterwards. There has been vigorous debate as to how best to measure presence, and researchers have yearned for a 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 well with established subjective presence measures;

Multi-level sensitive — is capable of distinguishing multiple levels of presence; and

Objective — is well shielded from both subject bias and experimenter bias.

We attempted to create such a measure and report our findings here. We investigated physiological reactions as measures of presence over multiple exposures, both on a single day and over multiple days. We also investigated the measures in multiple presence conditions using *passive haptics* (a rough physical model corresponding to the VE) and multiple *frame rates* (the number of times per second that the image in the headmounted display is updated to reflect the user s current position). The highlights of this investigation are presented in this chapter. A full discussion of the experimental design and measures are given in Chapter 3. Detailed results are given in Chapter 4.

1.1.1.2

Our thesis is that

To the degree that a virtual environment evokes presence (as defined above), it will evoke physiological responses similar to those evoked by the corresponding real environment, and greater presence will evoke a greater response. Hence, these physiological responses can serve as reliable, valid, multi-level sensitive, and objective measures of presence.

We used a VE that simulates a danger-of-falling, stress-inducing environment (see Figure 1.1) and selected certain physiological responses that were easy to measure from the hands and chests of the subject and have documented responses to this stress: heart rate, skin conductance, and skin temperature. Heart rate and skin conductance are known to increase and skin temperature decrease with exposure to heights and other stressors. For example, Emmelkamp and Felten reported on nineteen acrophobic patients heart rate reactions to climbing as high as they could on a fire escape (with a hand rail), waiting one minute, and looking down. Subjects ascended to the second landing on average. The average heart rate increase for subjects was 13.4 beats / minute [Emmelkamp, 1985]. Our subjects were non-phobic, so we would expected their heart rate reactions to be lower, but in the same direction. See Appendix A and [Andreassi, 1995; Guyton, 1986] for more discussion on physiological reaction.

Physiological measures of presence. We constructed three physiological measures based on differences between stress reactions and normal values. These were defined so that they should all increase with increased presence. That is, if there was more presence, there should have been more physiological reaction to the Pit Room (Figure 1.1), and these measures should each increase:

$$\Delta\textbf{Heart Rate} = \text{Mean Heart Rate}_{\text{Pit Room}} - \text{Mean Heart Rate}_{\text{Training Room}}$$

$$\Delta\textbf{Skin Conductance} = \text{Mean Skin Conductance}_{\text{Pit Room}} - \text{Mean Skin Conductance}_{\text{Training Room}}$$

$$\Delta\textbf{Skin Temperature} = \text{Mean Skin Temperature}_{\text{Training Room}} - \text{Mean Skin Temperature}_{\text{Pit Room}}$$

1.1.1.2

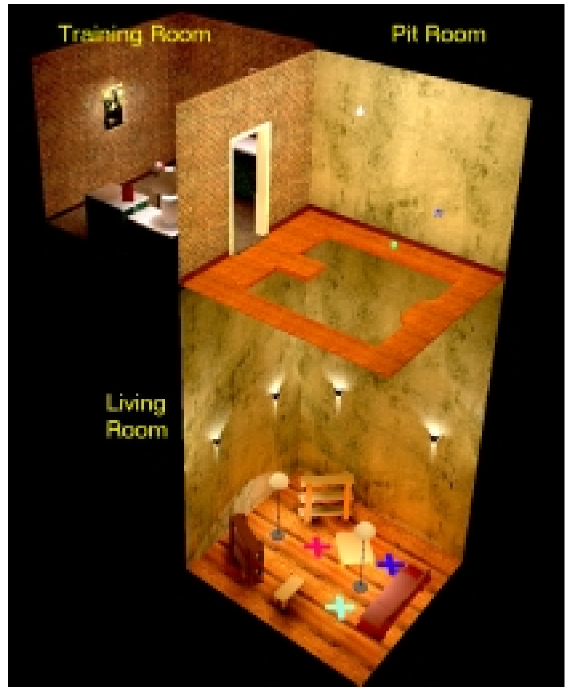


Figure 1.1. Side view of the virtual environment. Subjects start in the Training Room and later enter the Pit Room.

Reported Presence and Reported Behavioral Presence. To measure reported presence, we used a modified version of the University College London (UCL) Presence Questionnaire [Usoh, 1999]. The UCL questionnaire contains seven questions that measure *presence* (Reported Presence), three questions that measure *behavioral presence* (Reported Behavioral Presence) — Did the user report acting as he would in a similar real environment? — and three that measure *ease of locomotion* (Reported Ease of Locomotion) — Did the user report that it was easy and natural to move about in the virtual environment? Reported Ease of Locomotion is not a measure of presence and therefore is not discussed extensively in this dissertation. Responses for each question were on a scale of 1 to 7. The questionnaire was modified to better reflect our environment.

Observed Behavioral Presence. We videotaped all the subject sessions and then, from the tapes, scored presence depending upon various characteristic behaviors including *taking baby steps, testing the edge with the foot,* etc. During our sessions, technical problems caused some sessions tapes to be unusable due to lighting or due to difficulties with the recording equipment. In the Passive Haptics study, these technical problems left us with data for only 31 of 52 subjects. We defined the movements to be scored beforehand and had only one experimenter scoring for each study. A more detailed investigation of this measure should ensure a complete data set by ensuring that all sessions are properly recorded. A detailed investigation should also use multiple scorers and investigate the reliability among these scorers.

Figure 1.2. View of the 20 pit from the edge of the diving board.

The environment. The environment shown in Figures 1.1 and 1.2 consisted of 10,000 polygons and 41 megabytes of texture maps. This environment was used in the Frame Rate study. A similar environment was used for the Passive Haptics and Multiple Exposures studies. It had 20,000 polygons and 50 megabytes of texture. All environments were rendered in stereo on one Infinite Reality 2 pipe of an SGI Reality Monster. The head-mounted display was a Virtual Reality 8 with 640x480 tri-color pixel resolution in each eye. Users walked about in an 18 x 32 space, tracked with a high-accuracy, very-low-lag University of North Caroline (UNC) Hi-Ball optical tracker [Ward, 1992; Welch, 1997]

Experimental procedures. In the Multiple Exposures study, 10 subjects (average age 24.4; r = 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 book from the Training Room and placed it on a chair on the far side of the Pit Room. After that, they were instructed to return to the Training Room. The subjects performed this task three times per day on four separate days. In the Multiple Exposures study, we investigated the hypothesis that the presence-evoking power of a VE declines with multiple exposures. ΔHeart Rate was not successfully measured in this study due to problems with the sensor. We excluded subjects who had experienced VEs more than three times from all studies. Additional exclusions for subjects are listed in Chapter˚3.

In the Passive Haptics study, 52 subjects (average age 21.4; r = 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. 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. 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 dropping the book on the chair on the far side of the Pit Room. In the Passive Haptics study, we investigated the hypothesis that the 1.5-inch wooden ledge increased the presence-evoking power of the VE.

The Frame Rate study had 33 participants (average age 22.3; r = 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 other blocks floating in the Pit Room and dropped each on the same-colored Xs on the floor of the Living Room. The X-targets and green and blue blocks are visible in Figure 1.1. In this study, we investigated the effect of frame rate on presence. We hypothesized that the higher the frame rate, the greater the presence evoked.

Statistical significance. In this dissertation, we defined statistical significance at the 5% level. This is stated as P˚<˚0.050. Findings significant at the 5% level are discussed as demonstrated or shown . We also chose a method of statistical model construction in which we added variables to the model that were significant up to the 10% level (0.05 † P < 0.10).

Summary. Below we discuss our findings for the reliability, validity, multi-level sensitivity, and objectivity of the three physiological measures. We found that ΔHeart Rate met our requirements for a measure of presence.

1.1.1.2

1.3 Physiological measures of presence

1.3.1 Reliability

Reliability is the extent to which the same test applied on different occasions yields the same result [Sutherland, 1996]. Specifically, we wanted to know whether the virtual environment would consistently evoke a physiological reaction as the subject entered and remained in the Pit Room. The VE consists of three rooms. Users start in the Training Room, which looks like a foyer or other small room in a house. They later move to the Pit Room where, to get to the other side, they can either walk around the 20-foot drop to the room below using a two-foot-wide wooden catwalk or walk straight across — walking as if on a glass floor.

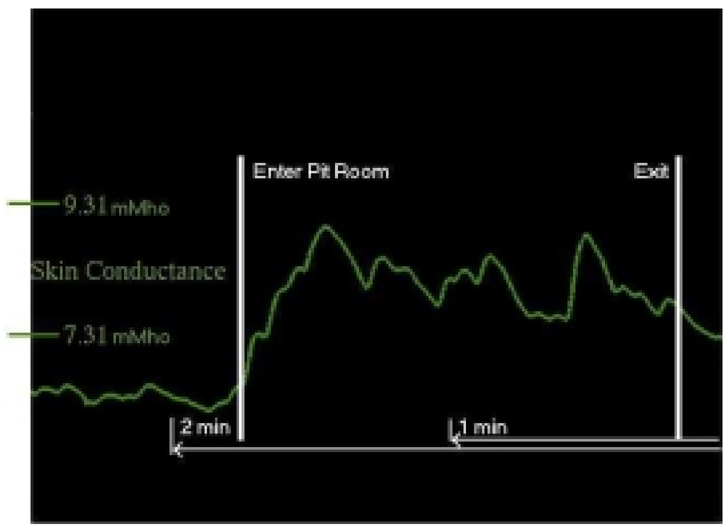


Figure 1.3. A typical skin conductance reaction to the Pit Room.

As we hypothesized, there were indeed significant physiological reactions to the Pit Room: heart rate and skin conductance were significantly higher and skin temperature was significantly lower in the Pit Room in all three studies. Figure 1.3 shows a typical skin conductance reaction to the Pit Room. Heart rate was higher in the Pit Room for 90% of the exposures to the VE, skin conductance was higher for nearly 95%, and skin temperature was lower for 90%. See Table 1.1.

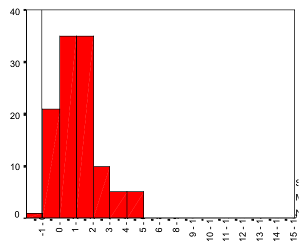
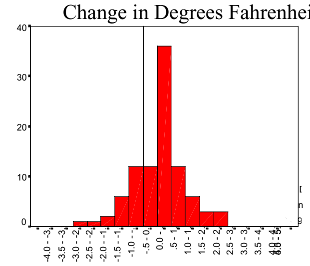
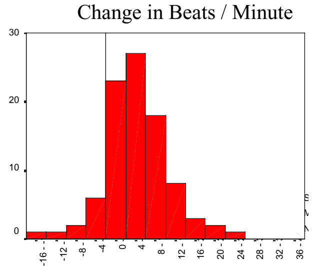
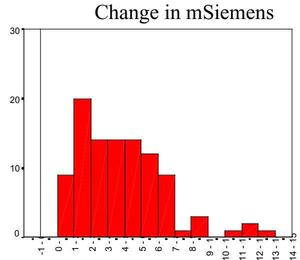
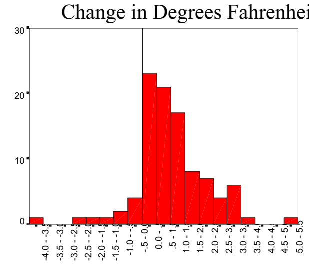
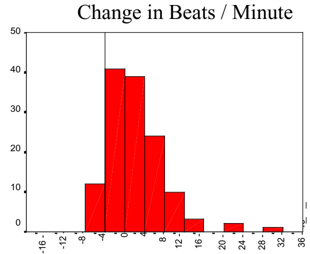
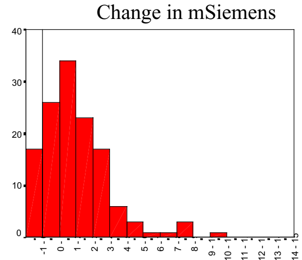
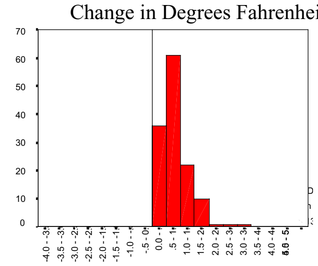
	Distribution of ΔHeart Rate	Distribution of ΔSkin Conductance	Distribution of ΔSkin Temperature
Effect of Multiple Exposures on Presence	Not Available	Change in mSiemens  Mean = 2.3 mSiemens Standard Deviation = 1.3 N = 112 Training Room Ave. = 8.3 mSiemens Count (Vals < 0.0) = 1 / 112	Change in Degrees Fahrenheit  Mean = 0.6 °F Standard Deviation = 0.9 N = 94 Training Room Ave. = 80.4 °F Count (Vals < 0.0) = 22 / 94
Effect of Passive Haptics on Presence	Change in Beats / Minute  Mean = 6.3 BPM Standard Deviation = 6.3 N = 92 Training Room Ave. = 85.9 BPM Count (Vals < 0.0) / N = 10 / 92	Change in mSiemens  Mean = 4.8 mSiemens Standard Deviation = 2.5 N = 100 Training Room Ave. = 6.7 mSiemens Count (Vals < 0.0) / N = 0 / 100	Change in Degrees Fahrenheit  Mean = 1.1 °F Standard Deviation = 1.2 N = 100 Training Room Ave. = 84.9 °F Count (Vals < 0.0) = 10 / 98
Effect of Frame Rate on Presence	Change in Beats / Minute  Mean = 6.3 BPM Standard Deviation = 5.8 N = 132 Training Room Ave. = 82.7 BPM Count (Vals < 0.0) = 12 / 132	Change in mSiemens  Mean = 2.0 mSiemens Standard Deviation = 2.0 N = 132 Training Room Ave. = 5.0 mSiemens Count (Vals < 0.0) = 17 / 132	Change in Degrees Fahrenheit  Mean = 0.8 °F Standard Deviation = 0.5 N = 132 Training Room Ave. = 83.6 °F Count (Vals < 0.0) = 0 / 132

Table 1.1. Differences in physiological measures between the Training Room and the Pit Room. The means of the distributions were significantly greater than zero (P < 0.001 for all measures in all studies).

We also wanted to know whether the physiological reactions to the environment diminished over multiple exposures. Since our hypotheses relied on presence in the VE evoking a stress reaction over a multiple exposures (2-12 exposures), we wanted to know whether physiological reactions to the VE would drop to zero or become unusably small due to habituation. In fact, each measure did decrease with multiple exposures (not necessarily significantly) in all studies (ΔSkin Temperature, Reported Presence, Reported Behavioral Presence, Observed Behavioral Presence, and ΔHeart Rate) or in all but one study (ΔSkin Conductance). None decreased to zero, though, even after twelve exposures to the VE. Table 1.2 shows the significant order effects. Figures 4.1 and 4.2 graph the reactions of each measure over multiple exposures.

A decrease in physiological reaction over multiple would not necessarily weaken validity, since the literature shows that habituation diminishes the stress reactions to real heights and other stressors [Abelson, 1989; Andreassi, 1995]. Since all measures, not just the physiological measures decrease over multiple exposures, the decreases may not be due to habituation. There may be, as Heeter hypothesized, a decrease in presence evoked by the environment as novelty wears off [Heeter, 1992].

Order Effects	ΔHeart Rate (ΔBPM)	ΔSkin Conductance (ΔmSiemens)	ΔSkin Temperature (Δ^{o}F)	Reported Presence (Count high)	Reported Behavioral Presence (Count high)	Observed Behavioral Presence (Count Behvs.)
Multiple Exposures	N/A	-0.7 (1st)	**-0.9 (1st)**	-	**-0.7 (1st)**	**-0.9 (Sess)**
Passive Haptics	-	-	-	**-0.8 (1st)**	**-0.4 (1st)**	-
Frame Rate	**-1.0 (Task)**	**-0.8 (1st)**	**-0.3 (1st)**	-	**-0.2 (Task)**	**-0.8 (1st)**

Table 1.2. Significant order effects for each measure in each study.
(1 st) indicates a decrease in a measure after the first exposure only. (Sess) indicates a decrease in the measure over subsequent sessions (days). (Task) indicates a decrease over tasks on the same day. There was an order effect for each measure in at least one study. N/A is Not available . Full descriptions of the order effects are given in Tables 4.2 to 4.4.

Orienting Effect. In general, each measure decreased after the first exposure. Moreover, there was a significant decrease after the first exposure for each measure except ΔHeart Rate in at least one of the studies (see Table 1.2). For physiological responses, this is called an *orienting effect* — a higher physiological reaction when one sees something novel [Andreassi, 1995]. Though this term traditionally refers to physiological reactions, we will also use the term for observed behavioral and reported reactions to the novel stimuli.

We attempted, with only partial success, to overcome this orienting effect by exposing subjects to the environment once as part of their orientation to the experimental setup and before the data-gathering portion of the experiment. In the Passive Haptics and Frame Rate studies, subjects entered the VE for approximately two minutes and were shown both rooms before the experiment started. These pre-exposures reduced but did not eliminate the orienting effects.

1.3.2 Validity

Validity is the extent to which a test or experiment genuinely measures what it purports to measure [Sutherland, 1996]. Since the concept of presence is itself vague and debatable, the question is then: How well do physiological reactions correlate with more traditional measures of presence? We investigated their correlations with several such measures.

Reported Presence. Among the physiological measures, ΔHeart Rate correlated best with the Reported Presence. There was a significant correlation in the Frame Rate study (corr. = 0.265, P˚=˚0.002) and a weak and non-significant positive correlation (corr. = 0.034, P˚=˚0.743) in the Passive Haptics study. In the Multiple Exposures study, where ΔHeart Rate was not available, ΔSkin Conductance had the highest correlation with Reported Presence (corr. = 0.245, P˚=˚0.009).

Reported Behavioral Presence. Both ΔHeart Rate and ΔSkin Conductance correlated well with the Reported Behavioral Presence. ΔHeart Rate had the highest correlation, and a significant one with Reported Behavioral Presence in the Frame Rate study (corr. = 0.192, P˚=˚0.028), and there was a weak and non-significant positive correlation between the two (corr. = 0.004, P˚=˚0.972) in the Passive Haptics study. In the Multiple Exposures study, where ΔHeart Rate was not measured, ΔSkin Conductance had the highest correlation with reported behavioral presence (corr. = 0.290, P˚=˚0.002). ΔSkin Conductance also had a non-significant positive correlation with Reported Behavioral Presence in the Passive Haptics Study (corr. = 0.106, P˚=˚0.280).

The correlations of the physiological measures with the reported measures give some support to their validities. The validity of ˇHeart Rate appears to be well established by its correlation with the well-established reported measures. There was also support for the validity of ΔSkin Conductance from its correlation with reported measures, though not as strong support as for ΔHeart Rate.

There was little support for the validity of ΔSkin Temperature. As noted by McMurray, the measure suffers two limitations: 1) skin temperature response is slow (can take on the order of minutes for full effect) and is affected by many factors (sympathetic activity, muscular activity, etc.), 2) the sensors for detecting temperature changes are slow and can take on the order of one to three minute to fully register a change in temperature [McMurray, 1999]. We believe that these two lags combined with the limited time of exposure to the Pit Room (on the order of one minute) do not allow for enough time for useful measurement of ΔSkin Temperature.

Observed Behavioral Presence. Observed Behavioral Presence consistently correlated well with Reported Behavioral Presence, but it had mixed correlations with Reported Presence.

Following hypothesized relationships. According to Singleton, the validation process includes examining the theory underlying the concept being measured, and The more evidence that supports the hypothesized relationships [between the measure and the underlying concept], the greater one s confidence that a particular operational definition is a valid measure of the concept [Singleton, 1993] . We hypothesized that presence should increase with frame rate and with the inclusion of the 1.5-inch wooden ledge. As presented in the next section, our physiological measures increased with frame rate and with inclusion of the 1.5-inch wooden ledge. This helps validate the physiological reactions as measures of presence.

1.3.3 Sensitivity and multi-level sensitivity

Sensitivity is the likelihood that an effect, if present, will be detected [Lipsey, 1998]. The fact that the physiological measures reliably distinguished between subjects being in the Pit Room versus the Training Room assured us of at least a minimal sensitivity. All measures did so in every study. For example, heart rate increased an average of 6.3 beats / minute (BPM) in the Pit Room ($P < 0.001$) compared to the Training Room in both the Passive Haptics and Frame Rate studies. See Table 1.1 for full details of the means and standard deviations for each measure.

Multi-level sensitivity. For guiding VE technological development and for better understanding the psychological phenomena of VEs, we need a measure that reliably yields a higher value as a VE is improved along some goodness dimension, i.e., is *sensitive* to multiple condition values. We call this *multi-level sensitivity*. The Passive Haptics study provided us some evidence of multi-level sensitivity. Anecdotally, we have observed that walking into the Pit Room causes a strong reaction in users and this reaction is greater in magnitude than the differences in reaction to the Pit Room between any two experimental conditions (e.g. with and without the 1.5-inch wooden ledge). Therefore, we expected the differences among the conditions to be less than the difference between the two rooms. For example, in Passive Haptics, we expected there to be a significant difference in the physiological measures between the two conditions (with and without the 1.5-inch wooden ledge), but expected it to be less than the difference between the Training Room and Pit Room in the lower presence condition (without the 1.5-inch wooden ledge). For ΔHeart Rate, we did find a significant difference between the two conditions of 2.7 BPM (P˚=˚0.016), and it was less than the inter-room difference for the without-ledge condition: 4.9 BPM. See Figure 1.4.

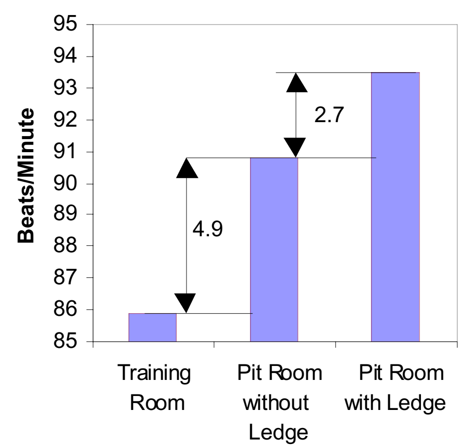


Figure 1.4. Heart Rate in the Passive Haptics study.

In the Passive Haptics study, we further tested the multi-level sensitivity by testing whether presence was significantly higher with the 1.5-inch wooden ledge. Presence as measured by ΔHeart Rate (2.7 BPM; P˚=˚0.016), ΔSkin Conductance (0.8 mSiemens; P˚=˚0.040), and Reported Behavioral Presence (0.5 high responses; P˚=˚0.004) were significantly higher with the wooden ledge. Reported Presence had a strong trend in the same direction (0.5 high responses; P˚=˚0.060). ΔSkin Temperature varied in the opposite direction; skin temperature decreased less when the 1.5-inch wooden ledge was present.

1.1.1.2

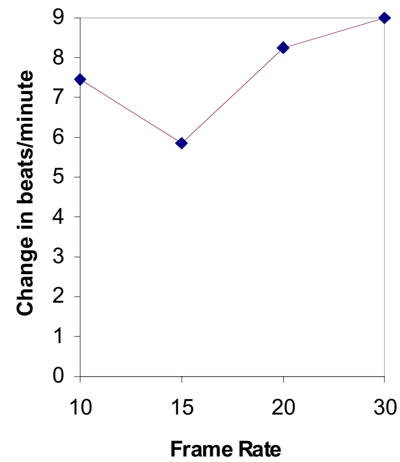


Figure 1.5. Average change in heart rate, after correcting for Loss of Balance, between Training Room and Pit Room at 10, 15, 20, and 30 frames per second.

In the Frame Rate study, we hypothesized that for graphics frame rates of 10, 15, 20, and 30 FPS, physiological reactions would increase monotonically with frame rate. They did not do exactly that (see Figure 1.5). During the 10 FPS condition, there was an anomalous reaction for all of the physiological measures and both the behavioral measures: Reported Behavioral Presence and Observed Behavioral Presence. That is, at 10 FPS, subjects had higher physiological reaction, reported more behavioral presence, and acted more present in the Pit Room. We believe that this reaction was due to discomfort, added lag, and reduced temporal fidelity while they were in the ostensibly dangerous situation of walking next to a 20-foot pit. This is discussed in more detail in Chapter 4.

We also observed that subjects often lost their balance while trying to inch to the edge of the wooden platform at this low frame rate (Loss of Balance). Controlling for these Loss of Balance incidents improved the significance of the statistical model for ΔHeart Rate (3.5 BPM higher when Loss of Balance; P°=°0.014) and brought the patterns of responses closer to the hypothesized monotonic increase in presence with frame rate — but did not completely account for the increased physiological reaction at 10 FPS. Loss of Balance was not significant in any other model.

1.1.1.2

Beyond 10 FPS, ˇHeart Rate performed well after statistically controlling for Loss of Balance. ˇHeart Rate significantly increased (3.2 BPM; P˚=˚0.004) between 15 FPS and 30 FPS and between 15 FPS and 20 FPS (2.4 BPM; P˚=˚0.024). There was also a non-significant increase between 20 FPS and 30 FPS (0.7 BPM; P˚=˚0.483) and a non-significant decrease between 10 FPS and 15 FPS (1.6 BPM; P˚=˚0.134). Reported Presence, Reported Behavioral Presence, and ΔSkin Temperature also increased with frame rate from 15-20-30 FPS, but with less distinguishing power. These findings support the multi-level sensitivity of ΔHeart Rate but do not support those of ΔSkin Conductance and ΔSkin Temperature.

1.3.4 Objectivity

The measure properties of reliability, validity, and multi-level sensitivity are established quantitatively. Objectivity can only be argued logically. We argue that physiological measures are inherently better shielded from both subject bias and experimenter bias than are either reported measures or measures based on behavior observations. Reported measures are liable to subject bias — the subject reporting what he believes the experimenter wants. Post-experiment questionnaires are also vulnerable to inaccurate recollection and to modification of impressions garnered early in a run by impressions from later. Subject reporting during the session, whether by voice report or by hand-held instrument, intrudes on the very presence illusion one is trying to measure.

Observed measures are obviously liable to scorer bias. The use of videotape helps by making it possible for the scorer to do replays and to make considered judgments. In some studies, however, it is impossible to hide the condition from the experimenter scoring the measure. For example, in the Passive Haptics study, the experimenter can see the 1.5-inch wooden ledge on the videotape. Behavioral measures are also somewhat liable to subject bias. We observed occasional intentionally exaggerated or intentionally suppressed fear behaviors near the pit.

Physiological measures, on the other hand, are much harder for subjects to affect, especially with no bio-feedback. They are not liable to experimenter bias, if instructions given to the users are properly limited and uniform. We read instructions from a script in the Multiple Exposures study. We improved our procedure in the later Passive Haptics and Frame Rate studies by playing instructions from a compact disk player located in the real laboratory and represented with a virtual radio in the VE.

1.1.1.2

1.3.5 Summary and discussion

The data presented here and later in Chapter 4 show that physiological reactions can be used as reliable, valid, multi-level sensitive, and objective measures of presence. Of the physiological measures, ΔHeart Rate performed the best. It significantly differentiated between the Training Room and the Pit Room and this reaction faded over multiple exposures, but never to zero. It correlated with the well-established reported measures. It distinguished between the inclusion of passive haptics and among frame rates after 10 FPS. As we argued above, it is objective. In total, it satisfies all of the requirements for a reliable, valid, multi-level sensitive, and objective measure of presence.

ΔSkin Conductance and ΔSkin Temperature have some, but not all, of the properties we desire in a measure of presence. In our investigation, at least one of the properties of reliability, validity, multi-level sensitivity, and objectivity were not met for each of these measures. We believe that ΔSkin Temperature performed poorly because the exposure to the VE was too short for useful measurement of changes in skin temperature. Moreover, we believe that ΔSkin Temperature has a response time much longer than is useful for our studies (around two minutes). We do not have a theory as to why ΔSkin Conductance was not multi-level sensitive in the Frame Rate study.

We found that ΔHeart Rate satisfied the requirements for a presence measure for our VE, which evokes a strong reaction, but it may not for all VEs. If this did not work for so strong a stimulus, it would not work for less stressful VEs. Our investigation is only a first step. More investigation would be needed to determine if physiological reaction could also work as a measure of presence for less stressful or non-stressing VEs.

Another desirable aspect of a measure is ease of operationalization. We did not measure the time taken for each measure, but after running many subjects we can say with some confidence that use of the physiological monitoring and the presence questionnaire added approximately the same amount of time to the experiment, with the questionnaire taking a little less time. The observed behavioral measure did not add to the time to conduct the experiment, but added considerable time after the experiment. It took about five minutes of both the experimenter s and subject s time to put the physiological sensors on and take them off for each exposure. It took about an extra minute at the beginning and end of each set of exposures to put on and take off the ECG sensor — it was left on between exposures on the same day. It took subjects about five minutes to fill out the 16-item UCL Presence Questionnaire. Time to review the videotape of each session was the longest — this took an average of eleven minutes per exposure (around 25 hours to review 132 sessions in the Frame Rate experiment, the only one for which we kept track of the time spent). A benefit of the presence questionnaire was that the experimenter was free to do something else while the subjects filled them out. The observed behavioral measure took no additional time for the subject and very little training was needed to do the scoring. It took some training to learn the proper placement of the physiological equipment on the hands and chest of the subject — thirty minutes would probably be sufficient for most graduate students. We avoided loosing time while connecting the physiological monitoring equipment by having one experimenter start up the VE while the other connected the physiological sensors.

Another aspect of ease of operationalization is ease of use. No subjects reported difficulties with the questionnaires. None had a problem with being recorded during the sessions. Technical problems, though, plagued our videotaped measure. Only about one in ten subjects reported noticing the physiological monitoring equipment on the hands during the VE exposures. Our experiment, though, was designed to use only the right hand, keeping the sensor-laden left hand free from necessary activity. No subjects reported noticing the ECG sensor once it was attached. In fact, many subjects reported forgetting about the ECG electrodes when prompted to take them off at the end of the day. There are groups investigating less cumbersome equipment including a physiological monitoring system that subjects wear like a shirt [Cowings, 2001].

Overall, questionnaires and physiological monitoring were easy to operationalize, the observed behavioral measure was less so.

1.4 Physiological reactions as between-subjects measures

We conducted all of the studies as within-subjects to avoid the variance due to natural human differences. That is, subjects experienced all of the conditions for the study in which they participated. This allowed us to look at relative differences in subject reaction among conditions and to overcome the differences among subjects in reporting (for the questionnaires), physiological reaction, and behavior (for the Observed Behavioral Presence measure).

1.1.1.2

The UCL questionnaire has been used successfully between-subjects [Usoh, 1999]. We suspected, however, that physiological reaction would not perform as well if taken between-subjects. Specifically, we expected that between-subjects physiological measures would not be able to significantly differentiate among presence conditions, since the variance among subjects would mask, at least in part, the differences in physiological reaction evoked by the different conditions. We also expected correlations with the reported measures to be reduced, since individual differences in physiological reaction and reporting would confound the correlations. For example, consider a subject presented with a low presence condition who reported low presence. If the subject was highly physiologically reactive, however, he still could have had a high physiological reaction relative to the group average — even if it were lower than it would have been if he was presented with a high presence condition. Such a case would reduce the correlations.

We expected that there would still be a consistent physiological reaction to the Pit Room, since we expected such a reaction for every exposure to the VE. We expected the significance to be slightly lower, however, because of the reduced size of the data set.

We discuss these assumptions in this section by analyzing the data using *only the first task* for each subject — eliminating order effects and treating the reduced data sets as between-subjects experiments. That is, we treat each experiment as if only the first task for each subject was run. This means that the analysis uses only 10 data points (10 subjects — first exposure only) for the Multiple Exposures study, 52 data points for the Passive Haptics study, and 33 data points for the Frame Rate study.

Reliability between-subjects: Physiological reaction in the Pit Room. As suspected, all of the physiological reactions were significantly higher in the Pit Room when analyzing between-subjects. See Table 1.3. Also, as expected, the significance values for the differences were lower when looking at only the first exposure than when looking at all exposures, due to the reduced number of data points. The means for the physiological measures for the first exposures were *higher* than for the full data set (except for ΔSkin Conductance in the Passive Haptics study). This follows, since we observed physiological orienting effects. The fraction of exposures in which heart rate and skin conductance were higher and skin temperature was lower in the Pit Room as compared to the Training Room is the same or better than these for the within-subjects data, and all are 90% or better. Heart Rate in Passive Haptics is the only exception (85% vs. 89%). See Table 1.3.

		First Exposure Only				All exposures			
Study	**Variable**	**Mean**	***P***	**N**	**Count < 0**	**Mean**	***P***	**N**	**Count < 0**
Multiple Exposures	**ΔSkin Conductance**	**2.9**	*.002*	9	0	2.3	*.000*	112	1
	ΔSkin Temperature	**1.2**	*.015*	7	0	0.6	*.000*	94	22
Passive Haptics	**ΔHeart Rate**	**6.2**	*.000*	46	7	6.3	*.000*	92	10
	ΔSkin Conductance	4.7	*.000*	50	**0**	**4.8**	*.000*	100	0
	ΔSkin Temperature	**1.1**	*.000*	49	3	1.1	*.000*	98	10
Frame Rate	**ΔHeart Rate**	**8.1**	*.000*	33	3	6.3	*.000*	132	12
	ΔSkin Conductance	**2.6**	*.000*	33	1	2.0	*.000*	132	17
	ΔSkin Temperature	**1.0**	*.000*	33	0	0.8	*.000*	132	0

Table 1.3 . Means and significance for one-sample t-test (test to see if the mean was significantly higher than zero). Also shown is the count of times that the measure was below zero. Physiological reaction, shown here for first task only and for all tasks together, was higher in the Pit Room. The higher mean is shown in bold face.

Validity between-subjects: Correlation with established measures. As expected, physiological reactions did not correlate as well with the questionnaires when analyzing between-subjects. There were no significant correlations between the physiological measures and any of the questionnaire measures in any of the studies.

Multi-level sensitivity between-subjects: Differentiating among presence conditions. We expected inter-subject variation in physiological reaction to mask the differences in physiological reactions evoked by the presence conditions (e.g. various frame rates). Contrary to this expectation, though, the physiological measures **did** differentiate among the conditions: physiological reaction to the Pit Room was significantly higher that to the Training Room for all measures in all studies (described above), and we found significant differences in the physiological measures among conditions in both the Passive Haptics and Frame Rate studies. (The condition was not varied in the Multiple Exposures study.)

In the Passive Haptics study, both ΔHeart Rate and ΔSkin Conductance performed well as between-subjects presence measures. In the base statistical model (not correcting for anything) both varied in the expected direction with some power (P˚=˚0.097 for ΔHeart Rate; P˚=˚0.137 for ΔSkin Conductance). After correcting for subjects level of computer game playing, the significance for ΔHeart Rate was reduced (P˚=˚0.180).

1.1.1.2

In the Frame Rate study, ΔHeart Rate performed well, but ΔSkin Conductance did not follow hypothesized patterns. ΔHeart Rate had an anomalous physiological reaction at 10 FPS. This was also the case for ΔHeart Rate in the full data set (compare Figures 1.5 and 1.6). Additionally, ΔHeart Rate differentiated among presence conditions: ΔHeart Rate at 30 FPS was higher than at 15 FPS and this difference was nearly significant (7.2 BPM; P°=°0.054).

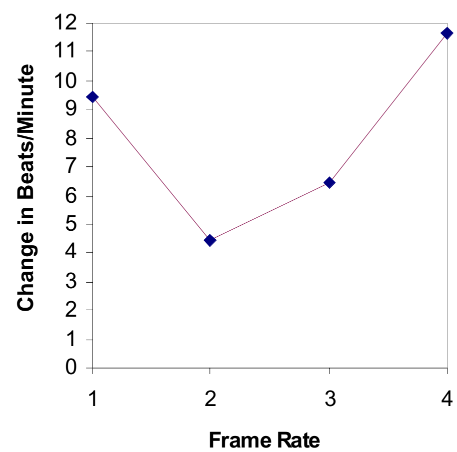


Figure 1.6. Between-subjects analysis: Response graph of ΔHeart Rate.

Overall, ΔHeart Rate shows promise as a between-subjects measure of presence. Though it did not correlate well with the reported measures (between-subjects), it did differentiate among the conditions with some statistical power in Passive Haptics and Frame Rate. ΔSkin Conductance and ΔSkin Temperature did not show as much promise as between-subjects measures. For more discussion of physiological reaction as between-subjects measures of presence, see Section 4.4.1.

1.5 The results of the studies

To establish the properties of the physiological presence measures, we conducted three controlled user studies, plus the pilot studies necessary to debug environment, equipment, and procedures. Each was a dualpurpose study, both contributing to the development and testing of physiological presence measures and investigating some other aspect of VEs.

1.5.1 Effect of multiple exposures on presence (Multiple Exposures)

Hypothesis: The presence-inducing power of a VE declines with multiple exposures, but not to zero.

Ten subjects had three exposures to the VE each day on four separate days — a total of twelve exposures each. The VE and the task were the same for each exposure.

Results. There was a significant order effect for each measure in at least one of the three studies, and when not significant, the trends were in the same direction. Table 1.2 summarizes the order-effect results significant at the P°<°0.050 level (**bold**) and P < 0.100 (normal text), not only for this study, but also for the two subsequent ones. The existence and magnitude of the significant order effects in all the measures supports the hypothesis that all presence measures decreases over 12 exposures to the same VE, but not to zero.

1.5.2 Effect of passive haptics on presence (Passive Haptics)

Hypothesis: Supplementing a visual-aural VE with even rudimentary, low-fidelity passive haptics cues significantly increases presence.

This experiment was only one of a set investigating the passive haptics hypothesis. The detailed design, results, and discussion for the set are reported elsewhere [Insko, 2001].

Design. Fifty-two subjects each had two exposures on separate days. For the passive haptics condition, the virtual ledge in the Pit Room was augmented with a registered real plywood ledge, 1.5 inches high. A user in a HMD, unable to see the real world, could feel the edge of the ledge with the foot. 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. Each subject experienced the environment with the 1.5-inch wooden ledge (high presence condition) and without it (low presence condition). Presentation of the conditions was counterbalanced across subjects. Figure 1.7 shows a subject standing on the 1.5-inch wooden ledge.

1.1.1.2

Figure 1.7. A subject drops a block into the virtual pit. He is standing on the edge of the 1.5-inch wooden ledge. The physiological monitoring equipment is attached to his left hand.

Results. As discussed above, ˇHeart Rate was significantly higher (P˚=˚0.016) with the wooden ledge than without it. Reported Behavioral Presence (P˚=˚0.004) and ΔSkin Conductance (P˚=˚0.040) were also significantly higher. Reported Presence had a strong trend (P˚=˚0.060) in the same direction.

1.5.3 Effect of frame rate on presence (Frame Rate)

Hypothesis: As frame rate increases from 10, 15, 20, 30 frames/second, presence increases.

Thirty-three subjects each had four exposures to the same VE and task, at each of several frame rates. Presentation order was counterbalanced across subjects.

1.1.1.2

Results. Discussed in Section 1.4 above, the hypothesis was confirmed for 15, 20, 30, FPS, but 10 FPS gave anomalous results.

1.6 Future work

Given a compelling VE and a good presence measure, the obvious strategy would be to degrade the VE quality parameters one at a time so as to answer: What makes a VE compelling? What are the combinations of minimum system characteristics to achieve this?

For example, we hope to study

- Aural localization,
- Visual Detail,
- Lighting realism,
- Self-avatar fidelity,
- Realistic physics in interactions with objects, and
- Interactions with other people or agents.

We want to begin to establish trade-offs for presence evoked: Is it more important to have lag below 50 ms or frame rate above 20 FPS? These tradeoffs could eventually lead to identification of *isosurfaces* for presence, as described by Ellis [Ellis, 1996]. In particular, physiological reaction satisfies his requirement that an independent measure of human performance or some other independent characteristic of the virtual environment should be shown to be determined by equivalence classes. We could compare the effect of varying system parameters (e.g. lag, frame rate, visual realism, etc.) on the extent of physiological reaction evoked. Assuming repeatable results, sets of VE system parameter (e.g. *Lag* = Lag_j, *Frame Rate*=FR_j, *Use of localized sound* = Yes, etc.) that evoke equal physiological reactions would be in the same equivalence class.

Future work should include using VEs that evoke more subtle reactions and different reactions than ours. To use physiological reaction as a measure of presence, *feeling presence* in the VE must evoke a physiological reaction distinct from that of the laboratory environment. Ours did this by evoking in subjects the perceived danger of moving about near a height. Other VEs might evoke presence in other stressful environments, exciting environments, interesting environments, relaxing environments, etc. If future investigators are unsure of the physiological reaction that the VE should evoke, then a controlled study in the corresponding real environment should be conducted.

Further investigation should also include VEs that expose the subject to the stressor for less time. In a study with a shorter exposure to the stressor, one should consider three things:

1) There is a lag of 2-3 seconds from time of stimulus (exposure to stressor) to onset of reaction for all physiological reaction including heart rate, skin conductance, and skin temperature [Andreassi, 1995].

2) Heart rate is affected by respiration. For accurate measurement, heart rate should be averaged over one or two respiration cycles. A respiration cycle averages 4 seconds [Seidel, 1995].

3) Skin temperature does not work well for exposures of less than 2 minutes.

We must eliminate the cables that tether subjects to the monitoring, tracking, and rendering equipment. Our subjects reported this encumbrance as the greatest cause of breaks in presence.

Chapter 2 Related work

The study of presence dates back, at the very least, to Plato s theory of Forms and his pondering the nature of *being* and reality [Plato, 380 B.C.]. The study of presence in virtual environments came into full swing with the first issue of MIT Press journal *Presence: Teleoperators and Virtual Environments* in 1992. In this chapter, we describe theories of presence that have been presented in the literature, discuss previous experiments on presence, and discuss the work of other groups that have studied physiological reactions to virtual environments (VEs).

2.1 Defining and describing presence explicitly

This section gives details of published definitions of presence and discusses taxonomies presented in the literature.

Steuer defines virtual environments in terms of presence and telepresence: a *virtual environment* is a real or simulated environment in which a perceiver experiences telepresence [Steuer, 1992]. He defines *presence* as the sense of being in an environment and *telepresence* as the experience of presence in an environment by means of a communications medium. He elaborates: In other words, presence refers to the natural perception of an environment, and telepresence refers to the mediated perception of an environment.

Steuer states that the two technical dimensions that contribute to the sense of presence in virtual environments are vividness and interactivity. He separates *vividness*, the ability of a technology to produce a sensorially rich mediated environment, into two categories: breadth and depth. *Breadth* refers to the number of senses stimulated by the VE (i.e. does the VE include visual, audio, haptic, and olfactory displays?) *Depth* refers to the resolution and quality of each of the included sensory displays.

1.1.1.2

He defines *interactivity* as the extent to which users can participate in modifying the form and content of a mediated environment [interactively].   It combines speed, range, and mapping.   *Speed* refers to response time. Real-time interaction (with no lag) is the fastest of possible speeds. *Range* is determined by the number of attributes of the mediated environment that can be manipulated and by the amount of variation possible within each attribute.   For example, range includes intensity (of sensory displays), organization (of the world), frequency characteristics (of the sensory displays), etc. *Mapping* is the way in which human actions are connected to actions in the mediated environment. For example, in [Slater, 1995b], Slater studies the effectiveness of two mappings of movement in a VE: subjects either walked in place or used a 3D mouse to move about within the VE.

Heeter defines three dimensions of presence: Subjective Personal Presence, Social Presence, and Environmental Presence [Heeter, 1992]. *Subjective Personal Presence* is a measure of the extent to which and the reasons why you feel like you are in a virtual world.   The factors that affect this type of presence are the sense of inclusion in the VE, representation of self within the VE, and familiarity with the VE.

Social Presence refers to the extent to which other beings (living or synthetic) also exist in the world and appear to react to you.   The factor that affects this type of presence is the evidence that you and other entities exist in the VE. For example, allowing users of a multi-user VE to communicate over an audio channel should increase social presence.

Environmental Presence is the extent to which the environment itself appears to know that you are there and reacts to you.   Examples include motion sensing lights, creaking floor boards, dynamic shadows, etc.

Held and Durlach assert that one should be able to measure presence with subjective scales, behavioral responses, and physiological reactions [Held, 1992].

They discuss factors that should contribute to presence:

- Increased sensory depth and breadth should increase evoked presence: this discussion corresponds closely with Steuer s vividness [Steuer, 1992].
- Displays and tacking systems should be free from artifactual stimuli that signal [their] existence.

- Head and virtual body movements should be slaved to the user, and lower lag in these movements should evoke more presence.
- The VE should be predictable.

Sheridan defines *presence* (or *virtual presence*) as the sense of being physically present with visual, auditory, or force displays generated by a computer and *telepresence* as the sense of being physically present with virtual object(s) at the remote teleoperator site   [Sheridan, 1992]. Sheridan postulates that the factors that affect virtual presence and telepresence are the same and that they are the extent of sensory information, control of relation of sensors to environment, and ability to modify the physical environment. The *extent of sensory information* refers to the number of senses stimulated and the extent of the stimulation by the displays of the VE. It corresponds closely to Steuer s depth and breadth of vividness [Steuer, 1992].   *Control of relation of sensors to the environment* refers to the ability of the VE to modify body-centered direction of sensory input as the user moves in the VE. *Ability to modify physical environment* includes both object manipulation in the VE and passive effects such as dynamic shadows.

Schloerb describes two novel definitions of presence and discusses their measurement [Schloerb, 1995]. He defines *objective presence* as the probability that a user will complete a task. For example,

> Consider the task of *throwing the ball into the basket*. It is assumed that some particular basket, ball, and manner of throwing are specified. If a person (the operator) can throw the ball into the basket when asked to do so, then he or she is objectively present.

Therefore, objective presence is different based on the task by which it is defined. *Subjective presence* is equal to the probability that [the user] perceives that he or she is physically present in a given remote [or virtual] environment. He states that presence can be measured along both axes: objective (based on task performance) and subjective (based on percentage chance subjects say they are in the environment depicted by the computer). He observes that no existing VE could evoke subjective presence. He addresses this by suggesting that if a subject s view of the *real* world was somehow degraded or altered so as to look less real, then subjective presence could be constructed as a function of the extent of the degradation to the real world and the probability of saying that he or she is in the VE. Sheridan discusses this in more detail [Sheridan, 1996].

1.1.1.2

Sheridan extends his previous work, [Sheridan, 1992], by discussing measurements of presence [Sheridan, 1996]. He states that three basic measures have been presented in the literature: reflex response [Held, 1992; Slater, 1993], subjective responses to questions [Heeter, 1992; Slater, 1994], and ability to discriminate between the virtual and real environment [Schloerb, 1995]. He proposes a fourth measurement where noise is added to both the real and virtual environments (degrade the images, frame rates, etc.) until the difference between the two is no longer distinguishable. The level of noise needed to degrade the real and virtual stimulation until the perceived environments are indiscriminable would be used as the measure of presence. No test was performed.

Ellis discusses the need to be able to find equivalence classes — or isosurfaces — for levels of presence [Ellis, 1996]. He limits his discussion to the case in which users of a medium really are trying to communicate a precise, often numerical message, and are more concerned about error than appeal or impact. He therefore discusses a presence measure that correlates with performance and is similar to objective presence discussed by Schloerb [Schloerb, 1995]. He requires that: (1) Measures of presence as a function of its constituents should result in identifiable surfaces or hypersurfaces so as to allow identification of level set equivalence classes and (2) an independent measure of human performance or some other independent characteristics of the virtual environment should be shown to be determined by equivalence classes. He states that a measure of presence should be a function of the quantified independent variables of the VE: visual fidelity, audio fidelity, interactivity, lag, etc.

Witmer and Singer define *presence* as the subjective experience of being in one place or environment, even when one is physically situated in another [Witmer, 1998]. With this they encompass both presence and telepresence. They state: presence is a normal awareness phenomenon that requires directed attention and is based in the interaction between sensory stimulation, environmental factors that encourage involvement and enable immersion, and internal tendencies to become involved. They also state that whereas full attention is not necessary for presence, it is likely that there is a minimum threshold for allocation of attentional resources before presence is experienced and that attention above that threshold is likely to increase presence.

Slater *et al.* define three aspects of *presence* [Slater, 1999]:

- The sense of being there in the environment depicted by the VE.

- The extent to which the VE becomes the dominant [reality], i.e., that participants will tend to respond to events in the VE rather than in the real world.
- The extent to which participants, after the VE experience, remember it as having visited a place rather than just having seen images generated by a computer.

They have studied the effect on presence of characteristics of subjects (e.g. perceptual position and preferred representation system) and of varying VE system parameters (e.g. inclusion of a virtual body, dynamic shadows, and walking metaphor). These studies are described in Section 2.2.1.

Lombard and Ditton give a multi-disciplinary overview of presence including work from VEs and from more traditional media such as television, film, radio, and text [Lombard, 1997; Lombard, 1999]. Their discussion is comprehensive and informative, but not all of it applies to presence in VEs. Based on their multidisciplinary literature search, they break presence up into six categories: *Presence as social richness*, *presence as realism*, *presence as transportation*, *presence as immersion*, *presence as social actor within the medium,* and *presence as medium as social actor.*

Presence as social richness is "the extent to which a medium is perceived as sociable, warm, sensitive, personal, or intimate when it is used to interact with other people." Social richness is typically measured with bipolar scales such as impersonal-personal, unsociable-sociable, insensitive-sensitive, and cold-warm.

Presence as realism is "the degree to which a medium can produce seemingly accurate representations of objects, events, and people." This includes *perceptual realism*, the extent of realistic stimuli presented to the senses (similar to Steuer s vividness [Steuer, 1992]), and *contextual realism*, how plausible or true-to-life the scene is. An airplane simulator flying backwards could have high perceptual realism, but low contextual realism.

Presence as transportation includes transporting a person to a place (a user may think: "I am here"), transport an object to the user’s space ("It is here"), and transporting two people to a shared space ("We are together").

Presence as immersion includes perceptual immersion and psychological immersion. *Perceptual immersion* describes the extent to which the perceptual system of the user is immersed in the VE and stimuli from the real world are excluded. *Psychological immersion*, on the other hand, describes the extent to which the user is involved, absorbed, engaged, and engrossed.

Presence as social actor within medium is the presence evoked by feeling co-located with a simulated entity within a medium. This includes feeling co-located with others in a multi-user VE or feeling present, within a VE, with an entity simulated by the computer.

Presence as medium as social actor involves social responses of media users not to entities (people or computer characters) within the medium, but to cues provided by the medium itself. They state that because computers use natural language, interact in real time, and fill traditionally social roles (e.g. bank teller and teacher), even experienced computer users tend to respond to them as social entities. When people talk to computers or televisions (often because the equipment is not functioning properly) they are treating the medium as a social actor.

Next they assert that *presence* — "the illusion that a mediated experience is not mediated" — can be split into two categories: "the medium can appear to be invisible" (*presence as invisible medium)* and "the medium can appear to be transformed into something other than a medium" (*presence as transformed medium*). They also state that presence "does not occur in degrees but either does or does not occur at any instant during media use; the subjective feeling that a medium or media-use experience produces a greater or lesser sense of presence is attributable to there being a greater or lesser number of instants during the experience in which the illusion of nonmediation occurs."

Lombard and Ditton then discuss a number of variables that they hypothesize affect presence:

Number and consistency of sensory outputs. The greater number of senses stimulated and the more consistent the stimuli, the greater the evoked presence.

Visual display characteristics. Better image quality should improve presence; increased image size and increased field of view should increase presence; coherent motion and realistic color should increase presence; use of stereoscopic imagery should increase presence.

Aural presentation characteristics. Better sound quality (frequency range, dynamic range, and signal to noise ratio) should increase presence. Appropriate three-dimensional sound and ambient noise should increase presence.

1.1.1.2

Stimuli for other senses. Appropriate olfactory cues, movement (either self-propelled or from the system), tactile stimuli, and use of force displays ([responding] to user input with the sensations of physical resistance) should each increase presence.

Interactivity. They name five variables that relate interactivity to presence. The greater *the number of inputs* that a medium accepts from a user, the more presence the system should evoke. Presence should increase with *the number of modifiable characteristics* of the media presentation. Presence should increase with *the range of change possible* in each media characteristic. The *correspondence between user input and media reaction* should increase presence by enforcing more natural cause-effect relationships. Finally, the *speed of response* to user input should affect presence, with fast responses evoking more presence.

Obtrusiveness of a medium. "For an illusion of nonmediation to be effective, the medium should not be obvious or obtrusive." Less obtrusive media should evoke more presence.

Live versus recorded or constructed experience. "Live" media (when events are displayed as they happen, such as live television) should evoke more presence than recorded or constructed media should.

Number of people. "A ... feature that may encourage a sense of presence is the number of people the user can (or must) encounter while using the medium." Greater social interactivity should evoke more presence.

Lombard and Ditton describe a number of variables relating the content of media to presence.

Social realism: More realistic storylines, characters, and actions should evoke more presence.

Use of media conventions. Use of media conventions is likely to reduce presence by reminding the user that they are engaging with a mediated environment. For example, using a computer in a traditional role, such as word processing, is likely to remind users that they are engaging with a computer, because many people associate word processing with computers. Users are not likely to be reminded that they are using a computer when the computer s role is less conventional, such as playing cards with friends, talking to and seeing their parents (teleconferencing), or reading a book.

Nature and number of tasks. The type of task in which the user participates, if any, may make it more or less difficult to establish presence [Heeter, 1992]. Sheridan points out that the degree of control in the task may also influence presence [Sheridan, 1992].

They discuss variables that relate characteristics of the user to presence. *Willingness to suspend disbelief*. People who are willing to suspend disbelief are more likely to experience a medium as presence-inducing.

Knowledge of and prior experience with the medium. Presence might increase with multiple exposures to a medium, as users become comfortable with it [Held, 1992]. Presence might also decrease as novelty wears off [Heeter, 1992].

They also discuss the effects of presence. They note that high-presence systems can evoke *arousal* and other *physiological effects and reactions*. They hypothesize that high presence might be related to *enjoyment, involvement, task performance, skills training, desensitization, persuasion (e.g. in advertisements), memory, and social judgment.*

2.2 Previous presence experiments

Many of the experiments investigating presence have been conducted by Mel Slater and his group — first at Queen Mary and Westfield College and more recently at University College London (UCL). First, we describe Slater *et al.* s research projects (2.2.1), and then we discuss work done by other groups (2.2.2). Unless stated otherwise, all findings reported here were significant at the P°<°0.050 level. To further clarify some of the lists of results, we state explicitly whether or not the results are significant.

2.2.1 Slater *et al.*

Representations systems, perceptual position, and presence. Slater and Usoh investigated the effect on presence of three things: 1) inclusion of a virtual body (VB), 2) users *perceptual position* (does the user remember events in the first, second, or third person?), and 3) users *primary representation systems* (does the user experience events primarily using the audio, visual, or kinesthetic representation system?) [Slater, 1993]. Nine of the seventeen subjects (computer science graduate students) were randomly assigned to the experimental group in which each subject was represented with a VB in the VE. An arrow represented the subjects in the eight-member control group. The subjects engaged in a number of tasks: movement about a cluttered room, reacting to flying objects, reacting to being virtually upside-down, building a structure from blocks, and walking a plank over a virtual precipice. The devices used to measure presence were a direct subjective question on a post-experiment questionnaire, a record of subjects behavioral reactions to the virtual objects flying at them (notes were taken during the experiment), and their behavioral reactions to socially conditioned responses such as being asked the time.

To assess the primary representation system, they had each subject write a post-experiment essay on his experience. The essays were broken up into sentences. Long sentences linked by a conjunction were counted as two sentences. The primary representation system was taken as a three-element vector: the ratios of the number of audio (A — Audio Ratio), visual (V — Visual Ratio), or kinesthetic (K — Kinesthetic Ratio) words used in the essay to the total number of sentences. The perceptual position was the three-element vector of ratios between the counts of reference frames used (first, second, or third person) and the total number of sentences.

They found that

- Independent of including the virtual body, the higher the Visual Ratio, the greater the sense of presence.
- For those with a virtual body, the higher the Kinesthetic Ratio, the greater the sense of presence.
- For those without a virtual body, the higher the Kinesthetic Ratio, the lower presence.
- Presence increased up to a ratio of 0.7 first-person usage and declined thereafter.

They stated the results as tentative due to the low number of subjects and the fact that the subjects did not represent the general population.

Walking metaphor. Slater *et al.* described an experiment in which sixteen subjects moved about in a VE with a visual cliff [Slater, 1995b]. Half of the subjects used a walking-in-place metaphor for movement in the VE, the other half flew by pointing a 3D mouse. In the experiment, subjects moved an object from the ground onto a chair at the other side of the virtual hole. Within the VE, subjects were represented with a virtual body consisting of a hand (tracked) and a simple human figure. They used two metrics of presence: a three-question presence questionnaire and whether the subject walked over the hole in the floor to reach the other side of the room. The questionnaire also included questions measuring the extent to which the subject felt associated with the VB.

They concluded that, for walkers , the greater the association with the VB, the greater the reported presence. For pointers there was no correlation between VB association and reported presence. They found that walking over the precipice to reach the chair (and deposit the object) was associated with lower reported presence. Analysis also showed that a high level of reported nausea (reported on a questionnaire) correlated significantly with a higher degree of presence.

Presence and presence depth. Slater *et al.* used a set of nested virtual worlds to investigate how four things affected *presence* (measured via post-experiment questionnaire) and *presence depth* (each additional world-to-world transition adds one level to the presence depth) [Slater, 1994]. They investigated the effect of 1) world-to-world transition method (virtual HMD or walking through virtual doors), 2) simulation of gravity, 3) simulation of a virtual actor, and 4) simulation of a virtual cliff.

The experiment used a fairy-tale-like story line to lead the twenty-four volunteers through a series of (nested) virtual worlds to collect swords. The volunteer group was counterbalanced into eight groups of three based on the four independent variables. Within each group, subjects were assigned to go through 2, 4, or 6 levels in the VE. Half of the subjects made the transitions from one virtual world to the next by donning a virtual HMD, and the other half walked through virtual doors. Half of the volunteers experienced a VE simulation of the visual cliff; half experienced the VE with no cliff. Half experienced the effect of gravity on the objects in the world, and half experienced no gravity. Half experienced the presence of a responsive virtual actor (following them); half experienced an unresponsive virtual actor.

They measured presence with a questionnaire. The questionnaire had three presence questions, and the presence score was taken as the number of high responses: 6s and 7s on a 7-point scale.   They tried alternate methods of combining the questions including the use of 5s, 6s, and 7s as high responses and a combination based on principal-components analysis. They found that the use of [m6] as high values best followed conditions for the study.

They surveyed subjects (via a pre-trial questionnaire) about their primary representation system:

Visual (V) — the world is experience visually,

Auditory (K) — the world is experienced via sound, or

1.1.1.2

Kinesthetic (A) — the world is experience kinesthetically

and their representation system:

egocentric — the world is experienced in first person — and

exocentric — the world is experienced in third person.

V, K, and A were computed as the sum of the rankings from the representation system questions. Egocentric perceptual position was the number of egocentric answers for the egocentric/ exocentric questions.

Their analysis revealed that

- Presence was positively associated with Visual and Kinesthetic, and negatively with Auditory.
- Presence was positively associated with the number of levels (depth) of the virtual environment experienced if the subject experienced the transitions using the virtual headmounted displays and negatively if the transitions were made with virtual doors.

They stated that gravity, visual cliff, and virtual actor variables did not show up as significant. This could be the result of the measurement of presence used. They argued that their presence measure was not sensitive enough to differentiate the small differences in presence that these simulation techniques might have evoked.

Dynamic shadows. Slater *et al.* described an experiment in which the effects of dynamic shadows on both presence and spatial judgment were studied [Slater, 1995a]. Eight subjects participated. Each was instructed to use the handheld 3D mouse to select and pick up the virtual spear closest to the wall from behind a virtual screen (Figure 2.1). The spears were the same height and placed at nearly the same distance, and the virtual screen hid the bottoms. Therefore, subjects could not have used position on the floor or foreshortening cues to aid correct spear choice. They hypothesized that subjects would be able to use the shadows of the spears on the walls to aid their judgment about the closeness to the walls, so that those runs that included shadows would result in a greater number of correct spears being chosen.

1.1.1.2

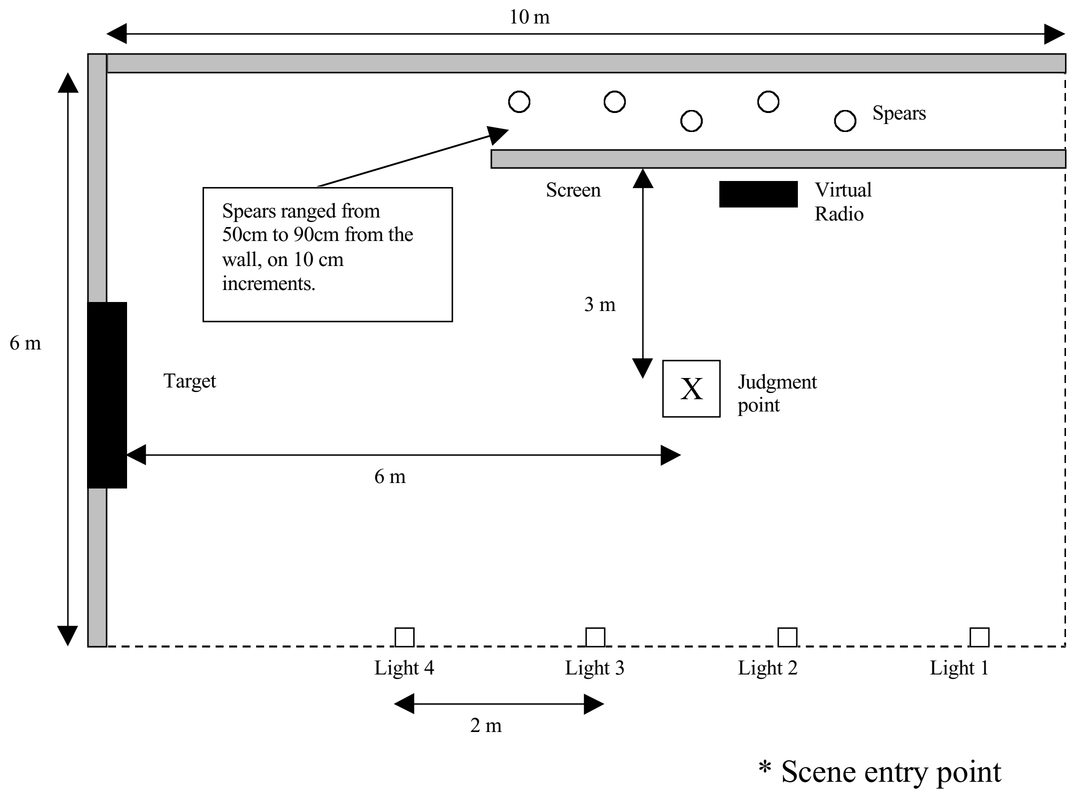


Figure 2.1. Diagram of environment used for the Slater *et al.* s dynamic shadow experiment (simplified from [Slater, 1995a]). Shadows were cast on the walls colored gray here. It was not stated, but it appears that the dotted lines were not visible to users. They did not state specifically if the room had two or four walls. Their description was of a virtual room which implies four walls, but their diagram showed just two walls and included a thin line indicated by our dotted line.

Subjects picked a spear, moved to the judgment point , turned toward the target, aimed the spear at a virtual target and threw the spear at the target. During flight their two-part task was to guide the spear with hand motions, using the 3D mouse, to the center of the target, and then to stop the virtual spear as close as they could to the instant that its point hit the target. In the latter task, the distance could have been positive or negative — the spear was able to pass through the wall. They hypothesized that shadows would aid in both of these tasks since the shadows on the wall and target would help users guide the spear as it flew toward the target s center and since, when the spear hit the wall, its point would meet its shadow(s). Each subject carried out five trials and the extent of dynamic shadow generation was varied among trials. The extent of dynamic shadow generation was controlled by varying the number of lights (0, 1, 2, 3, or 4 lights) that were casting shadows.

1.1.1.2

Spatial judgment was measured by the correctness of spear choice (the subjects were instructed to chose the spear closest to the wall), closeness of the spear to the center of the target, and distance from the virtual target that the subject stopped the spear s flight. Presence was measured via a presence questionnaire (as in [Slater, 1994]) and by having the subject point, while immersed, at a playing radio, whose visual direction in the VE was different from the audio direction in the real world. Presence was measured as the angle selected: closer to the virtual radio indicated higher presence.

They also had subjects write an essay before the session in order to determine subjects primary representation system: visual (V), auditory (A), and kinesthetic (K). This was explained above for [Slater, 1994].

They found

- Shadows made no difference at all to the selection of the correct spear (the one closest to the wall). No statistical values or means were given.
- Subjects were non-significantly better at guiding the spear toward the center of the target when shadows were present.
- Subjects were significantly better at stopping the spear as it hit the target when shadows were generated.
- Presence was significantly and positively related to the number of shadows for subjects whose visual system dominated over there auditory system (V>A) but not when A>V.
- The angle picked between the virtual and real radios was significantly related to the number of shadows generated, with a greater number of generated shadows being associated with pointing closer to the virtual radio.

Immersion, presence, and performance. Slater *et al.* examined the relationship among immersion, presence, and performance in a twenty-four-subject study (sixteen males and eight females) [Slater, 1996]. The subjects task was to reproduce a 3D chess game. The series of moves were the opening moves of a computer vs. computer game. Subjects could view the sequence of moves as many times as they wished. All of the subjects were introduced to VEs: they walked around and moved objects in the VE and were introduced to 3D chess.

1.1.1.2

The subjects were split into two groups: immersive (inside an HMD) and non-immersive (desktop VE). Subjects saw the 3D chessboard either in a garden with chessboard in a field on a table, or with no background setting. The metrics were a questionnaire for presence [Slater, 1994] and a count of the number of correct moves reproduced for performance.

The experimental data showed that

- Better performance (more chess moves correctly reproduced) was associated with HMD immersion and with the more realistic (garden) environment.
- Females did not perform as well as males.
- For females, SAT (Spatial Ability Test) scores were positively associated with performance. For males there was no relation between SAT and performance.
- Previous knowledge of chess was positively associated with better performance.
- Better performance was achieved with a greater number of practice sequences.
- HMD use was positively associated with higher presence.
- Presence was non-significantly higher in the garden environment as compared to the void.

Collision response. Uno and Slater discussed the effects of collision response on presence in VEs [Uno, 1997]. Eighteen subjects participated in two rounds of a virtual bowling game with three independent variables: elasticity of the colliding bodies; friction among the ball, the pins, and the lanes; and the accuracy of the shape used to compute the collisions. For the latter, the collision-defining computational shapes of the pins were simplified to ellipsoids in half of the trials. The dependent variable in the experiment was the subjective sense of presence as measured by six questions on a post-experiment questionnaire. The presence score was taken as the number of high responses for the presence questions [m6]. The post-experiment questionnaire also included questions on simulator sickness.

After the experiment, subjects were asked if they had observed any differences between the two rounds of bowling (reported on a questionnaire). In the case when elasticity was the changing parameter, half of the subjects noticed a change. In the case of friction, all of the subjects observed a change. In the case of the shape, no subjects observed the change. They also found that presence was negatively correlated with reported sickness and was not affected by either elasticity or shape (if friction was low). If friction was high, presence was positively associated with correct shape and negatively associated with elasticity.

Presence, co-presence, and group accord. Steed *et al.* studied the relationship among *presence*, *co-presence* (the sense of being with other people), and *group accord* (the sense of harmony, enjoyment, and cooperation with other people) [Steed, 1999]. In the experiment, twenty groups of three (two on desktops and the third in a HMD — all geographically distributed) solved a riddle that was described in text posters on the walls of the virtual room. They shared a virtual space and could communicate via a shared audio channel. Presence, co-presence, and group accord were measured using questionnaires — six, eight, and seven questions respectively. For presence and group accord, the questionnaires were scored as the number of high responses [m6]. Co-presence was measured as a sum of responses to its questions, not the count of high responses.

The analysis of the data showed that there was a significant relationship between presence and co-presence, that there was no significant effect of immersion on presence, that group accord and co-presence were significantly positively correlated, and that leadership increased significantly with immersion only for males.

Walking metaphors. In [Usoh, 1999], Usoh *et al.* described an extension to their earlier experiment, described in [Slater, 1995b]. The experiment used the visual cliff to investigate the role of walking metaphor on presence and ease of locomotion. The study consisted of 33 na ve subjects and 11 expert subjects who worked in the area of computer graphics. The study was performed between-subjects, and subjects were counterbalanced among real walking, walking-in-place, and point-and-fly. Questionnaires included Kennedy's simulator sickness questionnaire (SSQ) [Kennedy, 1993] and an extension of Slater s presence questionnaire [Slater, 1995b]. There was also a post-experiment oral debriefing.

They found that

- Presence correlated with association with the virtual body.
- Presence was higher for virtual walkers than flyers.
- Presence was higher for real walkers than virtual walkers. However, the difference between groups diminished and was not significant when oculomotor discomfort was taken into account

(much of the lower presence for virtual walkers was explained by their greater oculomotor discomfort).

- Real walking was seen as more natural, easy, and uncomplicated.
- There were no significant differences for behavioral presence measure among the locomotion types.
- There were no significant differences between the expert and naive groups.
- An unexpected result: The virtual environment was reported as very compelling.

Breaks in presence. Slater and Steed investigated a novel measure of presence. They used the number of times that a subject reported a *break in presence* (BIP — when something, either internal or external, caused a subject to remember he was in the laboratory) to assess presence [Slater, 2000]. The number of BIPs (transitions from virtual to real) was counted, and using some simplifying assumptions, a probabilistic Markov Chain model [was] constructed to model these transitions. This can be used to estimate the equilibrium probability of being present in the VE. In summary, a lower number of BIPs resulted in a higher score for this measure. Subjects reported a BIP only when it happened, thereby lessening the disruptive effect of the reporting. They also used a five-question version of their earlier presence questionnaire [Usoh, 1999] to assess presence. Body and hand movements were computed from tracker data.

The study investigated the effect of body movement on presence in VEs. Of the twenty subjects, ten touched virtual chess pieces on a virtual 3D chess board in order to move them (the active group). The other ten subjects clicked a handheld mouse button to move the pieces (the control group). The results revealed a significant correlation between an increase in the number of BIPs and lower presence as reported on the questionnaires. For the high activity group, there was also a significant positive correlation between body movement and presence. For the low activity group, there was not a significant association between body movement and presence. The mean presence levels for the two groups were contrary to expectation. The mean presence for the low activity group was non-significantly higher than that of the high activity group.

Presence questionnaires in reality. In [Usoh, 2000], Usoh *et al.* investigated the use of two questionnaires to discriminate real and virtual experiences. One questionnaire, the Slater, Usoh, and Steed questionnaire (SUS), was made up of six of the questions that the authors have used in previous questionnaires [Usoh, 1999]. Throughout this dissertation we refer to this questionnaire as the Reported Presence measure of the UCL Presence Questionnaire. The other questionnaire (WS) was the Witmer and Singer s presence questionnaire [Witmer, 1998]. The test was performed between-subjects. Ten subjects searched (individually) for a box in real office, the other ten searched (individually) for a box in a virtual office. Each group completed both questionnaires immediately after the experience.

They found that both questionnaires had higher values in the real world, but only the SUS was significantly so. They stated that the difference was significant due to only two questions:

Please rate your sense of being in the space, and

During the experience, I often thought I was really standing in the office space.

They conclude that although such questionnaires had been previously found to be useful when all subjects experience the same environment, their utility would be doubtful when comparing experiences across environments, since they poorly differentiated real and virtual environments.

2.2.2 Other presence studies

In addition to the work by Slater *et al.*, a number of other researchers have studied the effects of various VE system parameters on presence. Following is a description of these studies.

Presence and fear of heights. Regenbrecht *et al.* described a 37-subject study in which the relationship between presence and fear of heights was analyzed [Regenbrecht, 1997]. Subjects were tasked with finding books in the VE. In order to reach these books they had to cross one of two small virtual bridges in the VE or walk across the virtual depth (eight meters deep) as if on a glass ceiling. The length of the chasm crossed was not stated, but it was less than four meters (the size of their interaction space) and appeared in pictures in the text to be approximately 1-2 meters. All subjects experienced the same condition and each subject entered the environment only once. Before the experiment, they assessed fear of heights and avoidance behavior using Cohen s *height anxiety* and *height avoidance* questionnaires [Cohen, 1977]. After the 20-minute experiment, they used a questionnaire developed for this experiment to assess *presence* and *reported fear*.

1.1.1.2

The analysis showed that reported fear had a significant relationship with height anxiety (positive), height avoidance (negative), and presence (positive). That is, reported fear was significantly higher for subjects who reported higher presence and (pre-experiment) higher height anxiety. Reported fear was significantly lower, however, for subjects who reported higher height avoidance, which suggests that participants with an established avoidance behavior find a way to lower their fear in the [VE].

Presence, co-presence, and susceptibility for presence. Thie investigated the relationships among *presence, co-presence* (the extent that subjects feel they are with others in the VE) , and *susceptibility-for-presence* (willingness to accept the VE, to take in the VE, and to block out the real world) [Thie, 1998]. The experiment had sixteen sets of three users who performed a decision-making task (task not described) using a Netscape-based multi-user VE on non-immersive desktops. The subjects were split into two groups: one with maximized co-presence cues, the other with minimized co-presence cues. Maximizing social virtual presence cues was accomplished by adding an avatar representation in the VE and by allowing nicknames, enabling gestures , and indicating who said what in the accompanying text-based communication system. Thie measured susceptibility-for-presence, co-presence, and presence using a modification of questionnaires from [Psotka, 1993]. He also measured *comeback rate* by observing if subjects reentered the VE after the test but before leaving the lab. Subjects had to wait for some time (unspecified) after the experiment and were told they could either read or reenter the VE.

The results showed that co-presence and presence correlated. The results did not replicate Psotka's findings that susceptibility-for-presence and presence were related. Maximizing and minimizing the selected co-presence cues did not significantly affect any of the dependent measures.

Haptic feedback and presence, co-presence, and task performance. Sallnas investigated the effect of haptic feedback on presence, co-presence, task performance, and perceived task performance [Sallnas, 1999]. She also measured skin conductance, but has not yet analyzed the results. Fourteen male-female pairs collaborated to stack virtual blocks — the subjects had to push on opposite sides of the blocks in order to lift and stack the blocks. Half of the pairs had haptic feedback with the PHANToM. Subject pairs were not in the same room, but all had audio links. Sallnas used Witmer and Singer s presence questionnaire to measure presence [Witmer, 1998]. The co-presence questionnaire considered the social aspects of the experience: unsociable-sociable, insensitive-sensitive, impersonal-personal, cold-warm [Short, 1976]. Task performance was the amount of time to complete the stacking task. Perceived task performance was measured via questionnaire. The perceived task performance questionnaire was not explained.

The analysis showed that with haptics

- Task performance was significantly better ($P < 0.050$),
- There was no significant difference in co-presence,
- Presence was significantly higher ($P < 0.050$)
- Perceived performance was significantly higher ($P < 0.010$)

Sensory stimuli and presence. Dihn *et al.* discussed an experiment that studied the effect of tactile, olfactory, audio, and visual sensory cues on presence, memory of spatial layout, and memory of object location [Dihn, 1999]. The 322-subject study used two levels of visual details and the existence or absence of tactile, auditory, and olfactory information. After elimination of a few of the participants for not completing the questionnaires or for equipment failures, there were at least 15 subjects for each of the 16 experimental condition combinations.

The VE allowed users to proceed on a predefined path in a virtual office place. The subjects could not veer from the path, but could look around in the VE. While inside the VE, the possible sensory inputs were the smell of coffee near the coffee pot in the front room, hearing and feeling the wind from a fan, the sound of the copier running, hearing the toilet flush, and feeling the heat of the virtual sun (a heat lamp) while on the balcony. Visual fidelity reduction was accomplished by reducing the quality of texture mapping and taking away directional lighting in the virtual office. To measure presence, they used one question, rating the overall presence from 0 to 100, and a 13-item questionnaire adapted from Fontaine and Hendrix [Fontaine, 1992; Hendrix, 1996]. For memory assessment, they used a four-item questionnaire for spatial layout and a five-item questionnaire for object location.

They found that

- There was a significant correlation between presence (both measures) and both auditory and tactile cues.
- There was a notable trend (a non-significant correlation) between presence and olfactory cues.

1.1.1.2

- The difference in visual cues was not significant in predicting presence.
- There was a significant effect for olfactory and tactile cues on memory of object location.
- There were no significant effects for sensory cues on memory of spatial layout.

They stated that the lack of impact from visual fidelity on presence could have been due to the fact that both were at the low end of the visual fidelity spectrum.

2.3 Measuring physiological correlates to a virtual environment experience

Eberhart and Kizakevich. The earliest published experiments investigating physiological reactions to a VE experience were performed by Eberhart and Kizakevich [Eberhart, 1993]. The physiological signals their system monitored were core body temperature (a swallowed probe), skin temperature, skin resistance, and heart rate. They described two experiments. In the first, users navigated with a 2D mouse — once at low speed, once at high speeds. There was a non-significant increase in blood pressure at higher navigation speed and a non-significant drop in cardiac output over the course of each test. In the second experiment, the task was to keep the image of the hand inside a virtual cube while walking on a treadmill. The treadmill ran at two speeds. Feedback on performance was given either via instant audio and visual or via delayed audio. Detailed results were not given.

Jorgensen *et al*. used heart rate, skin temperature, and skin conductance to assess the effectiveness of navigation metaphors in VEs [Jorgensen, 1997]. At the time of publication, results were not available, though they did state that there were significant heart rate, skin temperature, and breathing responses during the flying task. We have not located further publication of their work.

Weiderhold *et al*. used heart rate, skin temperature, respiration, and skin conductance to provide objective evidence of phobia desensitization [Weiderhold, 1998]. At the time of the publication, data from only two patients (one phobic, one non-phobic) had been collected and analyzed. They found physiological support for the desensitization primarily from skin conductance. It was the quickest to react to phobic stimuli and showed the most change over treatment as desensitization occurred.

1.1.1.2

Pugnetti *et al.* In [Pugnetti, 1996; Pugnetti, 1995], Pugnetti *et al*. studied human responses to immersion in a VE using electroencephalography (EEG), and electrocardiography (ECG). Subjects navigated a VE version of the Wisconsin Card Sorting Test [Jones, 1948]: a series of virtual rooms in which there was a pattern to the correct choice of three exit doors. The choice was based on correctly following the clues on the entrance door: its color, shape, or number of dots. They were informed visually if the choice was correct: after a correct choice, they saw the next room, after an incorrect choice, they had an additional corridor to navigate. Their task was to find their way through a series of rooms by choosing the correct door to exit in each room.

They found central nervous system activity similar to that seen during learning in a real environment: amplitude of alpha waves (measured via EEG) increased over time and the brains reaction (quick, high amplitude brain waves) to irrelevant stimuli (a tone once per second) had greater latency and lower amplitudes — interpreted as subjects being engrossed in the VE. There were also physiological responses to the frustration of incorrect choices: heart rate from the ECG recordings served as a correlate of psychological frustration in sensitive subjects who were [performing poorly]"

Pugnetti, Meehan *et al.* expanded Pugnetti *et al.* s previous studies by investigating physiological correlates of a VE experience [Meehan, 2000c; Pugnetti, 2000]. We confirmed the earlier findings for learning-related brain activity in the environment and found significant physiological reaction to content of the virtual environment: heart rate and skin conductance increased when subjects performed poorly at the task in the VE. We also found that heart rate decreased over time in the environment, supporting the idea that subjects could relax in VEs even with much physiological and VE equipment attached.

Yamaguchi investigated fatigue caused by immersion in a VE [Yamaguchi, 1999]. Ten male subjects underwent a thirty minute controlled VE exposure including two psychological interviews by a virtual nurse — one low stress, one high stress. None of their physiological parameters (heart rate, skin conductance, core body temperature, urinary catecholamine release) indicated that significantly more fatigue occurred during the VE exposure than during the a control session in which subjects watched a video of a static picture of a living room with a TV set in it.

Cobb *et al.* investigated physiological and reported sickness effects caused during exposure to VEs [Cobb, 1999]. They measured heart rate, and salivary cortisol composition (SCC). They found that both heart rate and

1.1.1.2

SCC reflected well (the correlations were not given) the simulator sickness as reported on Kennedy s SSQ [Kennedy, 1993]. Heart rate rose as subjects put on the equipment and entered the VE (possibly due to anticipation of the experiment or novelty of the VE) and decreased thereafter. This decrease in heart rate over time was also found in [Meehan, 2000c].

1.1.1.3

Chapter 3 Experimental design

3.1 Research question

Researchers have investigated presence in virtual environments since the early 1990 s. The majority of the measures used in experiments and discussed in the literature have been subjective [Regenbrecht, 1997; Slater, 2000; Usoh, 1999; Witmer, 1998]. Most groups have used questionnaires or single question scales. Some groups have used behavioral measures. All of the measures attempted to assess whether users of virtual environments (VEs) felt present in the depicted world. There has been much investigation as to how to best do this [Lombard, 1997; Meehan, 2000a; Meehan, 2000b; Regenbrecht, 1997; Sheridan, 1996; Slater, 1999; Slater, 2000; Usoh, 1999; Witmer, 1998], and researchers have yearned for a measure that is reliable, valid, multi-level sensitive, and objective.

We propose measures to satisfy these requirements: physiological reactions. Our three experiments investigated the use of physiological reactions as reliable, valid, multi-level sensitive, and objective measures of presence in VEs.

In this chapter, we discuss our hypotheses about these measures, how the experimental design investigated these hypotheses, and details of the experimental design.

The terminology is defined below:

Multiple Exposures - The Effect of Multiple Exposures on Presence. The first experiment.

Passive Haptics - The Effect of Passive Haptics on Presence. The second experiment.

Frame Rate - The Effect of Frame Rate on Presence. The third experiment.

Task - A single exposure of the subject to the environment.

Session - A set of one or more tasks on a single day (Multiple Exposures and Frame Rate had multiple tasks per session, Passive Haptics did not).

1.1.1.2

For more discussion of validity, reliability, multi-level sensitivity, and objectivity of presence measures, please see Chapters 1 and 4.

3.2 Our environment and physiological reaction as a measure of presence

Many VEs evoke physiological reactions. The physiological reactions evoked will differ from VE to VE — as they do among real environments. Standing near a flowing stream with a view of a mountain in autumn should evoke a calming affect (increased parasympathetic nervous system (PNS) tone, decreased sympathetic nervous system (SNS) tone — see Appendix A). Standing in a raging fire while a building collapses around you should evoke a stress response (decreased PNS, increased SNS tone). Our understanding of what people mean by *presence* is that the psychological sense of being there should correspond to physiological reactions similar to those evoked by similar real environments. We also believe that the more presence a VE evokes, the more physiological reaction it should evoke. In short, we believe that the psychological and physiological responses to the VE should correlate.

In our VE, a 20-foot cliff was depicted (see Figure 3.1). It is well known that standing near a height and moving about at risk of falling causes physiological reactions in individuals. [Abelson, 1989]. In particular there is an increase in heart rate and skin conductance and a decrease in skin temperature. Below, we describe our hypotheses and how our experiments used our VE to investigate them. We chose our VE because users have reported strong reactions to it. If physiological measures of presence did not work with so strong a stimulus, they would not in more subtle VEs.

1.1.1.2

Figure 3.1. Side view of the virtual environment. Subjects start in the Training Room and later proceed to the Pit Room.

3.3 The measures

We hypothesized that, in our VE, physiological reaction to the Pit Room (Figure 3.1) would be high and there would be less physiological reaction to the Training Room. Therefore, we constructed our measures as differences between the reactions in the two rooms:

ΔHeart Rate = mean heart rate $_{\text{Pit Room}}$ - mean heart rate $_{\text{Training Room}}$

ΔSkin Conductance = mean skin conductance $_{\text{Pit Room}}$ - mean skin conductance $_{\text{Training Room}}$

ΔSkin Temperature = mean skin temperature $_{\text{Training Room}}$ - mean skin temperature $_{\text{Pit Room}}$

The order of the arguments in ΔSkin Temperature was switched so that the measure would increase with more physiological reaction (as do ΔHeart Rate and ΔSkin Conductance).

We chose heart rate, skin conductance, and skin temperature because 1) they are well studied and well understood measures, and 2) they are easily measured from the palms and chest of the subjects. See Appendix A for discussion of the physiological reactions and how we measured them.

1.1.1.2

We measured the physiological reactions with the ProComp+ tethered telemetry system from Thought Technologies, Ltd. The device can accommodate up to 8 sensors, two of which sample at a rate of 256˚Hz. The other six sample at 32 Hz. The Heart Rate was measured with the Blood Volume Pulse photoplethysmograph sensor (256˚Hz) in the Multiple Exposures study and with a three-electrode electrocardiograph (Ag-AgCl˚electrodes) in the Passive Haptics and Frame Rate studies (256˚Hz). Skin conductance was measured with two 1-cm^2 Ag-AgCl electrodes connected to the index and middle fingers of the left hand with Velcro (32˚Hz). Skin Temperature was measured with a 0.3-cm bead thermistor connected to the index finger of the left hand with porous tape (32˚Hz). The battery-powered analog to digital converter sent data via fiber-optic cable to a server running on a PC. The device and sensors are pictured in Figure 3.2. For further information on physiological reaction and the placement of the sensors, see Appendix A.

Figure 3.2. Procomp+ device.
From left to right: the electrocardiograph, skin conductance, and skin temperature sensors.

We used a modified version of the University College London Presence Questionnaire [Usoh, 1999] to measure Reported Presence (7 questions), Reported Behavioral Presence (3 questions), and Reported Ease of Locomotion (3 questions). To measure simulator sickness, we used Kennedy s Simulator Sickness Questionnaire (SSQ) [Kennedy, 1993]. To measure height anxiety and avoidance, we used Cohen s height questionnaire [Cohen, 1977]. These questionnaires are included in Appendix B.

To measure Observed Behavioral Presence —*the extent to which a user acts as if in a corresponding real environment* — we scored actions from videotapes of the sessions. It was scored as a count of behaviors believed to be associated with moving about near a real 20-foot drop. These actions were chosen because they were actions that we had seen users perform in demonstrations of our VE system or because we believed they were appropriate. The measure was scored by adding together the counts of each action. We believed *Walking across the 20-foot pit* as if it were a glass floor was a sign of lower presence, so the count of this was subtracted from the Observed Behavioral Presence score.

Observed Behavioral Presence = (S Count(j) | j != [1,2]) - Count (1) - Count (2)

	Behavior	Counts	
1	**Walks across 20-foot pit, outgoing**	Yes = 1	No = 0
2	**Walks across 20-foot pit, incoming**	Yes = 1	No = 0
3	**Slows motion when entering Pit Room**	Yes = 1	No = 0
4	**Leans against wall, outgoing**	Yes = 1	No = 0
5	**Leans against wall, incoming**	Yes = 1	No = 0
6	**Curls toes**	Count	
7	**Tests edge with foot**	Count	
8	**Kneels to feel ledge**	Count	
9	**Sticks out arms for balance**	Count	
10	**Takes series of baby steps**	Count of series of steps	
11	**Peers over ledge**	Count	
12	**Vocal Exclamations**	Count	
13	**Change of breath pattern**	Count	
14	**Loss of balance (not on the wooden ledge)**	Count	
15	**Loss of balance on wooden ledge**	Count	

Table 3.1. The items scored from videotape for the Observed Behavioral Presence measure.

3.4 Reliability, validity, multi-level sensitivity, objectivity, and our hypotheses

Singleton identifies three important aspects for a useful measure of psychological constructs: reliability, validity, and objectivity (which he calls lack of bias) [Singleton, 1993]. Lipsey points out that experimental measures must be sensitive [Lipsey, 1998]. We extend his discussion by stating that a measure must be multi-level sensitive. We constructed our hypotheses to analyze these four aspects of a measure: reliability, validity, multi-level sensitivity, and objectivity. Below, we discuss these properties of a measure and then summarize and discuss our hypotheses.

Reliability is the extent to which the same test applied on different occasions yields the same result [Sutherland, 1996]. We tested reliability of the physiological measures by looking at whether there was consistently greater physiological reaction to the Pit Room as compared to the Training Room — for multiple exposures and multiple subjects (Hypoth1). In general, when examining the reliability of a measure, one must investigate the extent to which adaptation or desensitization reduces repeatability. Therefore, we tested whether the measures decreased to zero over a limited number of exposures. We hypothesized that they would decrease over a limited number of exposures, but not to zero (Hypoth2).

Validity is the extent to which a test or experiment genuinely measures what it purports to measure [Sutherland, 1996]. Validity is first assessed subjectively by answering the question: Does the operational definition measure what it purports to measure? [Singleton, 1993]. We discuss why we subjectively expect physiological reactions to measure presence in our VE in Chapter 1 and earlier in this chapter.

Validity is statistically assessed by correlations with related or well-established measures of the same construct [Singleton, 1993]. We investigated the correlations of the physiological measures with the well-established UCL Presence Questionnaire (see Hypoth3).

Validity is also assessed by accumulation of research evidence that a measure consistently follows hypothesized relationships between the underlying concept and the independent variables. For example, suppose you have developed a measure of presence. In your first experiment, this measure yields significantly higher results when the VE uses a new global illumination algorithm as compared to Phong Shading. In absence of other evidence, one might not conclude that you are measuring presence at all, but instead are measuring lighting realism. Suppose you conduct another study in which your measure is significantly higher when using 3D aural localization as compared to no sound. Now, there is evidence that you are not measuring lighting realism. In absence of other evidence, however, one might conclude that you are measuring audio-visual realism. The more studies and the broader the range of studies in which a measure follows hypothesized relationships, the greater [your] confidence that a particular operational definition is a valid measure of the concept [Singleton, 1993]. We tested two independent hypothesized relationships for our measure. We expected presence, and therefore physiological reaction, to be higher with the inclusion of a 1.5-inch wooden ledge and to increase with increasing with frame rate (Hypoth4).

To be *objective*, the measure must be determined by and emphasize the features of the object or thing dealt with, rather than the thoughts and feelings of the [experimenter or subject] [Webster, 1994]. Lack of objectivity can come from two sources: Experimenter bias and subject bias. Subject bias can come from numerous sources including demand characteristics, cues in an experimental situation that communicate to subjects what is expected and what the experimenter hopes to find [Singleton, 1993]. Subject bias can also come from subject apprehension about the evaluation of their performance or [from] their resentment about being coerced into taking part in an experiment [Singleton, 1993] . Experimenter bias comes from experimenters non-verbally communicating their own expectations to subjects.

Providing a good cover story for or a distracter task in the experiment can help control bias. Both keep the subjects distracted and allow less-noticeable manipulation of the independent variable(s) and measurement of the dependent variable(s) [Singleton, 1993]. We had a distracter task in all three studies: carrying objects into the Pit Room to be dropped or placed there. In Passive Haptics, we also had a cover story: subjects were told they were visiting a famous professor s house and were performing his daily routine. In Frame Rate, we improved the distracter task, subjects picked up and dropped blocks to the lower floor in the Pit Room, but we did not come up with a suitable cover story.

Bias can also be overcome by keeping experimenters and subjects blind to the conditions of the experiment. We were able to keep subjects blind to the condition in all three studies. The subjects saw only half of the real laboratory — that corresponding to the Training Room. Styrofoam walls and a curtain blocked the view of the Pit Room. This kept subjects blind to the condition in Passive Haptics and kept subjects guessing as to whether there was really a 20-foot drop. In Frame Rate, subjects were not informed of the frame rate at which the VE was running — they were blind to the condition. In Multiple Exposures, there was no condition manipulated. The experimenters were not blind to the condition in either the Passive Haptics or Frame Rate studies. In Passive Haptics, the experimenter could see the 1.5-inch wooden ledge as he carried the cables for the subject. In Frame Rate, we chose to keep the experimenter aware of the condition in order to ensure that the subjects were exposed to the conditions in the proper orders. We have no reason to believe, however, that the experimenters knowledge of the condition biased the subjects physiological, behavioral, or questionnaire responses.

Bias can also be lessened by automation of the experiment and instructions given to the subjects [Singleton, 1993]. The nature of VEs is automatic. Subjects movements and object manipulations in the environment were handled automatically by the VE software. We additionally automated the experiment by providing automatic Internet-based administration of all questionnaires. An experimenter sat subjects down at a computer and clicked on the appropriate html link for their stage in the experiment (pre-exposure or post-exposure). After finishing a questionnaire, they were automatically forwarded to the next by the browser. At the end of a set of questionnaires, a web page asked them to tell the experimenter that they had completed the questionnaires.

Giving uniform instructions to the subjects also helped reduce bias. In Multiple Exposures, we accomplished this by reading the instructions from a script. In Passive Haptics and Frame Rate, we improved our design by playing the instructions from an audio compact disc. In all three studies, we did not talk to subjects during the experiment unless we had to warn them of some danger (e.g. if a subject was about to trip on cables). If subjects asked questions during the experiments, we did not respond.

In addition to the attempts to control bias described above, we also argue that the physiological measures are inherently exposed to less bias than either questionnaires or behavioral measures. This is argued in Chapter 1.

Sensitivity is the likelihood that an effect, if present, will be detected [Lipsey, 1998]. If a measure is also valid, then that difference will also represent the effect under investigation [Lipsey, 1998]. Greater sensitivity improves investigation because it improves the chances of detecting differences in the dependent variable caused by the manipulation of independent variables, thus helping establish relationships among the variables. Sensitivity also helps reduce the cost of experimentation. The more sensitive a measure, the fewer subjects needed to show statistical significance and the lower the time and monetary cost of the experiment.

For a measure to be useful, it must be sensitive to differences along some goodness scale. Therefore, we extend the idea of sensitivity to *multi-level sensitivity* — the ability of a measure to differentiate multiple levels of some condition value or independent variable. We expect our measures to increase monotonically as we improve the virtual environment along some goodness scale (e.g. increasing frame rate). Specifically, we expect that if x is the condition value and f(x) is our presence measure:

$$f(x_i) > f(x_j),\ iff\ x_i > x_j$$

$$f(x_i) = f(x_j),\ iff\ x_i = x_j$$

1.1.1.2

For this relationship to hold, x must be within some useful range. Personal experience suggests an upper-limit of 60 FPS for useful measurement. Above 60 FPS, we would expect the reactions to level off since we would not expect the differences in condition to be detected by the average subject. The frame rate experiment suggests a lower limit of 15 FPS for useful measurement of the physiological measure. Below this we began to see anomalous reactions to the condition. For Passive Haptics, an artificial range had to be constructed to meet the above definition. Ours, for example, was constructed as (0= Training Room, 1 = Pit Room without ledge, 2 = Pit Room with ledge). We investigated the multi-level sensitivity of the physiological measures in both Passive Haptics and Frame Rate (see Hypoth4).

In summary, we formed our hypotheses as follows:

Hypoth1: *There is a consistent physiological reaction to the VE* (**Reliability and Sensitivity**).

Hypoth2: P*resence measures decrease over multiple exposures to the same virtual environment, but not to zero* (**Reliability**).

Hypoth3: *Subjective, physiological, and behavioral presence measures correlate* (**Validity**).

Hypoth4: *Physiological presence can differentiate among multiple (high, medium, and low) presence conditions. Specifically, in terms of presence evoked: with passive haptics > without passive haptics; 30 FPS > 20 FPS > 15 FPS > 10 FPS, and the differences among these conditions are less than the gross differences between the Pit Room and the Training Room* (**Validity and Multi-level Sensitivity**).

Objectivity of the presence measures cannot be tested, but is argued in Chapter 1.

3.4.1 Discussion of hypotheses

Hypoth1. There is a consistent physiological reaction to the VE.

All three studies investigated whether autonomic reactions could be used to measure presence in VEs. We hypothesized that there would be physiological reaction to the 20-foot drop. Therefore, there would be consistently higher heart rate, skin conductance, and (lower) skin temperature in the Pit Room than in the Training Room.

1.1.1.2

Hypoth2: The physiological presence measures decrease over subsequent exposures to the same virtual environment, but not to zero.

We hypothesized that all presence measures would decrease from task to task on a single day — and over multiple days. We believed that subjects would acclimate to the environment, the VE would become less novel to them, and, therefore, that less presence would be evoked for all of the presence measures during each subsequent task in a single session and over multiple sessions

For our measures to be useful, they must not decrease to zero over a small number of exposures to the VE. We investigated 2, 4, and 12 exposures / subject. Physiological habituation over multiple exposures, if it occurred, would not decrease the validity of the measure, since the same habituation diminishes stress reactions to real heights [Abelson, 1989].

Multiple Exposures, Passive Haptics, and Frame Rate investigated Hypoth2 by looking at whether the reaction decreased over multiple exposures. In Multiple Exposures, there were three tasks per session and subjects came in for four sessions (on four different days). In Passive Haptics, subjects came in for one task per session for two session (on two different days). In Frame Rate, subjects completed four tasks during one session — they came in for only one day.

Hypoth3: Subjective, physiological, and behavioral presence measures correlate.

We hypothesized that the presence measures would correlate in all three studies (Hypoth3). That is, when a subject reported more presence, they would act more present, and they would have higher physiological reactions. We expected that the physiological measures and the behavioral measures would correlate better than either would with the reported (questionnaire) measures. We expected this since both were observed contemporaneously — during the session as opposed to reported after the session. We looked at correlations in all three studies.

Hypoth4: Physiological, behavioral, and reported presence measures can differentiate among multiple (high, medium, and low) presence conditions.

We hypothesized that the presence measures would be able to differentiate among high, medium, and low presence-evoking VEs (Hypoth4). There were many parameters which one could vary: frame rate, inclusion of passive haptics, lag, visual fidelity, interactivity, and many others. In Passive Haptics, we investigated two passive haptics environments: one with a 1.5-inch wooden ledge corresponding to the 20-foot drop (highly presence-evoking) and the control flat-floor condition in the Training Room (no 1.5-inch wooden ledge). We hypothesized that higher presence would be evoked by the with-ledge environment for all measures. In Frame Rate, we investigated four frame rates for visual imagery presentation: 10 frames per second (FPS) (low presence-evoking power), 15 FPS (medium-low), 20 FPS (medium-high), and 30 FPS (highly presence-evoking). We expected that presence evoked for 10 FPS and 15 FPS would be similar, with 15 FPS being slightly higher; that significantly more presence would be evoked by 20 FPS and 30 FPS than by 10 FPS and 15 FPS; and that presence evoked by 20 FPS and 30 FPS would be similar, with 30 FPS evoking slightly higher presence. In short, we expected a monotonic, but non-linear response scale.

3.5 Elements of the experimental design common to all studies

The common elements included

- An environment with three rooms, pictured in Figures 3.1 and 3.3.
- The presence measures used: behavioral, the UCL questionnaire, ΔHeart Rate, ΔSkin Conductance, and ΔSkin Temperature.
- Participant recruiting method and participant restrictions

The VE. The VE used in the experiments is similar to that used in [Slater, 1995b]. It is pictured in Figures 3.1 and 3.3. It had three rooms: a Training Room, a Pit Room, and a Living Room. The Pit Room had a narrow unguarded wooden catwalk around a 20-foot drop to the room below — the Living Room.

1.1.1.2

Figure 3.3. View of the 20 pit from the edge of the diving board.

Figure 3.4. A subject drops a block into the virtual pit. He is standing on the edge of the 1.5-inch wooden ledge. The physiological sensors are attached to the left hand.

The VE consisted of ten thousand polygons and 41 megabytes of texture maps. This environment was used in Frame Rate. A similar environment was used for Passive Haptics and Multiple Exposures. It had twenty thousand polygons and 50 megabytes of texture. One pipe of an SGI Reality Monster 2 was used for rendering in all experiments. The head-mounted display (HMD) was a Virtual Reality 8 with 640x480 3-color pixel resolution in each eye. Users walked about in an 18 x 32 space, tracked with a high-accuracy, very-low-lag UNC˚Tech Hi-Ball optical tracker [Ward, 1992; Welch, 1997].

The view from inside the HMD is shown in Figure 3.3, and a subject with the physiological sensors on the left hand is shown in Figure 3.4. His right hand holds a tracked control with push-buttons.

1.1.1.2

The Procedure. At the beginning of the first session, subjects were given an informed consent sheet to read and sign (Appendix B). In an attempt to lessen the first-exposure (orienting) effect seen in Multiple Exposures, subjects were exposed to the environment one time for less than 3 minutes before the first sessions in Passive Haptics and Frame Rate. The orienting effect is described in Chapters 1 and 4. A diagram of the flow of the experimental procedure is shown in Figure 3.5.

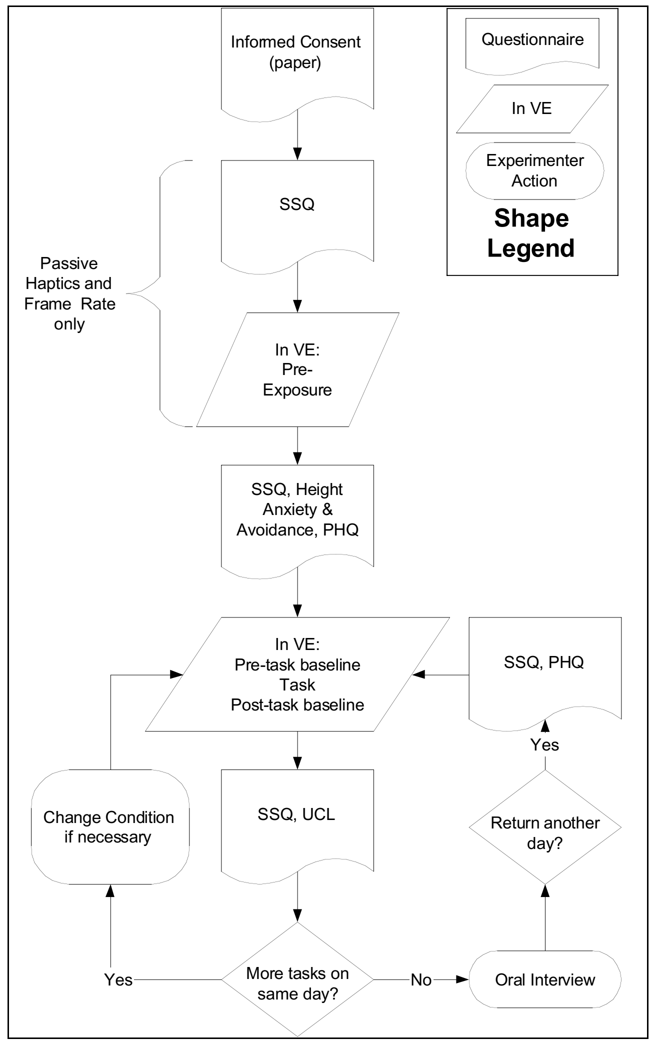


Figure 3.5. Flow of events for each subject.

Cohen s height anxiety and avoidance questionnaires were also given at the beginning of the first session. Kennedy s SSQ was given before and after each exposure in order to assess any sickness occurring during the sessions. Subjects were asked if they were in their usual state of good physical fitness and if they had taken any of the following in the past 24 hours: sedatives, tranquilizers, decongestants, anti-histamines, alcohol, or other medication (the Participant Health Questionnaire — PHQ in Figure 3.5). All questionnaires and forms were filled out on a computer except the informed consent, which was a paper form.

At the beginning of each task the subject was fitted with physiological monitoring equipment, HMD, and a backpack containing the analog-to-digital converter for the physiological equipment and the source for the magnetic tracker. The electrocardiograph (ECG) electrodes remained in place for all tasks on a given day to reduce the time and discomfort of removing and replacing them (in Passive Haptics and Frame Rate). All other equipment, including the skin temperature sensor, the skin conductance electrodes, and blood volume pulse sensor (in Multiple Exposures only), were taken off at the end of and replaced at the beginning of each task.

The session started in the virtual Training Room where the subjects were read instructions and trained to pick up and drop virtual objects, either by the experimenter (Multiple Exposures) or audio compact disk recording (Passive Haptics and Frame Rate). A pre-task baseline of the physiological measures was recorded during this time. After training, subjects performed the task: either carrying a book into the next room and dropping a it onto a chair (Multiple Exposures, Passive Haptics), or dropping three colored blocks onto X s of corresponding colors to the floor of the Living Room (Frame Rate). In Passive Haptics, subjects were also instructed to walk to the edge of the platform, put the toes of their shoeless feet over the edge (see Figures 3.6 and 3.7) and count to ten while looking around. Each subject was told to perform all tasks at his own pace. It typically took 40 seconds to complete the task in Multiple Exposures and 90 seconds in Frame Rate and Passive Haptics.

Figure 3.6. Subject with toes over 1.5-inch ledge.

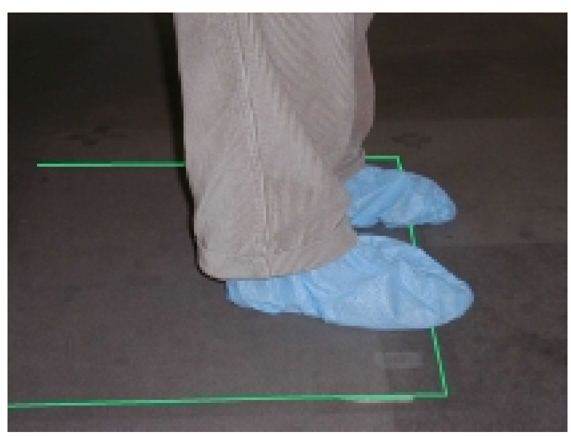


Figure 3.7. Subject with toes over visual ledge without 1.5-inch wooden ledge.

1.1.1.2

Once the task was completed, subjects returned to the Training Room, where they were asked to relax and stand still, but were free to look around. In Multiple Exposures and Passive Haptics this lasted about one minute to allow a post-experiment physiological baseline to be taken. This did not prove useful for our analysis, however, so we discontinued it for Frame Rate.

Immediately after the task was completed, the HMD and physiological monitoring equipment were removed. If there were tasks remaining that day for the subject, the ECG electrodes were not removed. The subject was then led to a computer to fill out the SSQ and the UCL Presence Questionnaire.

After the questionnaires were filled out for the last task of the session, an experimenter conducted an oral interview in which the subject was asked about the experience and encouraged to relay any thoughts on the experiences. The post-experiment oral interview was recorded both on tape and in notes taken by the experimenter.

The participants in each study were either friends of people in the UNC Computer Science Department or were recruited from undergraduate computer science classes, by fliers posted around campus, or by postings on campus newsgroups. Subjects were restricted to those reporting that they were 18 and over, had not experienced immersive virtual environments more than three times, were ambulatory, could use stereopsis for depth perception, had no history of epilepsy or seizure, were not overly prone to motion sickness, were in their usual state of good physical fitness at the time of the experiment, and were comfortable with the equipment.

3.6 Differences in experimental design

The elements that differed among the studies were

- The condition,
- The heart rate sensor,
- The task,
- The story read to the subject (either by the experimenter or played on CD), and
- The number of subjects participating.

1.1.1.2

3.6.1 Experimental design: Effect of multiple exposure on presence (Multiple Exposures)

In Multiple Exposures, the condition was the same for all sessions and tasks. In this study, we used a blood volume pulse sensor to measure heart rate — which produced an unusable signal. The task was to carry a virtual book from the Training Room to a chair on the far side of the Pit Room. Experimenters read instructions to the subjects from a script. There were 10 subjects (Average age 24.4, σ 8.2; 7 female, 3 male; 2 graduate, 5 undergraduate, 3 professional; $6/hour), each of whom was exposed to the environment three times each day on four different days.

The hypotheses were:

- Hypoth1: *There is a consistent physiological reaction to the VE.*
- Hypoth2: *Presence measures decrease over multiple exposures to the same virtual environment, but not to zero.*
- Hypoth3: *Subjective, physiological, and behavioral presence measures correlate.*
- We did not test Hypoth4 — whether measures could differentiate among high, medium, and low presence conditions in this experiment — the condition was not varied.

The results of this study are discussed in detail in Chapters 1 and 4. Subject data can be found in Appendix C.

3.6.2 Experimental design: Effect of passive haptics on presence (Passive Haptics)

In the second study, Passive Haptics, each subject entered the environment once on each of two different days — once for each condition. In one condition, a real 1.5-inch wooden ledge registered to the virtual 20-foot precipice was placed in the real environment. In the other condition, the wooden ledge was absent. The VE models used for each condition varied slightly. The apparent height of the virtual wooden ledge matched either the level of the real laboratory floor if the wooden ledge was absent, or 1.5-inch higher. The study was counter-balanced so that half the subjects experienced the VE with the 1.5-inch wooden ledge before they experienced it without the ledge. There was an orienting pre-exposure before the first exposure in which subjects walked to the doorway of the Pit Room, but did not enter. They looked around the Pit Room to get an understanding of the layout of the environment. We used an ECG to measure heart rate in this study.

We performed an 8-subject pilot study and predicted that we needed 59 subjects to get significance. In the pilot study, we did not instruct subjects to touch the ledge. After the pilot, we made improvements in the design: we instructed subjects to put their barefoot toes over the edge of the ledge and look around. We believed this design improvement would lower the number of subjects we needed for significance, but we still planned for 59 subjects.

We started 61 subjects, 6 did not return for their second visit, 1 subject was excluded because he was a VE expert, 2 were excluded because of big breaks in presence (BIPs) during one of their sessions:

- For one, the HMD went dark for a few seconds while he was on the ledge,
- The other moved too quickly and got tangled in the cables.

The 52 subjects (Average age 21.4, σ 4.3; 16 female, 36 male; 2 graduate, 47 undergraduate, 3 professional; $6/hour) were told a story relating the environment and the task (played from an audio compact disc). They were told they were visiting the home of a famous professor and they were to perform the tasks typical to his morning routine. Subjects were tasked with carrying a virtual book from the Training Room to the end of the wooden diving board, where they counted to ten and looked around. Then they carried the book to a chair on the far side of the Pit Room and then returned to the Training Room. In the Training Room, they were free to look around, but were instructed not to walk for one minute.

The hypotheses of this study were:

- Hypoth1: *There is a consistent physiological reaction to the VE.*
- Hypoth2: *Presence measures decrease over multiple exposures to the same virtual environment, but not to zero.*
- Hypoth3: *Subjective, physiological, and behavioral presence measures correlate.*
- Hypoth4: *Physiological presence can differentiate between high and low presence conditions. Specifically, in terms of presence evoked: with passive haptics > without passive haptics.*

1.1.1.2

The results of this study are discussed in detail in Chapters 1 and 4. Subject data can be found in Appendix C.

3.6.3 Experimental design: Effect of frame rate on presence (Frame Rate)

In the third experiment, Frame Rate, the subjects entered into the environment four times on a single day, experiencing a different frame rate each time. The VE was the same each time they entered, but the frame rate was held to 30, 20, 15, or 10 FPS during each trial. Subjects were counter-balanced as to the order they experienced each frame rate. See Table 3.2.

Number of Subjects	Frame rate order
4	10, 15, 30, 20
4	10, 20, 15, 30
4	15, 20, 10, 30
4	15, 30, 20, 10
4	20, 10, 30, 15
4	20, 30, 15, 10
5	30, 10, 20, 15
4	30, 15, 10, 20

Table 3.2. Frame rate orders with number of subjects per frame rate.

To hold the environment to the different frame rates, we performed a C++ Sleep before retrieving the latest tracker data. This ensured that the minimum lag from occurrence of tracked movement to viewing it in the HMD would remain the same. We measured lag and found that minimum lag for all of the frame rates was 35 milliseconds. Observed lag varied above this minimum by at most one frame time.

To measure lag, we used the technique described by Mine [Mine, 1993]. We connected our Hiball sensor to a pendulum. We displayed the same scene in the HMD as in the Frame Rate study with one exception — we added one large polygon in front of the eyes to obstruct the views of the scene. None of the scene was culled, but only the large colored polygon was visible during the lag test. We colored the polygon black or white depending on the pendulum s swing. On one side of its swing, the polygon was drawn white, and when it passed the center, black.

We connected two phototransistors to an oscilloscope. One of the phototransistors was placed at the bottom of a pendulum s swing to detect when the oscilloscope passed the center of its swing. The other was placed in the HMD to detect the change in the luminance of the single visible polygon. Distinct response curves

1.1.1.2

for each of the phototransistors were visible on the oscilloscope s screen. We had the oscilloscope display a snapshot of the response curves so that we could measure the lag between the pendulum/tracker phototransistor s response change and that of the HMD s phototransistor. Table 3.3 gives the range of observed lag values for each of five frame rates. All of the lags were at least 35 milliseconds and varied up to 35 milliseconds plus the amount of time a frame would be visible in the HMD.

Frames Per second	Observed Lag
60	35ms-49ms
30	35ms-57ms
20	35ms-75ms
15	35ms-91.5ms
10	37ms-134ms

Table 3.3. Table of observed lag in our virtual environment for five frame rate.

We performed two 4-subject pilot studies that predicted 25-120 subjects for significance (depending on the measure). We decided to run a minimum of 30 subjects.

The study had 33 subjects (Average age 22.3, σ 3.6; 8 female, 25 male; 9 graduate, 23 undergraduate, 1 professional; $10/hour) . The subjects listened to an audio compact disk that trained them to pick up and move blocks in the Training Room and gave them instructions for their task: pick up a red block from a pedestal in the Training Room and drop it on a red X on the lower floor in Pit Room, then grab and drop green and blue blocks (floating in the air in the room with the pit) onto the green and blue X s on the lower floor. The colored X s and blocks can be seen in Figures 3.1 and 3.3. This procedural improvement forced subjects to look down into the 20-foot pit. There was an initial exposure (held at 30 FPS for all subjects) in which the subject walked onto the wooden ledge in the room with the pit and looked for the green and blue blocks and the red, green, and blue X-targets on the floor below.

The hypotheses of this study were:

- Hypoth1: *There is a consistent physiological reaction to the VE.*
- Hypoth2: *Presence measures decrease over multiple exposures to the same virtual environment, but not to zero.*
- Hypoth3: *Subjective, physiological, and behavioral presence measures correlate.*

1.1.1.2

- Hypoth4: *Physiological presence can differentiate among multiple (high, medium, and low) presence conditions. Specifically, in terms of presence evoked: 30 FPS > 20 FPS > 15 FPS > 10 FPS.*

The results of this study are discussed in detail in Chapters 1 and 4. Subject data can be found in Appendix C.

1.1.1.3

Chapter 4 Discussion of results

The overall conclusions and recommendations were treated at the end of Chapter 1. Here we give the supporting detail.

4.1 Overview of statistics

In this research we used $P < 0.050$ as the cutoff for statistical significance. For clarity, we discuss results that were significant at the 0.050 level as *demonstrated*. That is, even though there is up to a 5% chance that a given result is false, we discuss it as if it were fact. So, instead of repeatedly stating the data significantly supported hypothesis A at the 0.050 level we state it as if it were fact: the data demonstrated hypothesis A to be true. All statistical calculations were performed using the Statistical Package for the Social Sciences (SPSS) version 10.0.1 [SPSS, 1999].

The comparison of average differences in physiological reaction between the Pit Room and the Training Room (Figure 1.1) was performed with a One-Sample T-Test. This test determines if the mean of a distribution is significantly greater than zero.

The correlations among measures were performed using the Bivariate Pearson Correlation. The correlation tests the extent of linear association between two variables: 1.0 is perfect correlation; -1.0 is perfect anti-correlation; 0.0 is no correlation.

Tests of the effects on presence of passive haptics and frame rate were performed with the Univariate General Linear Model, using the repeated measure technique described in the SAS 6.0 Manual [SAS, 1990]. This technique allowed us to investigate the effect of the condition while taking into account the effect of factors that change from exposure to exposure such as loss of balance on the 1.5-inch ledge (Loss of Balance). This technique prescribes adding *Subject ID* as a variable in the statistical models. Statistically, this controls for the inter-subject variation and decreases the degrees of freedom of the model, and therefore the significance, appropriately.

1.1.1.2

To find the best statistical model for each measure, we used Stepwise Selection and Elimination described by Kleinbaum *et al.* [Kleinbaum, 1998]. As suggested by Kleinbaum *et al.,* to account better (statistically) for variation in the dependent variable (e.g. ΔHeart Rate), we included variables that were significant at the P˚=˚0.100 level (strong trends) in the statistical models. The procedure is performed as follows:

1) Add the variable that has not already been added and is most highly correlated with the dependent variable.
2) Recalculate the statistical model.
3) Compare the highest P-value in the statistical model to a pre-selected significance level P˚=˚0.100,
4) If the highest P-value is higher than 0.100, take out the variable since it does not account for a significant portion of the variation of the dependent variable, and repeat from 1). If not, stop.

In the statistical tables in this dissertation, we attempt to aid the reader by using three fonts: **Bold** indicates findings significant at the 5% level (P < 0.050), regular text indicates findings that are significant at the 10% level (0.050 † P < 0.100 — strong trends), grayed text (e.ggrayed) indicates findings that are not significant. We also use abbreviations in some places. β is the estimated magnitude of an effect — the coefficient determined by the statistics. A P-value or P is the significance value for the variable. P-values are shown in italics. In a few of the tables, we show data from all three studies. In these tables, the studies are indicated by acronym: ME — the Multiple Exposures study, PH — the Passive Haptics Study, and FR — the Frame Rate study. The values in the tables, both β and P-values, were taken from SPSS, which rounds to the nearest 0.001. In cases where the value was less than 0.0005, the value is displayed in the charts as < 0.001.

4.2 Variables

Dependent variables. There were three categories of dependent variables (presence measures) in this research: reported, physiological, and observed. The reported measures were obtained via questionnaires. The physiological measures were recorded from the hands and chests of the subjects during the experiments. The observed behavioral measure was obtained by scoring height-related behaviors from videotape of the subjects.

1.1.1.2

For the reported measures, we used a modified version of the University College London (UCL) Presence Questionnaire [Usoh, 1999]. The UCL questionnaire contained three measures: *Reported Presence* (seven questions), *Reported Behavioral Presence* (three questions), and *Reported Ease of Locomotion* (three questions). Even though subjects rated each question on a scale of 1-7, Slater *et al.* used the ratings only to yield a High-Presence/ Low-Presence result. A judgment had to be made as to the high-low threshold. In Section 4.4.2, we discuss our decision to count [m5] as the high values.

Our physiological measures were constructed as the differences between the physiological reactions in the Training Room and the Pit Room. Each was constructed to increase with increased physiological reaction.

Independent and random variables. The variable *session* indicates the number of the day on which an exposure to the VE took place. *Task* indicates the number of the exposure within a single day. In Multiple Exposures, there were four sessions and three tasks per session. In Passive Haptics, there were two sessions, each with one task. In Frame Rate, there was one session with four tasks.

A variable that was significant in the Frame Rate study was Loss of Balance. Another variable that was significant was Level of Computer Game Playing. Subjects scored the question from 1 to 7:

To what extent do you play computer games?

I play computer games 1 (not at all)   7 (very much).

We used the raw response as our variable.

There were a number of other variables recorded on a questionnaire that were not significant in the analysis of the hypotheses: age, race, gender, association with the virtual body (post-experiment), university status, computer usage, and level of exercise (1°=° not°at°all   7°=°   *3°+°hours°/°week*). Subjects also filled out questionnaires on height anxiety and avoidance [Cohen, 1977] before the experiment and a simulator sickness questionnaire [Kennedy, 1993] before and after the experiment. The data from these questionnaires was not significant in our analysis.

1.1.1.2

4.3 Support for hypotheses

In Chapter 1, we discussed our goal of finding a presence measure that is reliable, valid, multi-level sensitive, and objective. Below we expand on the supporting statistics. We discuss the three physiological measures that are our primary focus: ΔHeart Rate, ΔSkin Conductance, and ΔSkin Temperature. We also discuss the reported measures, Reported Presence and Reported Behavioral Presence. The third reported measure, Reported Ease of Locomotion, is not a measure of presence. Therefore, we do not discuss it. We also discuss our ancillary investigation of Observed Behavioral Presence as a measure of presence.

4.3.1 Reliability

Reliability is the extent to which the same test applied on different occasions yields the same result [Sutherland, 1996]. We investigated reliability in two ways: 1) Did the Pit Room consistently evoke more physiological reaction than the Training Room? and 2) Did the physiological reactions to the Pit Room decrease over multiple exposures to the VE, just as physiological reaction decreases over multiple exposures to a real height (or other stressor) [Abelson, 1989; Andreassi, 1995], or approach zero after multiple exposures?

Differentiating between the Pit Room and the Training Room. As discussed fully in Chapter 1, average heart rate and skin conductance were significantly higher and skin temperature was significantly lower in the Pit Room as compared to the Training Room in all three studies. Moreover, these relationships were observed in 90% of the individual exposure data. See Table 1.1.

Order effects. The following presence measures decreased over multiple exposures in all studies: ΔHeart Rate, ΔSkin Temperature, Reported Presence, Reported Behavioral Presence, and Observed Behavioral Presence. ΔSkin Conductance decreased over multiple exposures in two of three studies. Our data also demonstrated *orienting effects* — increased reactions when one sees something nove[Andreassi, 1995]. These were seen for every measure except ΔHeart Rate in at least one of the studies. See Figures 4.1 and 4.2 for graphs of each variable over multiple exposures, Table 4.1 for a summary of significant order and orienting effects, and Tables 4.2 to 4.4 for statistical models of order effects for each of the measures in each of the studies. Overall, the physiological reactions to the Pit Room did decrease over multiple exposures but not to zero. The VE reliably evoked physiological responses in subjects, even over multiple exposures.

1.1.1.2

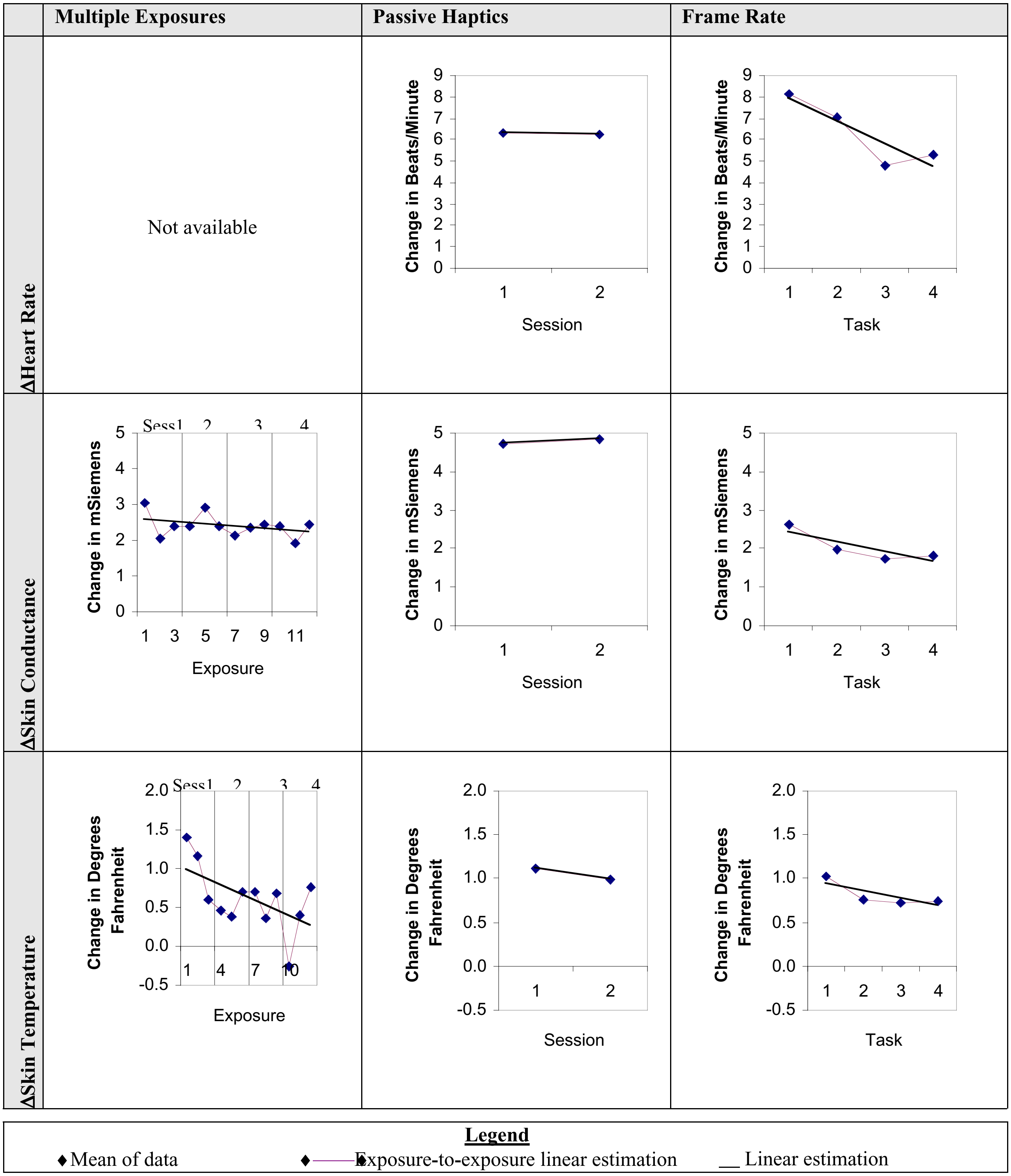
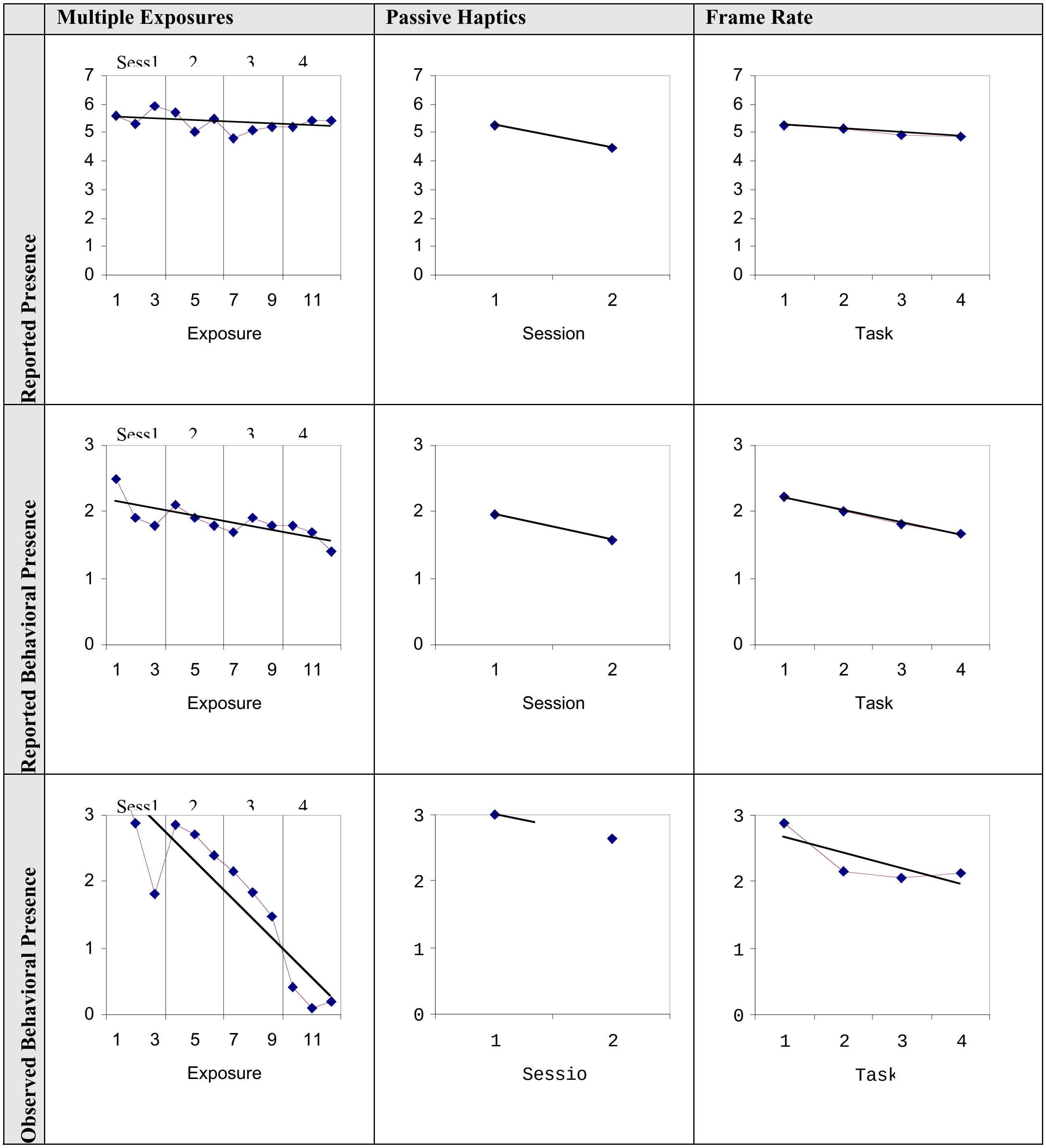


Figure 4.1. Pattern of change over multiple exposures for ΔHeart Rate, ΔSkin Conductance, and ΔSkin Temperature.

1.1.1.2



Legend

♦ Mean of data ♦——♦ Exposure-to-exposure linear estimation __ Linear estimation

Figure 4.2. Pattern of change over multiple exposures for Reported Presence, Reported Behavioral Presence, and Observed Behavioral Presence. Ordinates for the reported measures are the average count of questions scored high . Ordinates for Observed Behavioral Presence are the count of height-related reactions.

1.1.1.2

Order Effects	ΔHeart Rate (ΔBPM)	ΔSkin Conductance (ΔmSiemens)	ΔSkin Temperature (Δ°F)	Reported Presence (Count high)	Reported Behavioral Presence (Count high)	Observed Behavioral Presence (Count Behvs.)
Multiple Exposures	N/A	-0.7 (1st)	**-0.9 (1st)**	-	**-0.7 (1st)**	**-0.9 (Sess)**
Passive Haptics	-	-	-	**-0.7 (1st)**	**-0.4 (1st)**	-
Frame Rate	**-1.0 (Task)**	**-0.8 (1st)**	**-0.3 (1st)**	-	**-0.2 (Task)**	**-0.8 (1st)**

Table 4.1. Significant order effects for each measure in each study.
(1 st) indicates a decrease in a measure after the first exposure only. (Sess) indicates a decrease in the measure over subsequent sessions (days). (Task) indicates a decrease over tasks on the same day. There was an order effect for each measure in at least one study. N/A was Not available .

Multiple Exposures	ΔSkin Conductance		ΔSkin Temperature		Reported Behavioral Presence		Observed Behavioral Presence	
		P		***P***		***P***		***P***
Model		***< 0.001***		***0.002***		***< 0.001***		***< 0.001***
Intercept	**1.9**	***< 0.001***	**0.7**	***< 0.001***	**1.6**	***< 0.001***	**1.2**	***< 0.001***
Subject	**[-0.8, 1.5]**	***< 0.001***	**[-1.3, 0.2]**	***0.005***	**[-1.1, 1.1]**	***< 0.001***	**[-0.3, 7.6]**	***< 0.001***
First Exposure	-0.7	*0.059*	**-0.9**	***0.011***	**-0.7**	***0.004***	-	-
Task	-	-	-	-	-	-	-	-
Session (Day)	-	-	-	-	-	-	**-0.9**	***< 0.001***

Table 4.2. Significant order effects for each measure in Multiple Exposures. There were no significant order effects for Reported Presence in Multiple Exposures — columns for these variables are not included in the chart.

	Reported Presence		Reported Behavioral Presence	
		P		***P***
Model		***< 0.001***		***0.003***
Intercept	**1.8**	***< 0.001***	**2.0**	***< 0.001***
Subject	**[-1.5, 4.5]**	***< 0.001***	**[-2.0, 1.0]**	***0.009***
Increase with 1.5-inch ledge	0.5	*0.06*	**0.5**	***0.004***
First Exposure	**-0.8**	***0.002***	**-0.4**	***0.017***

Table 4.3. Significant order effects for each measure in Passive Haptics. There were no significant order effects for ΔHeart Rate, ΔSkin Conductance, ΔSkin Temperature, and Observed Behavioral Presence in Passive Haptics.

1.1.1.2

	ΔHeart Rate		ΔSkin Conductance		ΔSkin Temperature		Reported Behavioral Presence		Observed Behavioral Presence	
		P		***P***		***P***		***P***		***P***
Model		***< 0.001***		**< 0.001**		***< 0.001***		***< 0.001***		***< 0.001***
Intercept	**8.8**	***< 0.001***	**2.7**	***< 0.001***	**0.3**	***< 0.001***	**2.9**	***< 0.001***	**1.8**	***< 0.001***
Subject	**[-5.5, 12.1]**	***< 0.001***	**[-2.9, 5.4]**	***< 0.001***	**[0.0, 1.4]**	***< 0.001***	**[-2.0, 0.8]**	***< 0.001***	**[-3.0, 4.8]**	***< 0.001***
Frame Rate	[-2.7, 0.0]	*0.073*	-	-	-	-	[-0.4, 0.0]	*0.060*	-	-
First Exposure	-	-	**-0.8**	***< 0.001***	**-0.3**	***0.001***	-	-	**-0.8**	***< 0.001***
Task	**-1.0**	***0.003***	-	-	-	-	**-0.2**	***< 0.001***	-	-

Table 4.4. Significant order effects for each measure in Frame Rate. There were no significant order effects for Reported Presence in Frame Rate.

4.3.2 Validity

Validity is the extent to which a test or experiment genuinely measures what it purports to measure [Sutherland, 1996]. To examine validity, we performed correlations among the physiological measures and the well-established questionnaire measures of presence. Singleton states that: The more evidence that supports the hypothesized relationships [between the measure and the underlying concept], the greater one s confidence that a particular operational definition is a valid measure of the concept [Singleton, 1993]. Therefore, we also investigated validity by examining the measures in multiple passive haptics and frame rate conditions.

Among the physiological measures, ΔHeart Rate correlated best with the reported measures. It correlated positively with the Reported Presence and Reported Behavioral Presence in all three studies. It had significant correlations with Reported Presence and Reported Behavioral Presence in Frame Rate. There was no data available for ΔHeart Rate in Multiple Exposures. Overall, ΔHeart Rate s validity as a presence measure is supported by its correlations with the well-established reported measures. See Table 4.5 for details of the correlations.

1.1.1.2

Correlations		Reported Presence	Reported Behavioral Presence
ΔHeart Rate	**ME**		
	P		
	PH	0.034	0.004
	P	*0.743*	*0.972*
	FR	**0.265**	**0.192**
	P	***0.002***	***0.028***
ΔSkin Conductance	**ME**	**0.245**	**0.290**
	P	***0.009***	***0.002***
	PH	-0.002	0.106
	P	*0.986*	*0.280*
	FR	0.096	0.125
	P	*0.275*	*0.154*
ΔSkin Temperature	**ME**	-0.098	-0.040
	P	*0.349*	*0.699*
	PH	-0.075	-0.086
	P	*0.448*	*0.383*
	FR	0.171	0.066
	P	*0.050*	*0.454*
Observed Behavioral Presence	**ME**	-0.002	**0.344**
	P	*0.981*	**< *0.001***
	PH	**0.293**	**0.317**
	P	***0.021***	***0.012***
	FR	-0.002	0.163
	P	*0.982*	*0.070*

Table 4.5. Table of correlations among all measures for all three studies

ΔSkin Conductance also correlated well with the reported measures, but less so than ΔHeart Rate. ΔSkin Conductance had significant positive correlations with Reported Presence and Reported Behavioral Presence in Multiple Exposures (see Table 4.5). It also had non-significant positive and negative correlations with Reported Presence and Reported Behavioral Presence in the Passive Haptics and Frame Rate studies. Despite these variable non-significant correlations, its significant, positive correlations in Multiple Exposures lend support for the validity of ΔSkin Conductance as a measure of presence.

ΔSkin Temperature did not correlate well with the reported measures. There was no support from the correlations for the use of ΔSkin Temperature as a valid measure of presence. As noted in Chapter 1, we believe the poor correlations seen for ΔSkin Temperature were due to problems in the experimental design coupled with the limitations of the measure.

1.1.1.2

Observed Behavioral Presence correlated well with Reported Behavioral Presence in all three studies (See Table 4.5). It had significant positive correlations with Reported Presence and Reported Behavioral Presence in Passive Haptics. Observed Behavioral Presence had non-significant, negative correlations with Reported Presence in both Multiple Exposures and Frame Rate. Despite its significant positive correlations with Reported Behavioral Presence, its inconsistent correlation with Reported Presence bring its validity into question.

Another way to investigate the validity of a measure is to look at whether it changes with conditions as expected. In the next section, we discuss each measure s ability to differentiate between two passive haptics conditions (the VE with and without a real 1.5-inch wooden ledge) and among four frame rates (10, 15, 20, and 30 FPS). We expected physiological reaction to be higher when the 1.5-inch wooden ledge was included and to increase as frame rate increased.

4.3.3 Sensitivity and multi-level sensitivity

Sensitivity. As was shown in Chapter 1, the physiological measures reliably distinguished between the Training Room and the Pit Room. Average physiological reactions were higher in the Pit Room than in the Training Room ($P < 0.001$ for all measures in each study) and subjects had greater reactions in the Pit Room about 90% of the time. This guarantees us at least minimal sensitivity — we measured a reliable difference in reaction between the two rooms.

Multi-level sensitivity. A useful measure of presence will reliably yield higher values as a VE is improved along some goodness dimension. We call this *multi-level sensitivity.* Both Passive Haptics and Frame Rate provided us evidence of multi-level sensitivity for the physiological measures. Namely, both verified that there was a strong reaction to the Pit Room and that more reaction was evoked as the VE was improved (e.g. higher frame rate). Anecdotally, we have observed that walking into the Pit Room causes a strong subjective reaction in users and this reaction is greater in magnitude than the difference in subjective reaction to the Pit Room between any two experimental conditions (e.g. with and without the 1.5-inch wooden ledge). Therefore, we expected the differences among the conditions to be less than the differences between the two rooms. In terms of our data, this means that the smallest difference between the Pit Room and Training Room among all of the conditions should be larger than the greatest difference between any two conditions. We found exactly that in

1.1.1.2

all three studies for all measures. The data is given in Table 4.6. Figures 1.4 and 4.3 graphically depict the differences for ΔHeart Rate in Passive Haptics and Frame Rate.

		ΔHeart Rate	**ΔSkin Conductance**	**ΔSkin Temperature**
Passive Haptics	**Smallest Δ between Pit Room and Training Room among conditions**	4.9 BPM (no˚ledge)	4.4 mSiemens (no ledge)	0.9 °F (w/ ledge)
	Difference: passive haptics - no passive haptics	2.7 BPM	0.8 mSiemens	-0.4 °F
Frame Rate	**Smallest Δ between Pit Room and Training Room among conditions**	5.9 BPM (15˚FPS)	2.0 mSiemens (20 FPS)	0.8 °F (15 FPS)
	Greatest difference among conditions	2.7 BPM (30 FPS - 15˚FPS)	-0.4 mSiemens (20 FPS - 10 FPS)	-0.1 °F (15 FPS - 10 FPS)

Table 4.6. The differences in physiological reaction between the Training Room and the Pit Room were greater than the differences among conditions.

It is important to note that for ΔSkin Temperature in both Passive Haptics and Frame Rate, and for ΔSkin Conductance in Frame Rate, the greatest difference among conditions was in the *opposite* direction from that expected. In Frame Rate, we believe this difference was caused by an anomalous reaction by subjects at 10 FPS — explained below. This would have caused reaction at 10 FPS to be higher than at other frame rates. The decline in ΔSkin Temperature in Passive Haptics was due, we believe, to limitations in the measure and our design.

In Passive Haptics, we further tested the multi-level sensitivity of the physiological measures by investigating whether they could significantly differentiate between two conditions: a higher presence condition (inclusion of a 1.5-inch wooden ledge corresponding to the virtual ledge) and a lower presence condition (no wooden ledge included). ΔHeart Rate, ΔSkin Conductance, Reported Behavioral Presence, and Observed Behavioral Presence were significantly higher when the 1.5-inch wooden ledge was included — these measures were multi-level sensitive to the differences between high and low presence conditions. Table 4.7 shows the statistical models for each measure.

1.1.1.2

	ΔHeart Rate		ΔSkin Conductance		ΔSkin Temperature		Reported Presence		Reported Behavioral Presence		Observed Behavioral Presence	
	β	*P*	β	*P*	β	*P*	β	*P*	β	*P*	β	*P*
Corrected Model		***0.017***		***< 0.001***		***0.003***		***< 0.001***		***0.003***		***0.020***
Intercept	**9.6**	***< 0.001***	**4.7**	***< 0.001***	**1.6**	***< 0.001***	**1.8**	***< 0.001***	**2.0**	***< 0.001***	**1.7**	***< 0.001***
Subject	**[-16.2, 11.2]**	***0.026***	**[-2.7, 8.8]**	***< 0.001***	**[-3.4, 1.5]**	***0.004***	**[-1.5, 5.0]**	***< 0.001***	**[-2.0, 1.0]**	***0.009***	[-2.5, 8.0]	*0.099*
Session: 1st - 2nd	-	-	-	-	-	-	**-0.8**	***0.002***	**-0.4**	***0.017***	-	-
Increase with 1.5-inch ledge	**2.7**	***0.016***	**0.8**	***0.040***	-0.4	*0.063*	0.5	*0.060*	**0.5**	***0.004***	**2.5**	***< 0.001***

Table 4.7. Best models for each of the measures in the Passive Haptics study. ΔHeart Rate, ΔSkin Conductance, Reported Behavioral Presence, and Observed Behavioral Presence were significantly higher with the 1.5-inch wooden ledge. Only ΔSkin Temperature varied in the opposite direction (strong trend). *Session* was significant for Reported Presence and Reported Behavioral Presence.

Among the physiological measures, ΔHeart Rate most significantly differentiated the inclusion of the 1.5-inch wooden ledge. This supports the use of ΔHeart Rate as a multi-level sensitive measure of presence. ΔSkin conductance also increased significantly with the wooden ledge, which supports the use of ΔSkin Conductance as a measure of presence. ΔSkin Temperature varied in the opposite direction as hypothesized (strong trend), but we believe that to be meaningless for our exposure length. The data from Passive Haptics does not support the use of ΔSkin Temperature as a multi-level sensitive measure of presence.

The limited data for Observed Behavioral Presence showed the most significant increase with the 1.5-inch wooden ledge. Even though the Observed Behavioral Measure did not follow hypotheses as well in the other two studies, it performed well in Passive Haptics — it differentiated between higher and lower presence conditions.

Multi-level sensitivity: differentiating among multiple levels of presence. In Frame Rate, we investigated more fully whether physiological reaction could differentiate among multiple presence conditions: 10 FPS (lowest), 15 FPS, 20 FPS, and 30 FPS (highest). Table 4.8 shows the significance of the models for each measure. Table 4.9 shows the differences among the frame rates. Figures 4.3 to 4.9 show the response curves of each measure to frame rate.

1.1.1.2

	ΔHeart Rate		ΔSkin Conductance		ΔSkin Temperature		Reported Presence		Reported Behavioral Presence		Observed Behavioral Presence	
	β	*P*	β	*P*	β	*P*	β	*P*	β	*P*	β	*P*
Corrected Model		***< 0.001***		***< 0.001***		***< 0.001***		***< 0.001***		***< 0.001***		***< 0.001***
Intercept	**12.7**	***< 0.001***	**2.6**	***< 0.001***	**0.3**	***< 0.001***	**5.6**	***< 0.001***	**2.9**	***< 0.001***	**1.9**	***< 0.001***
Subject	**[-5.5, 11.2]**	***< 0.001***	**[-2.9, 5.4]**	***< 0.001***	**[0, 1.4]**	***< 0.001***	**[-5.3, 1.5]**	***< 0.001***	**[-2.0, 0.8]**	***< 0.001***	**[-3.0, 4.8]**	***< 0.001***
Session	**-1.0**	***0.002***	-	-	-	-	-	-	**-0.2**	***< 0.001***	-	-
First Exposure	-	-	**0.8**	***< 0.001***	**0.3**	***0.001***	-	-	-	-	**0.7**	***< 0.001***
Loss of Balance	**-3.5**	***0.014***	-	-	-	-	-	-	-	-	-	-
Frame Rate	**[-3.2, 0]**	***0.026***	[-0.2, 0.2]	*0.167*	[-0.1, 0.1]	*0.641*	[-0.2, 0.0]	*0.800*	**[-0.4, 0.0]**	***0.060***	[-0.4, 0.2]	*0.113*

Table 4.8. Statistical models for each measure in the Frame Rate study.

	ΔHeart Rate	ΔSkin Conductance	ΔSkin Temperature	Reported Presence	Reported Behavioral Presence	Reported Ease of Locomotion	Observed Behavioral Presence
Increase from 10 FPS to 15 FPS	-1.6	-0.0	-0.1	0.0	-0.3	**0.5**	-0.2
P	*0.134*	*0.892*	*0.198*	*1.000*	*0.083*	***0.004***	*0.331*
Increase from 15 FPS to 20 FPS	**2.4**	-0.4	0.1	0.2	0.2	-0.3	-0.3
P	***0.024***	*0.063*	*0.537*	*0.553*	*0.116*	*0.123*	*0.156*
Increase from 20 FPS to 30 FPS	0.7	0.2	0.0	0.1	0.2	0.2	0.4
P	*0.483*	*0.287*	*0.931*	*0.843*	*0.256*	*0.204*	*0.091*
Increase from 10 FPS to 20 FPS	0.8	**-0.4**	-0.1	0.2	-0.0	0.2	**-0.6**
P	*0.457*	***0.046***	*0.501*	*0.553*	*0.869*	*0.171*	***0.018***
Increase from 10 FPS to 30 FPS	1.6	-0.2	-0.1	0.2	0.1	**0.5**	-0.2
P	*0.160*	*0.346*	*0.558*	*0.429*	*0.331*	***0.009***	*0.487*
Increase from 15 FPS to 30 FPS	**3.2**	-0.2	0.1	0.2	**0.4**	-0.0	0.1
P	***0.004***	*0.419*	*0.481*	*0.429*	***0.008***	*0.784*	*0.781*

Table 4.9. Statistical significance for the differences among frame rates for each measure using the models in Table 4.8.

We hypothesized a monotonic increase in physiological reaction with frame rate. This was not the case. As depicted in the Figures 4.3 to 4.5, there was strong physiological reaction at 10 FPS. We believe that this was not caused by an increase in evoked presence, but instead, was caused by increased fear due to walking near a 20-foot drop with reduced temporal fidelity of visual input — the subject wasn t sure he could dependably see where he was walking. Our findings supported this. Reported Ease of Locomotion was lowest at 10 FPS

1.1.1.2

(see Table 4.8 and Figure 4.8), which indicates that subjects found it difficult to move about at this frame rate. Physiological reactions were anomalously high at 10 FPS, which tells us that subjects had fear at this frame rate. Reported Presence, however, was lowest at 10 FPS, which tells us that the increase in fear was not caused by feeling more presence near the 20-foot drop.

We believe the anomalous reaction at 10 FPS for both Reported Behavioral Presence and Observed Behavioral Presence was also caused, indirectly, by this fear. We believe our behavioral measures could not differentiate between the fear due to evoked presence near a 20-foot drop and the fear caused by moving about near a height with reduced visual temporal fidelity.

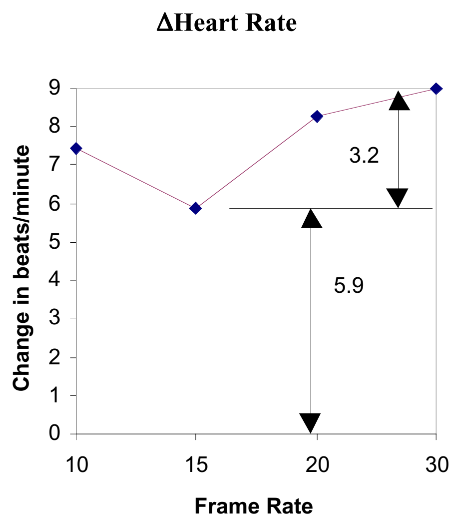


Figure 4.3. ΔHeart Rate at the four frame rates.

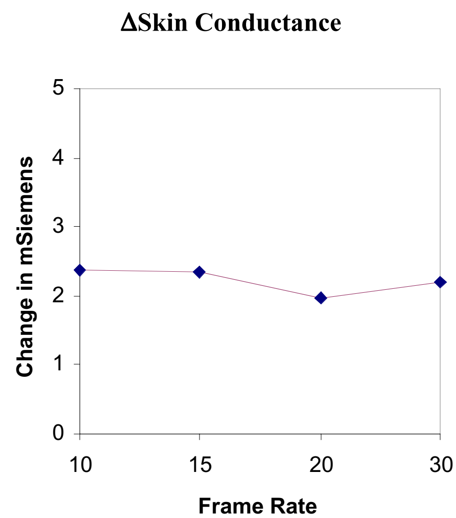


Figure 4.4. ΔSkin Conductance at the four frame rates.

1.1.1.2

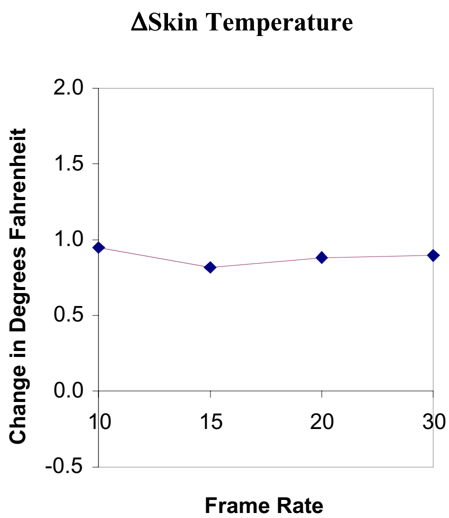


Figure 4.5. ΔSkin Temperature at the four frame rates.

Also associated with lower frame rates was Loss of Balance — when a subject lost his balance while searching for the 1.5-inch wooden ledge. This happened nine times at 10 FPS, five times at 15 FPS, once at 20 FPS, and once at 30 FPS. We believe the prevalence of Loss of Balance occurring at lower frame rates was also caused by the reduced temporal fidelity in the visuals — subjects had a hard time moving about and therefore had difficulty locating the 1.5-inch ledge. This caused them to occasionally find the wooden ledge before expected. We investigated statistical models to account for (or predict) the anomalous reaction as 10 FPS. The addition of Loss of Balance to the model for ΔHeart Rate was significant but did not completely account for the anomalous reaction at 10 FPS. The addition of Loss of Balance was not significant for any other measure s model. We also investigated whether Simulator Sickness caused the increase in physiological reaction at 10 FPS. Simulator Sickness was not significant in any model.

After 10 FPS, ΔHeart Rate and ΔSkin Temperature increased with frame rate as expected. ΔHeart Rate differentiated among presence conditions with more statistical power than any of the other presence measures, including the reported measures. The difference between 30 FPS and 15 FPS (3.5 BPM, P˚=˚0.004) was the most statistically significant difference between any two frame rates for any measure. ΔHeart Rate also differentiated significantly between 20 FPS and 15 FPS (2.4 BPM, P˚=˚0.024). Table 4.9 shows the statistical model and significance values for ΔHeart Rate and each of the other measures. In Frame Rate, ΔHeart Rate was a multi-level sensitive measure of presence. For ΔSkin Temperature, there was a non-significant monotonic increase with frame rate after 10 FPS. We believe that ΔSkin Temperature might have been a more multi-level sensitive measure of presence if the exposure to the stressor was longer, as discussed earlier.

ΔSkin Conductance did not perform well in this experiment. It had anomalous reaction to 10 FPS and 15 FPS. ΔSkin Conductance was higher at 30 FPS than at 20 FPS, though not significantly so. The data in Frame Rate does not support the use of ΔSkin Conductance as a multi-level sensitive measure of presence.

Reported Behavioral Presence, after 10 FPS, increased monotonically with frame rate and performed best among the reported measures. See Figure 4.6 and Table 4.9. It differentiated significantly between 15 FPS and 30 FPS (0.4 more high counts, P˚=˚0.008). As in Passive Haptics, Reported Behavioral Presence was the most multi-level sensitive of the reported measures in Frame Rate.

Reported Presence increased monotonically with frame rate and had no anomalous reaction at 10 FPS (Figure 4.7). However, it is not a multi-level sensitive measure of the effect of frame rate on evoked presence.

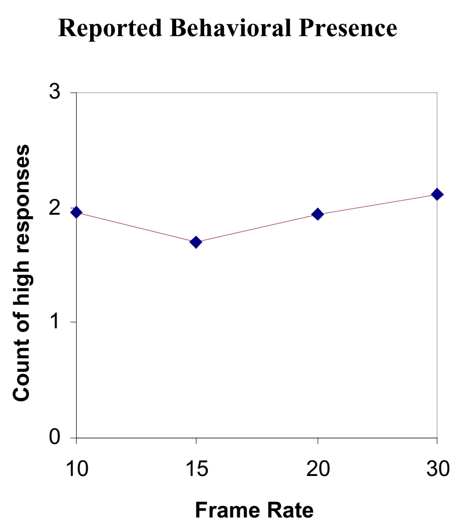


Figure 4.6. Reported Behavioral Presence at the four frame rates.

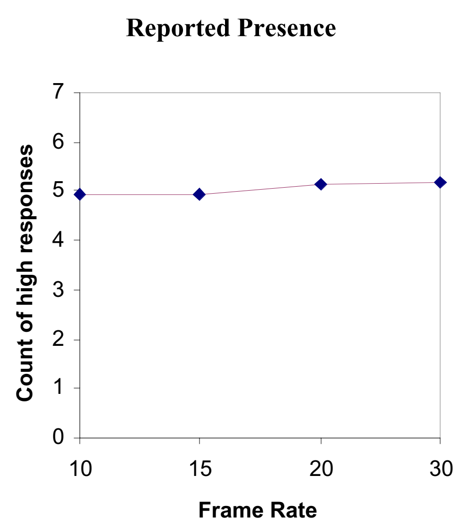


Figure 4.7. Reported Presence at the four frame rates.

1.1.1.2

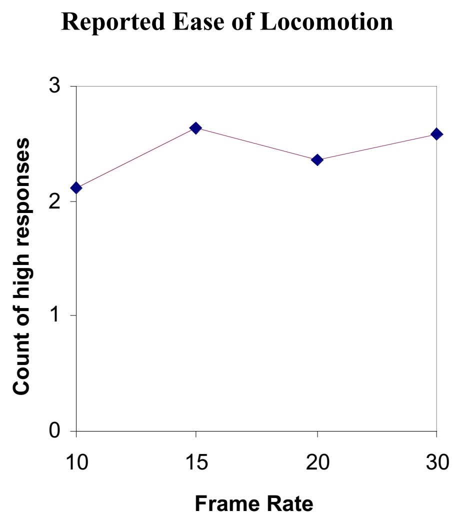


Figure 4.8. Reported Ease of Locomotion at the four frame rates.

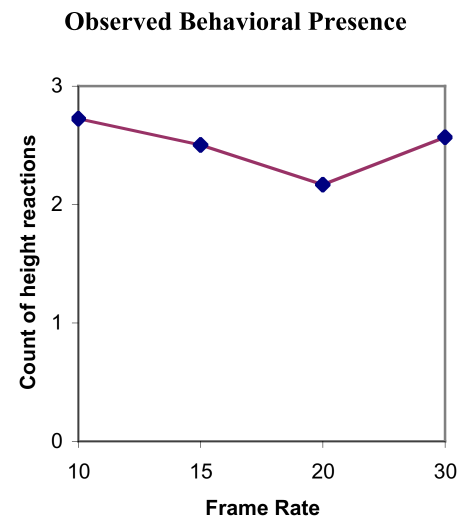


Figure 4.9. Observed Behavioral Presence at the four frame rates.

Observed Behavioral Presence had anomalous reactions at both 10 FPS and 15 FPS. It also had a non-significant increase from 20 FPS to 30 FPS. See Figure 4.9. Observed Behavioral Presence did not perform well in Frame Rate.

4.3.4 Objectivity

Reliability, validity, and multi-level sensitivity are investigated experimentally. Objectivity, on the other hand, can only be argued logically. We gave the argument for the objectivity of the physiological measures in Chapter 1.

4.3.5 Summary

The data presented in this chapter and in Chapter 1 show that physiological reactions are reliable, valid, multi-level sensitive, and objective measures of presence. All three physiological measures, ΔHeart Rate, ΔSkin Conductance, and ΔSkin Temperature, were reliable. All three measures significantly differentiated between Pit Room and Training Room. All three measures decreased with multiple exposures, as is seen in similar real-life situations [Abelson, 1989; Andreassi, 1995].

1.1.1.2

We found the measures to be valid — they correlated with well-established reported measures. Among the measures, ΔHeart Rate correlated the best with the reported measures. ΔSkin Conductance correlated well, but not as well as ΔHeart Rate. ΔSkin Temperature did not correlate well with the reported measures.

We found the measures to be multi-level sensitive — they differentiated among various presence conditions. ΔHeart Rate performed best. It significantly differentiated the inclusion of the 1.5-inch wooden ledge and, after 10 FPS, increased significantly with frame rate. We had poor results with ΔSkin Conductance and ΔSkin Temperature. ΔSkin Conductance was significantly higher with the 1.5-inch wooden ledge, but it showed anomalous reactions at both 10 and 15 FPS. ΔSkin Temperature was non-significantly *lower* with the 1.5-inch wooden ledge, but increased non-significantly and monotonically with frame rate after 10 FPS.

Each of the physiological measures was objective — free from bias from either the experimenter or the subjects. They were not exposed to bias from the experimenter, since the instructions read to the subjects were uniform. Bias from the subjects would have been difficult, especially since physiological reaction is hard to control, and no bio-feedback was given.

Overall, we suggest ΔHeart Rate as a reliable, valid, multi-level sensitive, and objective measure of presence. We believe that both ΔSkin Conductance and ΔSkin Temperature have potential as measures of presence, but more investigation would be needed.

Our Observed Behavioral Presence measure was not an objective measure of presence — it was exposed to bias from both the experimenter and the subject. It correlated well with Reported Behavioral Presence in all three experiments but had inconsistent correlations with Reported Presence. There was only a limited data set for Observed Behavioral Presence in Passive Haptics, but for that data, it significantly differentiated the 1.5-inch wooden ledge. It showed, however, anomalous reactions at both 10 FPS and 15 FPS in Frame Rate. Overall, we do not suggest Observed Behavioral Presence as a reliable, valid, multi-level sensitive, and objective measure of presence.

1.1.1.2

4.4 Other findings

4.4.1 Physiological reactions as between-subjects measures

We conducted all of the studies as within-subjects to avoid the substantial variances due to natural human differences. The UCL questionnaire has been used successfully between-subjects [Usoh, 1999]. How well would the physiological measures work in between-subjects studies? To investigate this, we analyzed the data looking at only the first task for each subject. Hence, we had just 10 data points (10 subjects — first exposure only) for the Multiple Exposures study, 52 data points for the Passive Haptics study, and 33 data points for the Frame Rate study. Highlights of the between-subjects analysis were give in Chapter 1. Supporting details are given here.

Reliability between-subjects: Physiological reaction in the Pit Room. As we suspected, all of the physiological reactions were significantly higher in the Pit Room when analyzing only the first exposure for each subject. The percentage of exposures in which the physiological reaction is higher in the Pit Room as compared to the Training Room were at least 90% for all measures in all studies, except ΔHeart Rate in Passive Haptics — 85%. Table 1.3 shows this. This consistent differentiation supports the reliability of physiological reactions as between-subjects measures of presence.

Validity between-subjects: Correlation with established measures. Our measures are defined so that, if valid, all the measures should correlate positively. As expected, physiological reactions did not correlate as well with the questionnaires when only the first exposure for each subject was considered. As shown in Table 4.10, ΔHeart Rate had a non-significant, positive correlation with Reported Presence and Reported Behavioral Presence in Frame Rate. It had non-significant negative correlations with Reported Presence and Reported Behavioral Presence in Passive Haptics. Overall, our data was inconclusive as to the validity of ΔHeart Rate as a between-subjects measure. The same was true for the other two physiological measures. The data for these two measures was inconclusive as to the validity of ΔSkin Conductance and ΔSkin Temperature.

1.1.1.2

Correlations	Study	Reported Presence	Reported Behavioral Presence
ΔHeart Rate	ME		
	P		
	PH	-0.234	-0.132
	P	*0.117*	*0.381*
	FR	0.319	0.196
	P	***0.070***	*0.274*
ΔSkin Conductance	ME	0.09	-0.439
	P	*0.818*	*0.238*
	PH	-0.079	0.09
	P	*0.583*	*0.534*
	FR	-0.074	0.28
	P	*0.681*	*0.115*
ΔSkin Temperature	ME	0.316	-0.434
	P	*0.489*	*0.331*
	PH	0.029	0.094
	P	*0.842*	*0.522*
	FR	0.068	0.213
	P	*0.709*	*0.233*
Observed Behavioral Presence	ME	0.109	0.522
	P	*0.837*	*0.288*
	PH	0.110	**0.379**
	P	*0.554*	***0.035***
	FR	-0.132	0.043
	P	*0.479*	*0.820*

Table 4.10. Analyzed between-subjects: correlations between the physiological and observed measures and the reported measures.

For the between-subjects analysis, Observed Behavioral Presence correlated positively with Reported Behavioral Presence in all three studies and did so significantly in Passive Haptics (where there was a reduced data set). It had inconsistent correlations with Reported Presence. See Table 4.10. Overall, our data was inconclusive as to the validity of Observed Behavioral Presence as a between-subjects measure.

Contrary to this expectation, though, the physiological measures **did** differentiate among the conditions: physiological reaction to the Pit Room was significantly higher that to the Training Room for all measures in all studies (described above), and we found significant differences in the physiological measures among conditions in both the Passive Haptics and Frame Rate studies

Multi-level sensitivity between-subjects: Differentiating among presence conditions. We expected, when analyzing the data between-subjects, that inter-subject variation in physiological reactivity would obscure the effects seen among conditions in the experiments. Contrary to this expectation, physiological reaction **did** differentiate among conditions when analyzing only the first exposure of each study. We found that physiological reaction to the Pit Room was significantly higher that to the Training Room for all measures in all studies (described in Chapter 1), and we found significant differences in the physiological measures among conditions in both the Passive Haptics and Frame Rate studies. In the Passive Haptics study, both ΔHeart Rate and ΔSkin Conductance varied in the expected direction with some statistical power (P˚=˚0.097 for ΔHeart Rate; P˚=˚0.137 forΔSkin Conductance). ΔSkin Temperature also increased with the 1.5-inch ledge in Passive Haptics, but with less statistical power (P˚=˚0.398). Table 4.11 shows the statistical models for each of the measures (between-subjects) in Passive Haptics. As shown in Table 4.12, controlling for Level of Computer Game Playing was significant for ΔHeart Rate. Subjects that reported playing more computer games had smaller increases in heart rate as they approached the virtual pit. After correcting for Level of Computer Game Playing, the significance of the 1.5-inch wooden ledge was decreased for ΔHeart Rate (P˚=˚0.180).

	ΔHeart Rate		**ΔSkin Conductance**		**ΔSkin Temperature**		**Reported Presence**		**Reported Behavioral Presence**		**Observed Behavioral Presence**	
	β	***P***	**β**	***P***	**β**	***P***	**β**	***P***	**β**	***P***	**β**	***P***
Corrected Model		*0.097*		*0.137*		*0.398*		*0.498*		*0.051*		***0.001***
Intercept	**7.9**	***< 0.001***	**5.2**	***< 0.001***	**1.2**	***< 0.001***	**4.9**	***< 0.001***	**2.2**	***< 0.001***	**4.5**	***< 0.001***
Increase with Passive Haptics	3.3	*0.097*	1.0	*0.137*	0.3	*0.398*	-0.3	*0.498*	0.5	*0.051*	**2.7**	***0.001***

Table 4.11. Analyzed between-subjects: statistical models for each measure in Passive Haptics.

	ΔHeart Rate	
	β	***P***
Corrected Model		***0.005***
Intercept	**13.0**	***< 0.001***
Increase with Passive Haptics	2.7	*0.180*
Increase with Computer Game Usage	**-1.6**	***0.004***

Table 4.12. Analyzed between-subjects: models when correcting for Level of Computer Game Playing for ΔHeart Rate in Passive Haptics.

Multi-level sensitivity between-subjects in Frame Rate. Even between-subjects, in the Frame Rate study, ΔHeart Rate followed hypothesized patterns after 10 FPS (see Figure 4.10). Additionally, ΔHeart Rate differentiated with some statistical power among presence conditions: ΔHeart Rate at 30 FPS was higher than at

15 FPS (P°=°0.054, nearly significant). ΔSkin Conductance and ΔSkin Temperature did not follow the hypothesized pattern (see Figures 4.11 and 4.12). Table 4.14 shows the (between-subjects) differences among frame rates for the presence measures. Overall, ΔHeart Rate showed the most promise as a multi-level sensitive between-subjects physiological measure of presence; it varied in the expected direction and differentiated nearly significantly among the conditions. ΔSkin Conductance and ΔSkin Temperature did not perform well between-subjects.

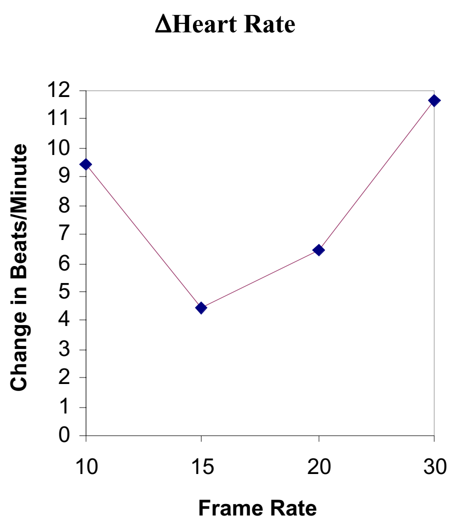


Figure 4.10. Analyzed between-subjects: ΔHeart Rate for each frame rate.

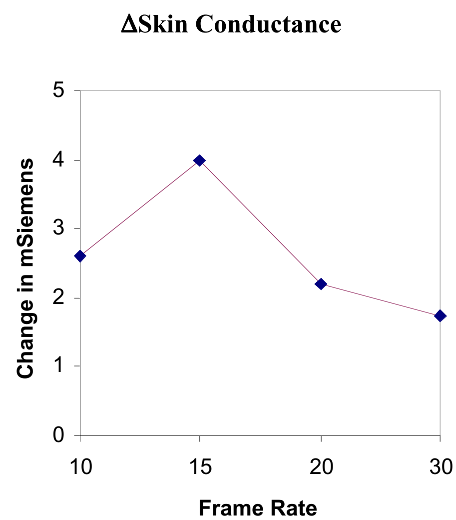


Figure 4.11. Analyzed between-subjects: ΔSkin Conductance for each frame rate.

	ΔHeart Rate		**ΔSkin Conductance**		**ΔSkin Temperature**		**Reported Presence**		**Reported Behavioral Presence**		**Observed Behavioral Presence**	
	β	***P***	**β**	***P***	**β**	***P***	**β**	***P***	**β**	***P***	**β**	***P***
Corrected Model		*0.218*		*0.222*		*0.320*		***0.002***		*0.567*		*0.993*
Intercept	**11.6**	***< 0.001***	**1.7**	***< 0.001***	**1.3**	***< 0.001***	**6.2**	***< 0.001***	**2.6**	***< 0.001***	**2.9**	***< 0.001***
Frame Rate	[-7.2, 0.0]	*0.218*	[0.5, 2.2]	*0.222*	[-0.5, 0.0]	*0.320*	**[-2.5, 0.0]**	***0.002***	[-0.6, 0.0]	*0.567*	[-0.2, 0.1]	*0.993*

Table 4.13. Analyzed between-subjects: the models in Frame Rate for each measure.

1.1.1.2

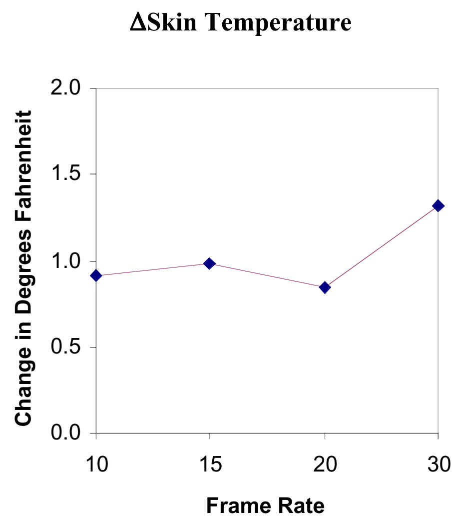


Figure 4.12. Analyzed between-subjects: ΔSkin Temperature for each frame rate.

	ΔHeart Rate	ΔSkin Conductance	ΔSkin Temperature	Reported Presence	Reported Behavioral Presence	Observed Behavioral Presence
Increase from 10 FPS to 15 FPS	-5.0	1.4	0.1	1.0	0.1	-0.1
P	*0.187*	*0.221*	*0.830*	*0.161*	*0.769*	*0.894*
Increase from 15 FPS to 20 FPS	2.0	-1.8	-0.1	**1.5**	0.1	-0.2
P	*0.587*	*0.119*	*0.630*	***0.039***	*0.769*	*0.868*
Increase from 20 FPS to 30 FPS	5.2	-0.5	0.5	-0.0	0.3	0.2
P	*0.159*	*0.686*	***0.091***	*0.967*	*0.462*	*0.868*
Increase from 10 FPS to 30 FPS	2.2	-0.8	0.4	**2.5**	0.6	-0.1
P	*0.541*	*0.445*	*0.153*	***0.001***	*0.185*	*0.894*
Increase from 15 FPS to 30 FPS	7.2	**-2.2**	0.3	**1.5**	0.4	-0.0
P	***0.054***	***0.048***	*0.223*	***0.038***	*0.302*	*1.000*

Table 4.14. Analyzed between-subjects: differences among frame rates.

Reported Presence performed well as a between-subjects presence measure in the Frame Rate study but not in the Passive Haptics study. It followed the hypothesized monotonic increase with Frame Rate (the responses at 20 FPS and 30 FPS were nearly equal on average — see Figure 4.13 and Table 4.14) and was more multi-level sensitive than any of the other measures in this study: Reported Presence was significantly higher at 30 FPS than at 10 FPS ($P < 0.001$) and at 30 FPS than at 15 FPS (P°=°0.038). See Table 4.14. Reported Presence, however, did not perform well between-subjects in the Passive Haptics study. It was non-significantly *lower* when the 1.5 wooden ledge was present. This was opposite the hypothesized direction. See Table 4.11.

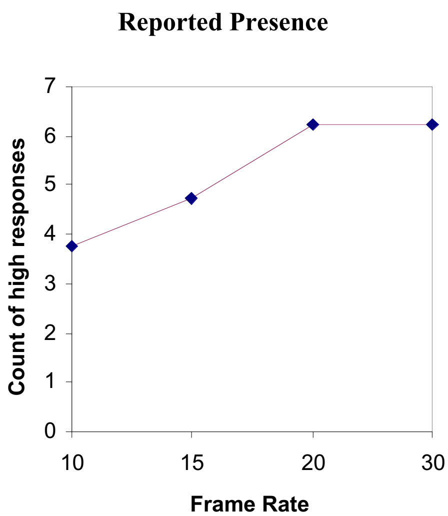


Figure 4.13. Analyzed between-subjects: Reported Presence for each frame rate.

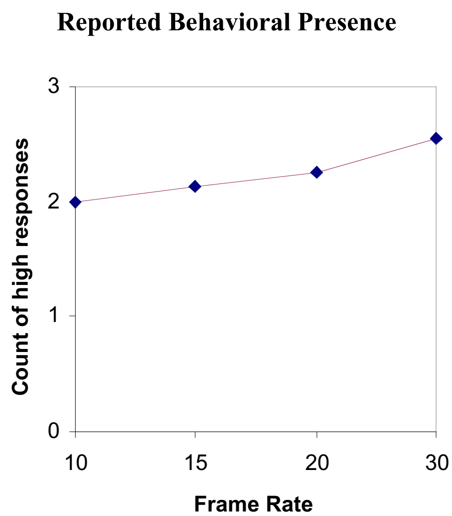


Figure 4.14. Analyzed between-subjects: Reported Behavioral Presence for each frame rate.

Reported Behavioral Presence was moderately multi-level sensitive (P°=°0.051 — nearly significant) in the Passive Haptics study. It followed the hypothesized pattern: a monotonic increase with Frame Rate (see Figure 4.14), but did not differentiate significantly among the different frame rates (See Table 4.14).

1.1.1.2

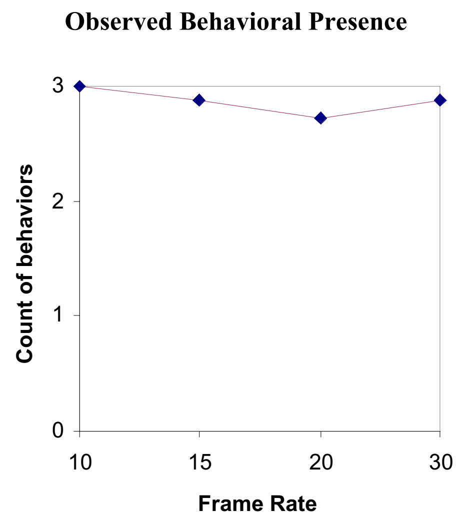


Figure 4.15. Analyzed between-subjects: Observed Behavioral Presence for each frame rate.

In Passive Haptics, Observed Behavioral Presence was significantly higher with the 1.5-inch wooden ledge included (between-subjects). Its significance (P°=°0.001) was higher than for any other between-subjects measure. In Frame Rate, however, Observed Behavioral Presence neither followed the hypothesized monotonic increase (see Figure 4.15) nor did it differentiate among frame rates (Table 4.14).

In conclusion, there was support for the use of physiological reaction as a between-subjects measure of presence. ΔHeart Rate did not correlate well with the reported measures, but it was able to differentiate among multiple presence conditions. We suggest it as the best physiological measure for between-subjects presence studies. ΔSkin Conductance and ΔSkin Temperature did not correlate well and did not follow hypotheses when analyzed between-subjects. Observed Behavioral Presence correlated well with Reported Behavioral Presence and differentiated with power for the reduced data set available for Passive Haptics, but did not follow hypotheses in Frame Rate. Our data did not support its use as a between-subjects measure of presence.

4.4.2 High-low threshold for presence questionnaire.

Even though each question in the UCL questionnaire was rated on a scale of 1-7, Slater *et al.* used the questions only to yield a High-Presence/ Low-Presence result. A judgment had to be made as to the high-low threshold. Slater *et al*. investigated the use of 6 and 7 [m6] as high responses and the use of 5, 6, and 7 [m5]

1.1.1.2

as high responses — as well as other constructions: addition of raw scores and a combination based on principal-components analysis. They found that scoring [m6] as high values best followed conditions [Slater, 1994]. We, however, found [m5] to better follow conditions.

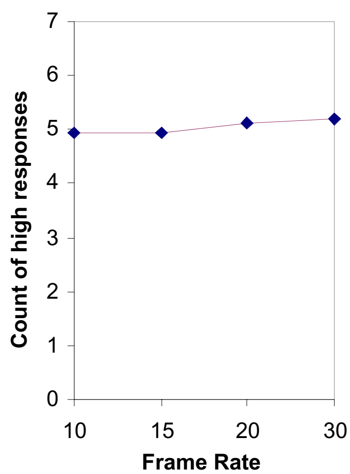
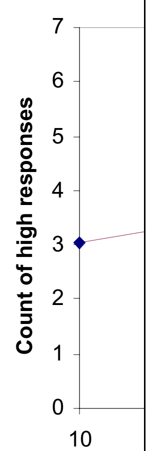
	Reported Presence [m5]	**Reported Presence [m6]**
Increase with Passive Haptics	Increase = 0.5, $P = 0.060$	Increase = 0.4, $P = 0.215$
Frame Rate		
Significance for difference 10FPS - 15FPS	Increase = 0.0, $P = 1.000$	Increase = 0.3, $P = 0.409$
15 FPS - 20 FPS	Increase = 0.2, $P = 0.553$	Increase = 0.1, $P = 0.885$
20 FPS - 30 FPS	Increase = 0.1, $P = 0.843$	Decrease = 0.6, $P = 0.090$

Table 4.15. Comparison of results for Reported Presence using either [m5] or [m6] as high values.

Using [m5] better followed conditions for Reported Presence for both Passive Haptics and Frame Rate (Table 4.15). Using [m5] differentiated more significantly than [m6] in Passive Haptics. In Frame rate, [m5] was more multi-level sensitive and followed the hypothesized monotonic increase; [m6] did not closely follow the hypothesis.

1.1.1.2

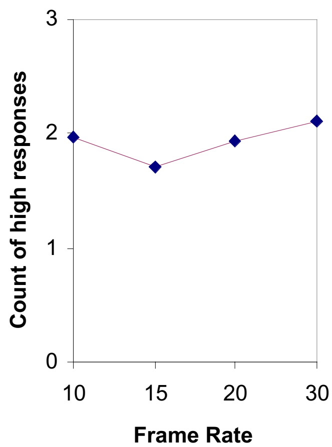
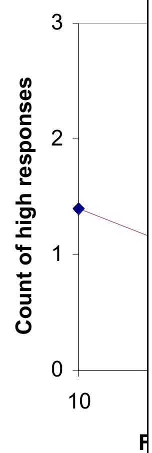
	Reported Behavioral Presence [m5]	Reported Behavioral Presence [m6]
Increase with Passive Haptics	**Increase = 0.4, *P°=°0.004***	**Increase = 0.4, *P°=°0.003***
Frame Rate		
Significance for difference 10FPS - 15FPS	Decrease = 0.3, *P°=°0.083*	Decrease = 0.3, *P°=°0.123*
15 FPS - 20 FPS	Increase = 0.2, *P°=°0.116*	Increase = 0.2, *P°=°0.175*
20 FPS - 30 FPS	Increase = 0.2, *P°=°0.256*	Decrease = 0.0, *P°=°0.831*

Table 4.16. Comparison of results for Reported Behavioral Presence using either [m5] or [m6] as high values.

For Reported Behavioral Presence, using [m6] performed only slightly better (P°=°0.003) than [m5] (P°=°0.004) in Passive Haptics. In Frame Rate, [m5] was more multi-level sensitive and more closely followed the hypothesized monotonic increase with Frame Rate than [m6]. See Table 4.16.

Given the evidence:

- For Reported Presence, [m5] more closely followed conditions and differentiates with more power among conditions for both studies,
- For Reported Behavioral Presence, [m5] better followed conditions and was more multi-level sensitive in Frame Rate; [m5] and [m6] performed equally in Passive Haptics;

Overall, use of [m5] best follows conditions.

1.1.1.2

Correlations. The physiological measures correlated better with the reported measures scored as [m6] than those scored using [m5]. See Table 4.17. Of the ten correlations that were positive and significant between a physiological measure and a reported measure (e.g. ΔHeart Rate and Reported Presence [m5] in Frame Rate), in every case the correlation with the [m6] measure was greater than the [m5] measure:

- ΔHeart Rate and Reported Presence in Frame Rate
- ΔHeart Rate and Reported Behavioral Presence in Frame Rate
- ΔSkin Conductance and Reported Presence in Multiple Exposures
- ΔSkin Conductance and Reported Behavioral Presence in Multiple Exposures
- ΔSkin Temperature and Reported Presence in Frame Rate.

Correlations	Study	Reported Presence [m5]	Reported Presence [m6]	Reported Behavioral Presence [m5]	Reported Behavioral Presence [m6]
ΔHeart Rate	**ME**				
	P				
	PH	0.034	0.003	0.004	0.006
	P	*0.743*	*0.976*	*0.972*	*0.955*
	FR	**0.265**	**0.305**	**0.192**	**0.225**
	P	***0.002***	***< 0.001***	***0.028***	***0.009***
ΔSkin Conductance	**ME**	**0.245**	**0.303**	**0.290**	**0.395**
	P	***0.009***	***0.001***	***0.002***	***< 0.001***
	PH	-0.002	0.055	0.106	0.041
	P	*0.986*	*0.577*	*0.280*	*0.674*
	FR	0.096	0.054	0.125	0.004
	P	*0.275*	*0.540*	*0.154*	*0.968*
ΔSkin Temperature	**ME**	-0.098	-0.092	-0.040	0.018
	P	*0.349*	*0.380*	*0.699*	*0.861*
	PH	-0.075	-0.007	-0.086	-0.105
	P	*0.448*	*0.944*	*0.383*	*0.291*
	FR	0.171	**0.221**	0.066	0.026
	P	*0.050*	***0.011***	*0.454*	*0.769*

Table 4.17. Table of correlations for the physiological measures with the reported measures using both [m6] and [m5] as "high" values.

To make our decision as to where to set the high and low mark for the presence measures, we had to consider the conflicting evidence: 1) using [m5] better followed conditions than [m6] and 2) the correlations were greater using [m6] than [m5]. While greater correlations would better demonstrate the validity of our measures, this would not be a suitable reason to choose a threshold. We felt that it would be better to choose a threshold using the logic that Slater *et al.* used: Which scoring better followed conditions? Therefore, since conditions were better followed using [m5], we chose to score 5, 6, and 7 as high values in the analysis of this dissertation.

The reporting of 5 s by subjects contributed to our using [m5] instead of [m6] as Slater *et al.* did. Over 25% of our subjects reported 5 s for Reported Presence in our studies (23% for the combination for Reported Presence, Reported Behavioral Presence, and Reported Ease of Locomotion). For the study for which data was published, Slater s subjects rarely (<10%) reported 5 values. One explanation for this may be that university students today expect more technically of a VE than they did several years ago. This heightened expectation may account for the increased number of 5 s reported in our studies.

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1.1.1.2

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1.1.1.2

Appendix A Stress response in human physiology

The human body releases chemicals into the circulating blood and near organs to regulate visceral functions. These functions include both homeostasis and stress reactions. Homeostasis includes body temperature regulation and blood flow control. We are interested in the body's stress, or fight-or-flight, response. In particular we are interested in heart rate, electrodermal, and skin temperature response to stress. The concepts are presented without citations and have been summarized from [Guyton, 1986] and [Andreassi, 1995].

A. 1 Autonomic nervous system

Peripheral response (activity in the internal organs) is controlled by the autonomic nervous system (ANS). This system controls heart contraction force and rate, sweat gland activity, skin temperature reaction, gastric motility, metabolism, blood glucose and coagulation levels, skeletal muscle strength, and many other visceral functions.

The ANS can effect a quick and strong reaction over a broad range of visceral functions. For example, heart rate can be doubled in 3-5 seconds and sweating can begin within 2 seconds. These reactions are brought about by chemicals released by the two parts of the autonomic nervous system: the sympathetic nervous system (SNS) and the parasympathetic nervous system (PNS).

The PNS governs the resting and rehabilitation of the body — homeostasis. It controls the systems needed to rebuild body tissue and reduce body stress level. The SNS manages the body s reaction to stress and preparation for periods of vigorous muscle activity. It controls the fight-or-flight reactions to situations perceived as adverse. At any given time both the PNS and SNS are active. It is the activation level of the two systems working in concert that determines the body s state.

Both the parasympathetic and sympathetic nervous systems work by firing neurons that cause the release of neurotransmitters. The PNS releases its neurotransmitters only at the organs to be stimulated. It selectively stimulates organs. The SNS releases neurotransmitters both at stimulated organs and into the blood stream. It stimulates all target organs simultaneously. Table A.1 outlines organs that are stimulated by the PNS and by the SNS and describes how those systems are affected once stimulated.

Organ	Effect of SNS Stimulation	Effect of PNS Stimulation
Eye: Pupil Ciliary muscle	**Dilation Slight relaxation**	**Constriction Constriction**
Sweat glands	**Copious sweating (cholinergic)**	**None**
Heart: Muscle	**Increased rate Increased force of contraction**	**Slowed rate Decreased force of contraction**
Lungs: Bronchi Blood vessels	**Dilated Mildly constricted**	**Constricted Dilated**
Systemic arterioles: Abdominal muscle Skin	**Constricted Constricted (α) Dilated (β_2, cholinergic) Constricted**	**None None None**
Blood: Coagulation Glucose	**Increased Increased**	**None None**
Basal metabolism	**Increased up to 100%**	**None**
Adrenal medullary secretion	**Increased**	**None**
Mental activity	**Increased**	**None**
Skeletal muscle	**Increased glycogenolysis Increased strength**	**None**

Table A.1. The effect of parasympathetic and sympathetic nervous system activity on various human organs. Summarized from Guyton, Pg. 691 [Guyton, 1986].

A. 2 Peripheral response to stress

The sympathetic nervous system governs peripheral stress response. Peripheral stress response includes increase in heart rate, increase in electrodermal activity, and decrease in skin temperature. Also, breathing becomes shallower and more rapid and less blood flows to the intestines. During times of stress SNS activity increases, releasing more neurotransmitters into the blood and at target organs. The stress response produced is summarized in Table A.1. The stress responses we chose to use in this research are change in heart rate, electrodermal activity, and skin temperature.

An organ s response to SNS stimulation occurs within 2-3 seconds (from direct stimulation to the organ) and continues for one to two minutes after stimulation ceases (due to neurotransmitters circulating in the blood).

1.1.1.2

A. 2. 1 Heart rate response to stress

Heart rate (HR) increases in times of stress. Sympathetic stimulation increases both the rate and strength of contraction. The combination of increased rate and force helps the circulatory system deliver more oxygen and nutrients to the large muscle groups. This helps the body prepare to either fight its way out of stress or escape from danger.

HR can be measured in a number of ways. Two common ways are via blood volume pulse (BVP) and electrocardiogram (ECG). BVP measurement works by monitoring at a high frequency (32Hz) the amount of blood in a specific region of the body. The amount of blood in the region is determined by either shining infrared light on the skin and measuring how much of the light is reflected to a neighboring photosensor or by shining light through a thin region, such as the earlobe, and recording the amount of light transmitted. The amount of light received at the photosensor over time can be analyzed to determine HR.

It has been known since 1856 that the heart s contractions are accompanied by electrical changes. By the 1900 s scientists had developed methods of measuring and recording these electrical changes from the surface of the skin — the birth of the ECG.

The signal produced by the heart on an ECG is a 5-part wave: the PQRST wave, depicted in Figure A.1. The explanation of what is causing these electrical signals is described in the figure.

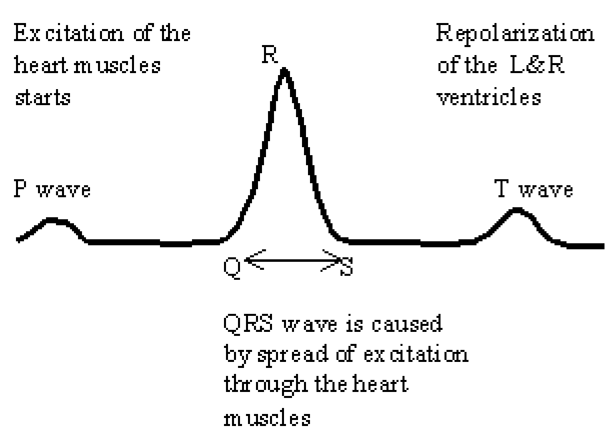


Figure A.1. A typical PQRST wave.

1.1.1.2

There are many possible lead placements for ECG sensors. When subjects are moving, it is important to chose ECG lead positions that reduce movement artifacts. McMurray suggests the lead placement illustrated in Figure A.2 [McMurray, 1999]. It maximizes the amplitude of the signal by placing the leads across the heart while minimizing artifacts by minimizing the amount of muscle mass beneath the leads. The ground lead stabilizes the signal.

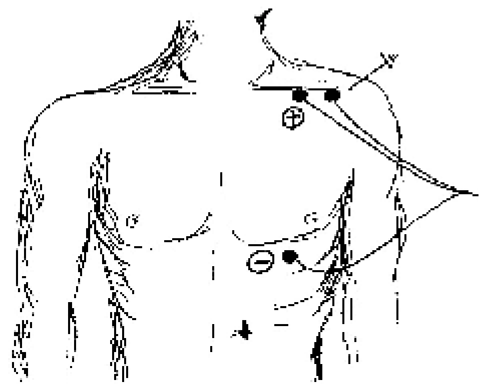
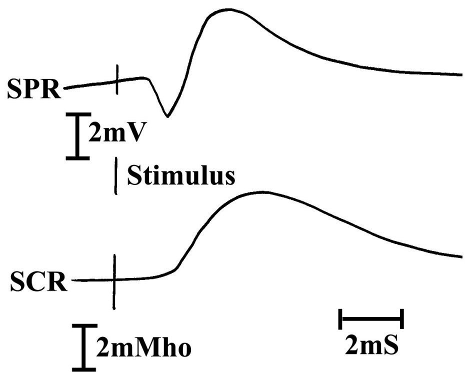


Figure A.2. Placement of ECG leads

A. 2. 2 Electrodermal response to stress

Electrodermal activity (EDA) is produced by two types of sweat glands: apocrine and eccrine. The apocrine glands open into hair follicles located in genital areas and armpits and respond primarily to thermal stimulation. The eccrine glands have a wide distribution over the body and are most concentrated on palms of hands and soles of feet. Eccrine sweat glands respond primarily to SNS stimulation, hence to stress, by increasing sweat gland activity. We use eccrine gland activity (SNS) in our investigation.

There are two measures of EDA: skin potential (SP) and skin conductance (SC). The techniques and ideas behind measuring SP are attributed to Tarchanoff (1890) and SC to Fere (1888). Both researchers investigated the relationship between EDA and physical and emotional stimuli. SP is a measure of electrical activity caused by sweat gland activity. It is measured with a unipolar arrangement: the potential on the skin of the palm or fingers and a ground lead on an inactive site such as the forearm or earlobe. Skin potential can change slowly over time (called a change in skin potential level (SPL)) or it can change quickly (called a skin potential reaction SPR). A typical SP reaction wave is depicted in Figure A.3.



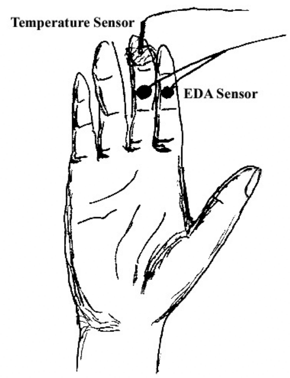


Figure A.3. Typical Skin potential reaction (SPR -above) and skin conductance reaction (SCR - below).

Figure A.4. Bipolar placement of electrodermal sensors and placement of temperature sensor.

SC is the preferred method of measuring EDA because of the natural relationship between the signal and its interpretation — skin conductance goes up with emotional stimuli. Skin conductance level (SCL) is the low frequency change in skin conductance. Skin conductance reactions (SCRs) are the high-frequency, short duration changes in skin conductance. A typical SCR is illustrated in Figure A.3. In this dissertation we call skin conductance level skin conductance for simplicity.

SC is a measured by passing a weak electrical current across the skin and determining, from the voltage produced, the conductance on the skin. Electrode placement is bipolar with the two electrodes usually on adjacent fingers (illustrated in Figure A.4).

SNS activity can cause both increasing SCL, if the SNS activity is long-lasting, and, if the SNS activity is short-lived, SCRs. SC reaction to stimuli typically occurs within 2-3 seconds and can last as long 1-2 minutes.

A. 2. 3 Skin temperature response to stress

Skin temperature (ST) on the hands, feet, lips, nose, and ears decreases in times of stress. The skin has below it an extensive capillary system called the *venous plexus*. In the areas of the skin listed above, blood is supplied to the venous plexus via a direct connection to the arteries: the *arteriovenous anastomoses*. When stimulated by the SNS, these anastomoses constrict, reducing blood flow to these areas of the skin to almost nothing. This reduction in blood flow to the subcutaneous venous plexus causes the reduction in skin temperature.

Reduction in blood flow to the skin also allows the volume of blood usually stored in the skin — usually 5%-10% of total blood volume — to be released into the circulatory system. This release of a blood reservoir, like the increase in heart rate, can be seen as a preparation for fight or flight reaction: it allows a greater amount of blood to flow to the large muscle groups.

McMurray, points out that skin temperature reactions can be best observed by placing a thermistor at the end of one of the fingers and holding it in place with thin porous tape [McMurray, 1999]. The placement at the end of the finger allows one to see a quick reaction and is little influenced by blood flow in the underlying muscle. The thin porous tape ensures faster reaction by reducing thermal insulation.

Time to reach a peak ST can be several minutes (up to 5) due to lag both in the subject's ST and in the sensor. Therefore, exposures to the stressor of several minutes are suggested for measures using average skin temperature [McMurray, 1999].

A. 2. 4 Relationship between electrodermal activity and skin temperature

The relationship between electrodermal activity and skin temperature differs in stressful and non-stressful situations. In non-stress situations, an increase in sweating is usually accompanied by an increase in skin temperature. Both are used for thermal regulation. The evaporation of the sweat works with the increase in blood near the surface of the skin to lower the core temperature of the body. Similarly, a decrease in blood flow and sweat gland activity occur together to conserve body heat. This type of sweating occurs primarily in the armpits and near the genitals. In stressful situations, in contrast, skin temperature drops while, at the same time, sweat activity increases on the palms of the hands and feet.

1.1.1.2

Appendix B Documents used with subjects

B. 1 University College London Presence Questionnaire

Below is a reproduction of the UCL Presence Questionnaire we used. We extended the questionnaire used in [Usoh, 1999]. We included an additional question on level of exercise, Question 21, and wording was changed in Question 2 so that the question referred to objects in our environment — the room with the counters and radio. The questionnaire was administered using the Internet.

The questionnaire yields three scores: Reported Presence (Questions 2, 5, 12, 14, 15, 17, 18), Reported Behavioral Presence (Questions 1, 8, 10), and Reported Ease of Locomotion (Questions 4, 6, 9).

Each question is scored on a scale from 1 to 7. As discussed in Chapters 1 and 4, each of these measures is scored by counting the number of high responses. We investigated using both 5, 6, and 7 as high responses and using 6 and 7 as high responses. In Question 1, the scale is inverted, so we used the either 1, 2, and 3 as high responses or 1 and 2. The measures are summed as follows:

Reported Presence = Σ High (2, 5, 12, 14, 15, 17, 18)

Reported Behavioral Presence = Σ High (1, 8, 10)

Reported Ease of Locomotion = Σ High (4, 6, 9)

1.1.1.2

VE Questionnaire

ID:

The following questions relate to your experience.

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

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

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

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

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

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

3 Gender, Age, and Race/ Ethnicity:

Male. Female. Age.

Race/ Ethnicity:
- American Indian or Alaskan Native
- Asian or Pacific Islander
- Black, not of Hispanic Origin
- Hispanic
- White, not of Hispanic Origin
- Other

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

To move through the computer generated world was...

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

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

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

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

1.1.1.2

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

To get from place to place was...

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

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

I associated with the computer generated body...

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

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

Compared to real life my reaction was...

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

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

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

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

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

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

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

11 What is your University status?

My status is as follows:
1. Undergraduate student
2. Graduate student
3. Research Associate
4. Staff member - systems/technical staff
5. Faculty
6. Administrative staff
7. Other (please write in)...

1.1.1.2

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

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

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

13 Have you experienced virtual reality before?

I have experienced virtual reality...

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

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

I had a stronger sense of being in...

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

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

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

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

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

I use a computer...

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

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

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

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

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

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

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

20 To what extent do you play computer games?

I play computer games...
(Not at all) 1. 2 3 4 5 6 7 (Very much)

21 How many hour per week do you exercise?

During an average week, I exercise...

Less than 0.5 hours
0.5 hours
1 hour
1.5 hours
2 hours
2.5 hours
3 or more hours

Further Comments

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

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

1.1.1.2

B. 2 Simulator Sickness Questionnaire

Below is a reproduction of the Kennedy s Simulator Sickness Questionnaire [Kennedy, 1993]. We administered this questionnaire via the Internet. A html link to a page with definitions of some of the terms was also available for subjects. This is reproduced after the questionnaire. We added one question assessing hunger since subjects reported hunger in our precursor work [Meehan, 2000c; Pugnetti, 2000] and we speculated this to be a precursor to nausea. No such relationship was found. This questionnaire was completed once before and once after each task. We did not add hunger into the equation for *Simulator Sickness*, but instead used Kennedy s original formulation.

Kennedy *et al.* suggested using the total score, called Simulator Sickness below, from the post-exposure test as the indicator of sickness. They also suggested looking at the difference between pre- and post-exposure scores to help explain any sickness seen.

For each question, a score of none (0), slight (1), moderate (2), or severe (3) were assigned. The scores were then combined as follows:

Nausea = Σ(Questions 1, 6, 7, 8, 9, 15, 16)

Column2 = Σ(Questions 1, 2, 3, 4, 5, 9, 11)

Column3 = Σ(Questions 5, 8, 10, 11, 12, 13, 14)

Nausea = 9.54 x Column1

Ocular Discomfort = 7.58 x Column2

Disorientation = 13.92 _ Column3

Simulator Sickness = 3.74 x (Column1 + Column2 + Column3) (Range: 0-235)

1.1.1.2

The questionnaire

For each of the following conditions, please indicate how you are feeling right now, on the scale of none through severe. Circle your response.

1.	General Discomfort	None	Slight	Moderate	Severe
2.	Fatigue	None	Slight	Moderate	Severe
3.	Headache	None	Slight	Moderate	Severe
4.	Eye Strain	None	Slight	Moderate	Severe
5.	Difficulty Focusing	None	Slight	Moderate	Severe
6.	Increased Salivation	None	Slight	Moderate	Severe
7.	Sweating	None	Slight	Moderate	Severe
8.	Nausea	None	Slight	Moderate	Severe
9.	Difficulty Concentrating	None	Slight	Moderate	Severe
10.	Fullness of Head	None	Slight	Moderate	Severe
11.	Blurred Vision	None	Slight	Moderate	Severe
12.	Dizzy (with your eyes open)	None	Slight	Moderate	Severe
13.	Dizzy (with your eyes closed)	None	Slight	Moderate	Severe
14.	Vertigo	None	Slight	Moderate	Severe
15.	Stomach Awareness	None	Slight	Moderate	Severe
16.	Burping	None	Slight	Moderate	Severe
17.	Hunger	None	Slight	Moderate	Severe

In the space below, please list any additional symptoms you are experiencing (continue on the back if necessary).

1.1.1.2

Definitions for Simulator Sickness Questionnaire

The following information was available through a html link from the SSQ form.

Explanation of Conditions

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

B. 3 Height Anxiety Questionnaire

This questionnaire was administered via the Internet before the first exposure to the VE. It was developed by Cohen [Cohen, 1977]. Height Anxiety was scored as a simple sum of all of the responses.

Height Questionnaire

ID:

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

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

1. Diving off the low board at a swimming pool.
(Not at all anxious) 0 1 2 3 4 5 6 (Extremely Anxious)

2. Stepping over rocks crossing a stream.
(Not at all anxious) 0 1 2 3 4 5 6 (Extremely Anxious)

3. Looking down a circular stairway from several flights up.
(Not at all anxious) 0 1 2 3 4 5 6 (Extremely Anxious)

4. Standing on a ladder leaning against a house, second story.
(Not at all anxious) 0 1 2 3 4 5 6 (Extremely Anxious)

5. Sitting in the front of an upper balcony of a theater.
(Not at all anxious) 0 1 2 3 4 5 6 (Extremely Anxious)

6. Riding a ferris wheel.
(Not at all anxious) 0 1 2 3 4 5 6 (Extremely Anxious)

7. Walking up a steep incline in country hiking.
(Not at all anxious) 0 1 2 3 4 5 6 (Extremely Anxious)

8. Airplane trip (to San Francisco).
(Not at all anxious) 0 1 2 3 4 5 6 (Extremely Anxious)

9. Standing next to an open window on the third floor.
(Not at all anxious) 0 1 2 3 4 5 6 (Extremely Anxious)

10. Walking on a footbridge over a highway.
(Not at all anxious) 0 1 2 3 4 5 6 (Extremely Anxious)

11. Driving over a large bridge (Golden Gate, George Washington).
(Not at all anxious) 0 1 2 3 4 5 6 (Extremely Anxious)

12. Being away from window in an office on the 15th floor of a building.
(Not at all anxious) 0 1 2 3 4 5 6 (Extremely Anxious)

13. Seeing window washers 10 flights up on a scaffold.
(Not at all anxious) 0 1 2 3 4 5 6 (Extremely Anxious)

14. Walking over a sidewalk grating.
(Not at all anxious) 0 1 2 3 4 5 6 (Extremely Anxious)

15. Standing on the edge of a subway platform.
(Not at all anxious) 0 1 2 3 4 5 6 (Extremely Anxious)

16. Climbing a fire escape to the 3rd floor landing.
(Not at all anxious) 0 1 2 3 4 5 6 (Extremely Anxious)

17. On the roof of a 10 story apartment building.
(Not at all anxious) 0 1 2 3 4 5 6 (Extremely Anxious)

18. Riding the elevator to the 50th floor.
(Not at all anxious) 0 1 2 3 4 5 6 (Extremely Anxious)

19. Standing on a chair to get something off a shelf.
(Not at all anxious) 0 1 2 3 4 5 6 (Extremely Anxious)

20. Walking up the gangplank of an ocean liner.
(Not at all anxious) 0 1 2 3 4 5 6 (Extremely Anxious)

1.1.1.2

B. 4 Height Avoidance Questionnaire

This questionnaire was administered via the Internet before the first exposure to the VE. It was developed by Cohen [Cohen, 1977]. Height Avoidance was scored as a simple sum of all of the responses.

Height Questionnaire

ID:

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

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

1. Diving off the low board at a swimming pool.
(Would not avoid it) 0 1 2 (Would not do it under any circumstances)

2. Stepping over rocks crossing a stream.
(Would not avoid it) 0 1 2 (Would not do it under any circumstances)

3. Looking down a circular stairway from several flights up.
(Would not avoid it) 0 1 2 (Would not do it under any circumstances)

4. Standing on a ladder leaning against a house, second story.
(Would not avoid it) 0 1 2 (Would not do it under any circumstances)

5. Sitting in the front of an upper balcony of a theater.
(Would not avoid it) 0 1 2 (Would not do it under any circumstances)

6. Riding a ferris wheel.
(Would not avoid it) 0 1 2 (Would not do it under any circumstances)

7. Walking up a steep incline in country hiking.
(Would not avoid it) 0 1 2 (Would not do it under any circumstances)

8. Airplane trip (to San Francisco).
(Would not avoid it) 0 1 2 (Would not do it under any circumstances)

9. Standing next to an open window on the third floor.
(Would not avoid it) 0 1 2 (Would not do it under any circumstances)

10. Walking on a footbridge over a highway.
(Would not avoid it) 0 1 2 (Would not do it under any circumstances)

11. Driving over a large bridge (Golden Gate, George Washington).
(Would not avoid it) 0 1 2 (Would not do it under any circumstances)

12. Being away from window in an office on the 15th floor of a building.
(Would not avoid it) 0 1 2 (Would not do it under any circumstances)

13. Seeing window washers 10 flights up on a scaffold.
(Would not avoid it) 0 1 2 (Would not do it under any circumstances)

14. Walking over a sidewalk grating.
(Would not avoid it) 0 1 2 (Would not do it under any circumstances)

15. Standing on the edge of a subway platform.
(Would not avoid it) 0 1 2 (Would not do it under any circumstances)

16. Climbing a fire escape to the 3rd floor landing.
(Would not avoid it) 0 1 2 (Would not do it under any circumstances)

17. On the roof of a 10 story apartment building.
(Would not avoid it) 0 1 2 (Would not do it under any circumstances)

18. Riding the elevator to the 50th floor.
(Would not avoid it) 0 1 2 (Would not do it under any circumstances)

19. Standing on a chair to get something off a shelf.
(Would not avoid it) 0 1 2 (Would not do it under any circumstances)

20. Walking up the gangplank of an ocean liner.
(Would not avoid it) 0 1 2 (Would not do it under any circumstances)

B. 5 Informed Consent

This is the informed consent form for the Frame Rate study. The informed consent forms for the Passive Haptics and Multiple Exposures study are identical except for description of the extent of participation and reimbursement. Details of the studies are given in Chapter 3.

Introduction and purpose of the study:

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

The principal investigator is Michael Meehan (UNC Chapel Hill, Department of Computer Science, 259 Sitterson Hall, 962-1979, email: meehan@cs.unc.edu). The Faculty advisor is Dr. Frederick Brooks, Jr. (UNC Chapel Hill, Department of Computer Science, 216 Sitterson Hall, 962-1931, email: brooks@cs.unc.edu).

What will happen during the study:

We will ask you to come to the laboratory for one sessions, which will last approximately 1 hour. During the sessions, you will perform a few simple tasks within the VE. You will also be given questionnaires asking about your perceptions and feelings during and after the VE experience. Approximately 30 people will take part in this study.

We will use computers to record your hand, head, and body motion during the VE experience. We will use sensors on your fingers and chest to record heart rate and other physiological measures. We will also make video and audio recordings of the sessions.

Protecting your privacy:

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

Risks and discomforts:

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

Your rights:

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

Institutional Review Board approval:

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

Summary:

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

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

- I will visit the laboratory once for approximately 1 hour.
- I will wear a virtual environment headset to perform tasks, and my movements, physiological signals (via sensors on my fingers and chest), and behavior will be recorded

by computer and on videotape, and I will respond to questionnaires between and after the sessions.

- I may experience slight feelings of disorientation, nausea, or dizziness during or shortly after the VE experiences.

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

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

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

______________________________ ______________

Signature of Participant Date

B. 6 Participant Health Questionnaire

The questionnaire reproduced below was administered pre-session via the Internet.

Participant Health Questionnaire

This is filled out when the subject comes to the lab. Once for each day they are there.
Please circle your answers to the following questions:

1. Are you in your usual state of good fitness (health)? Yes No
If not, please explain: ____
____

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

(a) Sedatives or tranquilizers
(b) Decongestants
(c) Anti-histamines
(d) Other
(e) None

1.1.1.2

B. 7 Questions asked in oral interview

The experimenters used the questions below as a guide during their post-session debriefing of subjects.

VR Research study: Debriefing sheet

Debrief by:______________________________

Questions	**Comments**
How do you feel? — sickness	
What did you think about your experience?	
How much did you feel you were in the environment? ? >50% or <50% of the time?	
Any comments on moving around? difficulty, natural	
Any comments on your virtual body? behavior, identified with it	
Any comments on the pit room? - fear of falling, realism	
Any comments on environment? what made it real, what brought you out	
What influenced you to choose path to chair?	
Audio tape number:______ **Start counter:___________** **Stop counter:____________**	

Subject ID:_____.

1.1.1.2

Appendix C Experiment data

Variable	Description
Subject	The ID given to the subject
Session	The day number. E.g. *session*=2 is the second day that the subject participates.
Task	The number of the task, or exposure, for a given day.
Condition	The code for the condition. In the Passive Haptics study: 0. 1.5 inch wooden ledge was not included. 1. 1.5 inch wooden ledge was included. In the Frame Rate study: 10. The content of the visual display was updated ten frames per second. 15. The content of the visual display was updated fifteen frames per second. 20. The content of the visual display was updated twenty frames per second. 30. The content of the visual display was updated thirty frames per second.
Simulator Sickness	Reported simulator sickness as reported on Kennedy s Simulator Sickness Questionnaire [Kennedy, 1993]. See Appendix B.
Reported Presence [m6]	Reported Presence as reported on the University College London Presence Questionnaire. A count of the questions on which the participant reported 6 or 7 on a scale of 1 to 7. There are seven questions on Reported Presence.
Reported Presence [m5]	Reported Presence as reported on the University College London Presence Questionnaire. A count of the questions on which the participant reported 5, 6, or 7 on a scale of 1 to 7. There are seven questions on Reported Presence.
Reported Behavioral Presence [m6]	Reported Behavioral Presence as reported on the University College London Presence Questionnaire. A count of the questions on which the participant reported 6 or 7 on a scale of 1 to 7. There are three questions on Reported Behavioral Presence.
Reported Behavioral Presence [m5]	Reported Behavioral Presence as reported on the University College London Presence Questionnaire. A count of the questions on which the participant reported 5, 6, or 7 on a scale of 1 to 7. There are three questions on Reported Behavioral Presence.
Reported Ease of Locomotion [m6]	Reported Ease of Locomotion as reported on the University College London Presence Questionnaire. A count of the questions on which the participant reported 6 or 7 on a scale of 1 to 7. There are three questions on Reported Ease of Locomotion.
Reported Ease of Locomotion [m5]	Reported Ease of Locomotion as reported on the University College London Presence Questionnaire. A count of the questions on which the participant reported 5, 6, or 7 on a scale of 1 to 7. There are three questions on Reported Ease of Locomotion.
Association with Virtual Body	Association with Virtual Body as reported on the University College London Presence Questionnaire on a scale from 1=not at all 7=very much .
Gender	Gender: 1=male; 2=female
Age	Age.
University Status	University Status: 1. Undergraduate student 2. Graduate student 3. Research Associate 4. Staff member - systems/technical staff 5. Faculty 6. Administrative staff 7. Other
Virtual Environment Experience	The amount of experience that the subject has had with virtual environments: 1=not at all 7=a great deal .
Computer Usage	The amount that subjects use a computer: 1=not at all 7=very much
Computer Game	The amount that subjects play computer games: 1=not at all 7=very much

1.1.1.2

Usage	
Height Anxiety	Height Anxiety as reported on Cohen s questionnaire [Cohen, 1977]. See Appendix B.
Height Avoidance	Height Avoidance as reported on Cohen s questionnaire [Cohen, 1977]. See Appendix B.
ΔHeart Rate	Change in heart rate between the Pit Room and the Training Room.
ΔSkin Conductance	Change in skin conductance between the Pit Room and the Training Room.
ΔSkin Temperature	Change in skin temperature between the Pit Room and the Training Room.
Observed Behavioral Presence	Observed Behavioral Presence scored from videotape.
Loss of Balance on Ledge	Count of the number of times that a subject lost balance while on the 1.5 inch wooden ledge.

Table C.1. Table of variables with brief explanations.

C. 1 Effect of multiple exposures on presence in virtual environments

Data for the experiment Effect of Multiple Exposures on Presence in Virtual Environments (Multiple Exposures).

Subject	Session	Task	Simulator Sickness	Reported Presence [m 6]	Reported Presence [m 5]	Reported Behavioral Presence	Reported Behavioral Presence	Reported Ease of Locomotion [m 6]	Reported Ease of Locomotion [m 5]	Gender (1=male, 2=female)	Age	University Status	Virtual Environment Experience	Computer Usage	Computer Game Usage	Height Anxiety	Height Avoidance	ΔSkin Conductance Level	ΔSkin Temperature	Observed Behavioral Presence
0	1	1	22.44	1	4	1	2	0	2	2	20	7	1	6	2	24	9	2.87	2.19	5
0	1	2	14.96	0	1	0	0	0	3	2	20	7	1	6	2	24	9	0.92	2.62	3
0	1	3	14.96	2	5	0	1	0	3	2	20	7	1	6	2	24	9	3.85	-0.12	2
0	2	1	18.7	0	4	0	2	0	0	2	20	7	1	6	2	24	9	2.00		7
0	2	2	18.7	0	4	0	1	0	2	2	20	7	1	6	2	24	9	2.74	-0.23	3
0	2	3	26.18	0	2	0	1	0	1	2	20	7	1	6	2	24	9	1.08	-0.22	3
0	3	1	37.4	0	3	0	0	0	0	2	20	7	1	6	2	24	9	0.76	1.78	4
0	3	2	33.66	0	3	1	1	0	3	2	20	7	1	6	2	24	9	0.83	-1.39	4
0	3	3	33.66	2	4	1	2	0	3	2	20	7	1	6	2	24	9	1.98	0.09	4
0	4	1	29.92	0	4	2	2	1	3	2	20	7	1	6	2	24	9	1.51	-1.37	-1
0	4	2	29.92	2	6	1	1	0	3	2	20	7	1	6	2	24	9	0.91	-0.58	-1
0	4	3	22.44	2	6	1	2	3	3	2	20	7	1	6	2	24	9	2.23	0.55	0
1	1	1	11.22	4	5	1	2	2	2	2	27	7	2	7	1	33	8			1
1	1	2	37.4	4	6	2	2	1	3	2	27	7	2	7	1	33	8	2.67	-0.35	3
1	1	3	86.02	3	5	1	2	2	3	2	27	7	2	7	1	33	8			5
1	2	1	44.88	5	7	3	3	1	1	2	27	7	2	7	1	33	8	5.00	0.55	7
1	2	2	67.32	3	4	3	3	1	2	2	27	7	2	7	1	33	8	2.67	0.34	5
1	2	3	86.02	4	5	2	3	3	3	2	27	7	2	7	1	33	8	2.21	1.77	5
1	3	1	26.18	5	6	3	3	3	3	2	27	7	2	7	1	33	8	4.75		3
1	3	2	41.14	4	5	3	3	3	3	2	27	7	2	7	1	33	8	4.50	1.15	4
1	3	3	48.62	3	6	3	3	2	3	2	27	7	2	7	1	33	8	6.16	1.27	
1	4	1	3.74	2	3	1	1	3	3	2	27	7	2	7	1	33	8	5.26	1.24	2
1	4	2	11.22	3	3	0	1	3	3	2	27	7	2	7	1	33	8	1.79	2.98	0
1	4	3	26.18	0	3	1	1	3	3	2	27	7	2	7	1	33	8			-1
2	1	1	63.58	5	7	3	3	1	3	1	21	7	1	7	5	26	5	5.84	2.92	3
2	1	2	26.18	6	6	1	1	3	3	1	21	7	1	7	5	26	5	3.97		2
2	1	3	11.22	5	5	1	1	3	3	1	21	7	1	7	5	26	5	2.95	-0.15	-2
2	2	1	26.18	5	6	1	2	3	3	1	21	7	1	7	5	26	5	6.25	-0.42	6
2	2	2	14.96	5	6	1	1	3	3	1	21	7	1	7	5	26	5	3.89	-0.36	5
2	2	3	26.18	6	7	0	0	3	3	1	21	7	1	7	5	26	5		-0.51	3
2	3	1	26.18	4	5	1	1	2	3	1	21	7	1	7	5	26	5	1.79		3

1.1.1.2

2	3	2	22.44	5	6	1	1	3	3	1	21	7	1	7	5	26	5	2.22	0.22	1
2	3	3	29.92	6	7	1	1	3	3	1	21	7	1	7	5	26	5			0
2	4	1	11.22	4	6	1	1	3	3	1	21	7	1	7	5	26	5	2.83	-0.77	-1
2	4	2	18.7	6	6	1	1	3	3	1	21	7	1	7	5	26	5	2.37	0.61	-1
2	4	3	11.22	6	6	1	1	3	3	1	21	7	1	7	5	26	5			1
3	1	1	11.22	5	7	3	3	3	3	2	47	1	1	6	3	37	7	2.41	0.83	
3	1	2	14.96	5	6	3	3	3	3	2	47	1	1	6	3	37	7	3.25		
3	1	3	22.44	6	7	2	3	3	3	2	47	1	1	6	3	37	7	2.30		
3	2	1	22.44	4	6	3	3	3	3	2	47	1	1	6	3	37	7	2.10	0.49	0
3	2	2	22.44	2	4	2	3	3	3	2	47	1	1	6	3	37	7			3
3	2	3	22.44	4	7	1	2	3	3	2	47	1	1	6	3	37	7	1.73	0.78	3
3	3	1	86.02	7	7	3	3	3	3	2	47	1	1	6	3	37	7	2.02	0.03	4
3	3	2	82.28	6	6	3	3	3	3	2	47	1	1	6	3	37	7	2.81	1.05	3
3	3	3	86.02	7	7	3	3	3	3	2	47	1	1	6	3	37	7	2.32	0.8	2
3	4	1	59.84	3	6	1	2	3	3	2	47	1	1	6	3	37	7	1.69	-0.47	0
3	4	2	48.62	5	6	3	3	3	3	2	47	1	1	6	3	37	7	3.47	1.37	0
3	4	3	52.36	6	7	1	2	3	3	2	47	1	1	6	3	37	7	1.80	0.93	1
4	1	1	11.22	3	7	1	2	0	2	1	21	1	1	5	5	10	1	0.76		
4	1	2	0	5	7	1	2	0	3	1	21	1	1	5	5	10	1	1.57	0.62	
4	1	3	0	7	7	2	3	3	3	1	21	1	1	5	5	10	1	3.25	0.75	
4	2	1	7.48	7	7	2	3	3	3	1	21	1	1	5	5	10	1	3.22		-2
4	2	2	3.74	7	7	3	3	3	3	1	21	1	1	5	5	10	1	4.25	1.4	-1
4	2	3	11.22	7	7	3	3	3	3	1	21	1	1	5	5	10	1	2.45	0.87	-2
4	3	1	14.96	7	7	2	3	3	3	1	21	1	1	5	5	10	1	2.91		-2
4	3	2	14.96	7	7	2	3	3	3	1	21	1	1	5	5	10	1	3.35	0.13	-2
4	3	3	14.96	6	6	2	2	3	3	1	21	1	1	5	5	10	1	2.84	1.11	-2
4	4	1	18.7	7	7	2	2	3	3	1	21	1	1	5	5	10	1	3.08	0.24	-2
4	4	2	14.96	7	7	2	2	2	3	1	21	1	1	5	5	10	1	2.02	0.44	-2
4	4	3	26.18	7	7	2	2	3	3	1	21	1	1	5	5	10	1	2.32	0.56	-2
5	1	1	22.44	4	4	3	3	0	1	2	23	2	1	7	4	22	5	2.37	0.12	
5	1	2	29.92	2	3	0	2	0	1	2	23	2	1	7	4	22	5	1.18	0.69	
5	1	3	33.66	5	7	2	2	0	3	2	23	2	1	7	4	22	5	1.27	0.32	7
5	2	1	3.74	4	7	2	2	1	3	2	23	2	1	7	4	22	5	1.56	0.26	
5	2	2	22.44	5	6	2	3	3	3	2	23	2	1	7	4	22	5	2.31	-2.3	7
5	2	3	18.7	6	7	2	3	3	3	2	23	2	1	7	4	22	5	3.04	0.79	7
5	3	1	18.7	6	7	2	3	3	3	2	23	2	1	7	4	22	5	1.29		7
5	3	2	7.48	6	7	2	3	3	3	2	23	2	1	7	4	22	5	1.70	-0.97	6
5	3	3	14.96	6	7	3	3	3	3	2	23	2	1	7	4	22	5	1.28		5
5	4	1	0	6	7	2	3	3	3	2	23	2	1	7	4	22	5	1.89	-0.98	
5	4	2	0	7	7	3	3	3	3	2	23	2	1	7	4	22	5	1.89	-1.71	5
5	4	3	29.92	7	7	3	3	3	3	2	23	2	1	7	4	22	5	2.21	0.17	6
6	1	1	37.4	3	4	3	3	0	0	2	23	2	1	7	5	26	4	2.28	0.62	5
6	1	2	37.4	2	5	2	2	0	0	2	23	2	1	7	5	26	4	0.67	2.47	3
6	1	3	37.4	0	5	0	1	0	0	2	23	2	1	7	5	26	4	1.71	0.91	0
6	2	1	29.92	2	3	0	0	0	0	2	23	2	1	7	5	26	4	1.45	0.68	1
6	2	2	37.4	2	4	0	0	0	0	2	23	2	1	7	5	26	4	2.41	1.65	1
6	2	3	37.4	4	4	0	0	0	1	2	23	2	1	7	5	26	4	0.77	1.74	1
6	3	1	33.66	0	3	0	0	1	2	2	23	2	1	7	5	26	4	0.91		-1
6	3	2	41.14	3	6	0	0	0	2	2	23	2	1	7	5	26	4	0.91	0.98	-1

6	3	3	37.4	2	4	0	0	0	3	2	23	2	1	7	5	26	4	0.68	0.57	-1
6	4	1	33.66	3	4	0	1	0	3	2	23	2	1	7	5	26	4	0.72	-0.79	-2
6	4	2	33.66	4	4	0	0	0	3	2	23	2	1	7	5	26	4	1.05	1.15	-1
6	4	3	41.14	3	4	0	0	0	1	2	23	2	1	7	5	26	4	1.63		-2
7	1	1	48.62	6	7	3	3	1	3	2	20	1	1	5	2	56	11	1.12	0.96	7
7	1	2	59.84	6	7	2	3	0	1	2	20	1	1	5	2	56	11	1.42	1.12	5
7	1	3	71.06	2	6	2	2	0	2	2	20	1	1	5	2	56	11	0.98	1.25	5
7	2	1	29.92	0	6	0	2	0	3	2	20	1	1	5	2	56	11	0.39	0.81	1
7	2	2	41.14	1	6	2	2	0	0	2	20	1	1	5	2	56	11	0.91		4
7	2	3	48.62	0	4	0	3	0	1	2	20	1	1	5	2	56	11	0.71		2
7	3	1	7.48	0	0	0	0	0	0	2	20	1	1	5	2	56	11	1.02	-0.01	2
7	3	2	11.22	0	0	0	2	0	2	2	20	1	1	5	2	56	11	1.33	0.85	2
7	3	3	22.44	0	0	0	1	0	2	2	20	1	1	5	2	56	11	1.07	0.52	5
7	4	1	0	0	1	0	2	0	3	2	20	1	1	5	2	56	11	2.30		2
7	4	2	14.96	0	1	0	2	0	3	2	20	1	1	5	2	56	11	1.67	-0.23	0
7	4	3	0	0	0	0	0	1	3	2	20	1	1	5	2	56	11	1.33	-0.02	0
8	1	1	0	3	6	1	1	0	2	2	22	1	2	6	2	12	2	6.42		3
8	1	2	0	4	7	1	1	1	2	2	22	1	2	6	2	12	2	2.91	1.16	3
8	1	3	0	7	7	2	2	3	3	2	22	1	2	6	2	12	2	1.78	0.61	2
8	2	1	41.14	1	5	1	1	0	0	2	22	1	2	6	2	12	2	-0.75	0.56	2
8	2	2	33.66	1	3	2	2	0	0	2	22	1	2	6	2	12	2	4.45	2.07	2
8	2	3	33.66	5	6	2	2	1	3	2	22	1	2	6	2	12	2	5.40	0.65	4
8	3	1	3.74	4	5	2	2	0	1	2	22	1	2	6	2	12	2	3.96	0.8	
8	3	2	3.74	2	5	2	2	1	2	2	22	1	2	6	2	12	2	3.80	0.94	
8	3	3	3.74	3	5	2	2	2	3	2	22	1	2	6	2	12	2	3.83	1.63	0
8	4	1	0	5	7	2	2	3	3	2	22	1	2	6	2	12	2	3.01		3
8	4	2	0	6	7	2	3	3	3	2	22	1	2	6	2	12	2	2.78	-0.48	3
8	4	3	0	6	7	2	2	3	3	2	22	1	2	6	2	12	2	3.19	1.54	1
9	1	1	14.96	4	5	0	3	2	3	1	20	1	3	7	5	21	8	1.66	0.99	
9	1	2	18.7	3	5	3	3	3	3	1	20	1	3	7	5	21	8	1.66	1.22	
9	1	3	7.48	5	5	1	1	3	3	1	20	1	3	7	5	21	8	1.96	0.61	
9	2	1	3.74	3	6	2	3	2	3	1	20	1	3	7	5	21	8	2.58	0.96	-1
9	2	2	3.74	5	6	1	1	3	3	1	20	1	3	7	5	21	8	2.76		-2
9	2	3	3.74	4	6	1	1	3	3	1	20	1	3	7	5	21	8	3.07	0.54	-2
9	3	1	11.22	3	5	1	2	3	3	1	20	1	3	7	5	21	8	2.03	0.97	-1
9	3	2	11.22	4	6	1	1	3	3	1	20	1	3	7	5	21	8	1.91	0.63	-1
9	3	3	14.96	5	6	1	1	3	3	1	20	1	3	7	5	21	8	0.70	0.71	-1
9	4	1	0	5	7	1	2	3	3	1	20	1	3	7	5	21	8	1.77	0.57	-2
9	4	2	3.74	6	7	1	1	3	3	1	20	1	3	7	5	21	8	1.36	0.52	-2
9	4	3	0	6	7	1	1	3	3	1	20	1	3	7	5	21	8			-2

Table C.2. Table of data for Multiple Exposures.
Blank cells indicate unavailable data.

C. 2 Experiment data for effect of passive haptics on presence in virtual environments

Data for the experiment Effect of Passive Haptics on Presence in Virtual Environments (Passive Haptics).

Subject	Session	Condition	Simulator Sickness	Reported Presence [m 6]	Reported Presence [m 5]	Reported Behavioral Presence [O6]	Reported Behavioral Presence [m 5]	Reported Ease of Locomotion [m 6]	Reported Ease of Locomotion [m 5]	Association with Virtual Body	Gender (1=male, 2=female)	Age	Race	University Status	Virtual Environment Experience	Computer Usage	Computer Game Experience	ΔHeart Rate	ΔSkin Conductance Level	ΔSkin Temperature	Height Anxiety	Height Avoidance	Observed Behavioral Presence
10	1	1	0	5	7	3	3	0	3	6	1	21	2	1	1	7	6	4.36	4.84	2.90	31	10	8
10	2	0	0	4	6	3	3	3	3	6	1	21	2	1	1	7	6	3.06	6.56	0.37	31	10	0
11	1	1	14.96	1	5	1	1	2	2	5	1	20	5	1	1	5	1	8.55	6.03	1.07	3	1	6
11	2	0	22.44	0	3	0	0	2	2	2	1	20	5	1	1	5	1	7.51	5.26	0.83	3	1	1
14	1	1	7.48	4	5	2	3	0	2	6	2	18	2	1	1	7	4	12.88	7.65	0.33			6
14	2	0	7.48	0	4	0	1	0	0	3	2	18	2	1	1	7	4	7.70	7.21	0.39			5
15	1	1	3.74	2	5	0	1	2	3	2	1	22	5	1	1	6	6	2.77	7.10	0.18	18	0	5
15	2	0	0	2	3	0	1	2	2	2	1	22	5	1	1	6	6	1.84	3.79	0.47	18	0	2
16	1	0	89.76	6	6	3	3	2	3	7	2	22	4	1	1	7	3	7.87	7.21	0.73	47	11	5
16	2	1	7.48	1	5	0	1	3	3	5	2	22	4	1	1	7	3	10.29	5.77	-0.17	47	11	2
17	1	1	0	0	1	3	3	0	1	1	2	45	5	7	1	3	1	17.36	6.16	3.64	9	5	4
17	2	0	0	0	0	1	2	2	2	1	2	45	5	7	1	3	1	21.61	5.23	2.49	9	5	0
18	1	1	44.88	4	5	2	2	3	3	3	2	27	4	7	1	5	2		13.96		10	2	4
18	2	0	18.7	7	7	2	3	3	3	5	2	27	4	7	1	5	2		12.19		10	2	5
19	1	1	26.18	3	5	1	2	1	3	4	2	18	2	1	1	7	2	6.79	6.92	0.50	16	2	7
19	2	0	11.22	0	5	0	0	2	3	5	2	18	2	1	1	7	2	4.15	6.23	1.81	16	2	0
20	1	0	0	5	7	3	3	3	3	7	2	19	5	1	1	7	3	9.51	3.74	0.14	7	6	3
20	2	1	0	5	7	3	3	3	3	6	2	19	5	1	1	7	3	0.93	12.15	0.20	7	6	6
21	1	0	22.44	5	7	1	1	3	3	5	1	20	5	1	4	7	7	7.05			40	1	4
21	2	1	0	6	7	0	3	2	3	4	1	20	5	1	4	7	7	11.06			40	1	13
22	1	0	14.96	2	3	0	0	1	2	3	1	19	5	1	1	7	2	6.19	1.84	0.30	11	0	-1
22	2	1	3.74	1	3	0	1	0	2	3	1	19	5	1	1	7	2	9.02	2.16	0.22	11	0	3
23	1	0	3.74	7	7	1	1	2	3	5	1	20	5	1	2	7	4	4.91	1.98	1.58	8	0	1
23	2	1	0	7	7	3	3	2	3	5	1	20	5	1	2	7	4	9.65	2.50	1.08	8	0	3
27	1	0	37.4	1	5	1	2	0	0	2	1	22	5	1	1	6	3	1.48	5.38	0.85	18	6	5
27	2	1	26.18	0	1	0	0	1	2	2	1	22	5	1	1	6	3	4.25	4.68	1.50	18	6	5
28	1	0	33.66	5	7	2	3	1	2	4	1	19	5	1	4	7	7	-0.34	6.41	3.39	56	2	1

28	2	1	44.88	5	5	1	1	1	1	5	1	19	5	1	4	7	7	5.11	5.30	0.77	56	2	-1
29	1	0	3.74	5	7	1	2	1	3	3	1	19	5	1	1	6	1	0.51	4.03	3.31	10	0	0
29	2	1	7.48	5	7	2	3	1	3	4	1	19	5	1	1	6	1	0.78	6.00	3.33	10	0	1
30	1	0	3.74	5	7	1	3	3	3	4	1	22	5	1	2	5	5	2.92	4.21	1.14	18	2	3
30	2	1	3.74	3	6	2	2	2	3	4	1	22	5	1	2	5	5	7.96	4.77	1.87	18	2	4
31	1	1	11.22	0	2	0	1	3	3	3	1	19	5	1	1	6	3	16.70	9.14	0.82	11	2	
31	2	0	18.7	0	0	0	1	2	2	1	1	19	5	1	1	6	3	7.51	7.30	0.41	11	2	
33	1	0	0	5	7	2	3	3	3	5	1	20	5	1	1	7	6	-2.45	5.16	0.58	0	1	1
33	2	1	7.48	4	7	2	3	3	3	5	1	20	5	1	1	7	6	20.56	7.84	-0.17	0	1	2
34	1	1	0	6	7	3	3	0	1	3	1	21	5	1	1	6	1	1.10	5.63	0.97	8	2	
34	2	0	11.22	4	5	0	0	2	3	4	1	21	5	1	1	6	1	-1.50	6.14	5.08	8	2	
35	1	1	7.48	0	5	2	2	0	2	5	2	20	2	1	1	6	5	7.56	4.14	1.47	50	13	5
35	2	0	7.48	1	3	1	2	2	2	4	2	20	2	1	1	6	5	9.17	3.16	1.78	50	13	2
36	1	0	22.44	1	6	1	1	2	3	6	1	19	5	1	2	7	2	10.80	4.11	0.65	4	0	2
36	2	1	26.18	0	4	0	1	1	2	2	1	19	5	1	2	7	2	7.74	5.06	0.29	4	0	2
37	1	1	0	2	6	1	1	3	3	6	1	20	5	1	1	5	6	6.60	7.47	1.33	18	1	4
37	2	0	3.74	0	2	0	0	1	3	5	1	20	5	1	1	5	6	7.27	4.32	2.42	18	1	-2
38	1	1	0	0	4	2	2	2	2	4	1	19	6	1	1	7	5	10.50	1.06	2.64	23	11	1
38	2	0	0	2	4	1	2	2	2	6	1	19	6	1	1	7	5	6.04	2.18	0.50	23	11	2
39	1	1	3.74	1	5	0	1	2	3	3	2	19	5	1	1	7	1	27.70	2.46	0.97	17	3	
39	2	0	18.7	2	4	1	2	1	2	2	2	19	5	1	1	7	1	2.14	2.57	0.62	17	3	
40	1	0	0	1	3	1	1	2	3	3	1	21	5	1	1	7	5	-3.07	5.60	1.32	5	0	2
40	2	1	0	2	4	1	1	2	2	2	1	21	5	1	1	7	5	-0.40	2.49	-0.01	5	0	11
41	1	1	18.7	1	5	2	2	1	1	2	2	19	3	1	1	7	6	-5.41	4.72	0.45	38	7	0
41	2	0	7.48	0	1	0	2	0	0	2	2	19	3	1	1	7	6	-10.46	11.84	0.15	38	7	-2
42	1	0	0	4	5	0	1	3	3	5	1	18	5	1	1	7	2		2.71	0.91	0	0	1
42	2	1	0	2	4	1	2	3	3	5	1	18	5	1	1	7	2		8.85	1.67	0	0	2
43	1	1	11.22	3	5	3	3	3	3	4	1	21	5	1	1	7	1	9.66	2.93	-3.57	49	15	
43	2	0	22.44	4	7	3	3	1	3	4	1	21	5	1	1	7	1	0.39	1.22	0.29	49	15	
44	1	1	7.48	4	6	2	3	0	3	6	1	19	5	1	1	3	6	-12.37	2.95	1.08	33		7
44	2	0	3.74	4	6	2	2	1	3	5	1	19	5	1	1	3	6	1.03	2.72	2.20	33		3
45	1	1	3.74	2	5	3	3	0	1	3	1	20	5	1	1	6	3	6.40	6.88	2.28	10	1	
45	2	0	0	0	0	0	0	0	0	3	1	20	5	1	1	6	3	2.78	3.61	3.07	10	1	
46	1	1	0	5	6	3	3	3	3	6	1	18	3	1	1	7	4	9.71	2.92	0.68	17	5	
46	2	0	0	6	6	1	2	3	3	5	1	18	3	1	1	7	4	4.77	2.73	1.33	17	5	
48	1	0	26.18	6	6	2	3	3	3	5	1	22	2	1	1	7	4	9.73	7.27	1.39	22	4	
48	2	1	0	7	7	3	3	3	3	6	1	22	2	1	1	7	4	10.83	7.76	-1.07	22	4	
49	1	1	3.74	0	2	1	1	2	2	3	2	21	5	1	2	7	1	9.38	1.72	2.66	37	6	2
49	2	0	11.22	0	0	0	0	0	0	1	2	21	5	1	2	7	1	3.86	6.17	0.98	37	6	-1
50	1	0	7.48	1	4	2	3	0	2	6	1	28	5	7	2	6	4	8.17	2.35	0.82	17	6	4
50	2	1	0	4	7	2	3	2	3	6	1	28	5	7	2	6	4	12.03	4.25	0.31	17	6	0
51	1	1	3.74	6	6	1	3	3	3	2	2	22	5	1	2	6	2	13.09	2.09	2.79	47	6	
51	2	0	0	2	4	1	1	1	3	2	2	22	5	1	2	6	2	5.91	3.22	2.16	47	6	
52	1	0	11.22	2	6	0	0	2	3	2	2	29	5	2	2	6	1	7.66			12	3	
52	2	1	7.48	1	4	0	0	2	2	3	2	29	5	2	2	6	1	0.51			12	3	
53	1	0	22.44	2	6	1	2	0	2	4	2	21	5	1	4	6	1	4.97	1.39	0.29	73	16	
53	2	1	26.18	3	6	2	2	0	3	4	2	21	5	1	4	6	1	12.43	2.41	0.28	73	16	
54	1	1	3.74	5	6	1	2	2	3	3	1	22	5	1	1	7	6		5.25	1.11	11	1	
54	2	0	0	0	4	1	1	2	2	3	1	22	5	1	1	7	6		3.02	2.11	11	1	

1.1.1.2

55	1	1	59.84	5	6	0	2	1	2	4	1	21	5	1	1	4	2	12.46	6.53	3.07	35	0	
55	2	0	41.14	3	4	0	0	1	1	2	1	21	5	1	1	4	2	9.00	2.26	2.16	35	0	
56	1	0	11.22	1	3	1	1	0	0	3	1	21	5	1	1	5	2		5.66	0.54	5	0	
56	2	1	3.74	0	4	2	2	0	0	2	1	21	5	1	1	5	2		5.04	0.63	5	0	
57	1	0	0	4	7	1	1	3	3	5	1	27	5	2	1	5	5	4.59	1.63	1.24	12	4	1
57	2	1	0	7	7	2	3	3	3	3	1	27	5	2	1	5	5	3.17	3.92	1.82	12	4	7
58	1	0	0	4	6	2	2	3	3	5	1	19	5	1	6	7	7		4.72	1.02	4	2	0
58	2	1	0	7	7	2	2	3	3	6	1	19	5	1	6	7	7		3.53	-0.75	4	2	3
61	1	0	7.48	4	7	0	1	3	3	2	2	20	5	1	1	4	3	13.27	2.72	-0.30	10	1	
61	2	1	7.48	0	2	0	0	2	3	2	2	20	5	1	1	4	3	9.35	2.71	-1.75	10	1	
62	1	0	11.22	3	4	1	1	1	2	3	2	20	5	1	1	7	1	2.42	9.11	-0.80	18	2	
62	2	1	18.7	3	5	0	2	0	1	3	2	20	5	1	1	7	1	5.71	6.11	0.69	18	2	
63	1	0	0	5	6	1	2	0	3	5	1	23	5	1	1	3	3	-5.43	4.14	0.95	2	0	2
63	2	1	0	5	7	1	1	0	3	5	1	23	5	1	1	3	3	3.24	9.36	0.75	2	0	3
64	1	0	0	0	1	0	1	2	3	4	1	21	5	1	2	6	4	1.84	2.69	1.20	0	1	0
64	2	1	7.48	0	0	1	1	2	2	5	1	21	5	1	2	6	4	3.30	3.63	0.46	0	1	1
65	1	1	7.48	5	7	1	1	1	2	4	1	19	5	1	2	6	2	9.58	4.22	1.54	11	3	
65	2	0	3.74	5	7	1	1	0	3	3	1	19	5	1	2	6	2	7.47	3.75	1.50	11	3	
66	1	1	11.22	2	3	3	3	0	1	4	1	19	2	1	1	7	6	3.83	5.17	0.44	21	5	
66	2	0	3.74	0	3	2	3	0	0	4	1	19	2	1	1	7	6	2.33	3.35	0.40	21	5	
67	1	1	3.74	6	7	1	2	2	3	6	1	18	2	1	5	5	4		4.01	1.38	0	0	
67	2	0	0	6	7	2	2	3	3	6	1	18	2	1	5	5	4		3.20	0.43	0	0	
68	1	0	11.22	1	4	1	2	3	3	6	2	22	2	1	1	6	2	7.18	2.04	0.73	20	0	
68	2	1	3.74	5	6	2	2	3	3	7	2	22	2	1	1	6	2	13.29	1.20	-2.00	20	0	
69	1	1	0	7	7	2	3	3	3	7	1	20	5	1	1	7	3	-2.85	3.75	1.22	0	1	
69	2	0	3.74	7	7	1	1	3	3	7	1	20	5	1	1	7	3	18.14	1.84	1.53	0	1	
70	1	1	14.96	1	3	2	3	1	2	2	1	21	6	1	1	6	2	12.89	5.03	0.49	11	2	
70	2	0	11.22	1	1	1	1	1	2	2	1	21	6	1	1	6	2	3.61	3.60	3.11	11	2	

Table C.3. Table of data for Passive Haptics.
Blank cells indicate unavailable data.

C. 3 Experiment data for effect of frame rate on presence in virtual environments

Data for the experiment Effect of Frame Rate on Presence in Virtual Environments (Frame Rate).

Subject	Task	Condition	Simulator Sickness	Reported Presence [m 6]	Reported Presence [m 5]	Reported Behavioral Presence [m 6]	Reported Behavioral Presence [m 5]	Reported Ease of Locomotion [m 6]	Reported Ease of Locomotion [❍5]	Association with Virtual Body	Gender (1=male, 2=female)	Age	Race	University Status	Virtual Environment Experience	Computer Usage	Computer Game Experience	ΔHeart Rate	ΔSkin Conductance Level	ΔSkin Temperature	Height Anxiety	Height Avoidance	Los of Balance on Ledge	Observed Behavioral Presence
10	1	30	29.92	7	7	2	3	3	3	7	1	22	5	1	1	7	2	10.56	2.63	2.88	13	1	0	2
10	2	10	33.66	7	7	2	2	3	3	7	1	22	5	1	1	7	2	5.98	3.80	1.98	13	1	0	1
10	3	20	33.66	7	7	2	2	3	3	7	1	22	5	1	1	7	2	3.22	2.40	0.99	13	1	0	1
10	4	15	37.4	7	7	2	2	3	3	7	1	22	5	1	1	7	2	7.22	1.94	1.18	13	1	1	1
11	1	30	0	1	6	2	2	0	3	5	1	34	5	2	1	6	2	6.43	0.07	0.51	14	3	0	2
11	2	10	0	0	5	2	3	1	3	5	1	34	5	2	1	6	2	8.83	0.03	0.55	14	3	1	5
11	3	20	0	0	0	0	1	0	1	3	1	34	5	2	1	6	2	0.31	-0.09	0.85	14	3	0	2
11	4	15	0	0	0	0	0	0	3	2	1	34	5	2	1	6	2	6.86	-0.08	0.40	14	3	0	3
12	1	30	11.22	1	4	1	3	1	3	3	1	24	5	2	3	5	2	9.16	0.41	1.58	14	1	0	
12	2	10	18.7	0	5	3	3	0	2	5	1	24	5	2	3	5	2	13.47	-0.08	0.47	14	1	0	
12	3	20	14.96	4	7	1	2	0	1	6	1	24	5	2	3	5	2	12.18	-0.12	0.34	14	1	0	
12	4	15	18.7	2	5	0	2	2	3	6	1	24	5	2	3	5	2	8.61	-0.14	0.80	14	1	0	
13	1	30	18.7	7	7	2	2	1	2	6	1	23	3	2	1	6	6	34.12	0.90	1.13	63	12	0	4
13	2	10	26.18	7	7	2	2	1	2	7	1	23	3	2	1	6	6	9.82	0.94	0.84	63	12	0	2
13	3	20	22.44	7	7	2	2	3	3	7	1	23	3	2	1	6	6	8.67	1.12	0.93	63	12	0	2
13	4	15	18.7	7	7	2	2	2	3	7	1	23	3	2	1	6	6	-0.09	1.41	0.56	63	12	0	2
19	1	30	48.62	6	7	2	3	3	3	3	1	20	2	1	4	7	6	10.59	2.46	1.09	57	9	0	6
19	2	10	93.5	0	0	0	2	2	3	2	1	20	2	1	4	7	6	6.51	-0.13	0.85	57	9	0	4
19	3	20	71.06	1	5	3	3	2	3	2	1	20	2	1	4	7	6	3.57	-0.27	1.47	57	9	0	4
19	4	15	71.06	2	4	2	3	2	3	2	1	20	2	1	4	7	6	3.63	0.24	0.58	57	9	0	3
20	1	30	3.74	3	7	2	3	2	3	6	1	20	3	1	2	6	7	7.50	1.39	1.68	38	7	0	4
20	2	15	3.74	5	7	0	3	3	3	6	1	20	3	1	2	6	7	2.99	1.06	1.32	38	7	0	3
20	3	10	14.96	4	7	2	2	2	3	5	1	20	3	1	2	6	7	2.08	1.46	1.39	38	7	0	4
20	4	20	3.74	3	7	3	3	3	3	6	1	20	3	1	2	6	7	4.53	1.87	0.83	38	7	0	6
21	1	30	7.48	2	5	1	2	1	1	4	1	21	5	1	1	7	2	7.92	1.96	1.62	4	0	0	2
21	2	15	3.74	4	7	2	2	1	2	5	1	21	5	1	1	7	2	7.46	1.80	0.58	4	0	0	0
21	3	10	3.74	7	7	2	2	2	3	6	1	21	5	1	1	7	2	12.01	1.14	1.05	4	0	0	1
21	4	20	3.74	7	7	1	1	3	3	5	1	21	5	1	1	7	2	26.35	1.50	3.14	4	0	0	-1

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22	1	30	7.48	6	6	2	2	3	3	7	2	24	5	2	1	7	1	8.92	1.66	0.73	5	1	0	1
22	2	15	3.74	7	7	1	2	3	3	6	2	24	5	2	1	7	1	6.88	0.90	0.44	5	1	0	2
22	3	10	3.74	7	7	2	2	3	3	7	2	24	5	2	1	7	1	7.98	1.14	0.45	5	1	0	1
22	4	20	3.74	7	7	2	2	3	3	7	2	24	5	2	1	7	1	8.43	1.27	0.54	5	1	0	1
23	1	30	22.44	1	7	1	3	0	3	4	2	20	5	1	1	6	2	9.41	4.22	0.67	18	5	0	2
23	2	15	33.66	6	7	1	2	1	3	5	2	20	5	1	1	6	2	13.67	4.00	1.15	18	5	0	1
23	3	10	44.88	7	7	2	3	1	3	5	2	20	5	1	1	6	2	15.44	4.69	1.23	18	5	1	2
23	4	20	52.36	7	7	3	3	3	3	5	2	20	5	1	1	6	2	12.83	4.85	0.95	18	5	1	3
30	1	20	26.18	4	6	3	3	3	3	4	1	20	5	1	1	7	4	27.75	8.48	1.53	18	4	0	2
30	2	30	18.7	3	5	1	2	3	3	5	1	20	5	1	1	7	4	15.65	7.25	0.55	18	4	0	2
30	3	15	7.48	2	5	0	1	3	3	5	1	20	5	1	1	7	4	10.73	5.35	0.54	18	4	0	1
30	4	10	7.48	5	7	1	3	3	3	5	1	20	5	1	1	7	4	15.24	6.97	0.30	18	4	1	3
31	1	20	7.48	5	7	2	3	3	3	5	2	22	5	1	1	7	1	6.92	1.49	0.49	0	0	0	0
31	2	30	7.48	7	7	3	3	3	3	5	2	22	5	1	1	7	1	18.83	3.38	0.43	0	0	0	1
31	3	15	7.48	7	7	2	2	3	3	5	2	22	5	1	1	7	1	3.22	3.48	0.43	0	0	0	1
31	4	10	7.48	7	7	2	2	3	3	6	2	22	5	1	1	7	1	4.65	2.61	0.38	0	0	0	2
32	1	20	3.74	3	5	0	1	3	3	3	1	18	2	1	1	7	3	1.80	2.13	0.46	29	3	0	5
32	2	30	3.74	2	5	0	1	3	3	6	1	18	2	1	1	7	3	1.05	3.98	0.49	29	3	0	4
32	3	15	3.74	1	6	0	0	3	3	6	1	18	2	1	1	7	3	0.71	2.71	0.59	29	3	1	4
32	4	10	3.74	2	6	0	0	2	3	5	1	18	2	1	1	7	3	1.82	2.16	1.34	29	3	0	3
33	1	10	0	0	2	1	1	1	2	7	1	20	2	1	3	7	6	2.97	2.06	0.87	21	2	0	2
33	2	20	0	0	1	0	1	3	3	6	1	20	2	1	3	7	6	3.20	1.72	0.07	21	2	0	0
33	3	15	0	0	1	0	0	3	3	4	1	20	2	1	3	7	6	1.30	2.83	0.46	21	2	0	1
33	4	30	7.48	0	1	0	0	3	3	4	1	20	2	1	3	7	6	3.68	3.25	0.86	21	2	0	2
40	1	10	14.96	2	4	2	3	1	2	7	1	21	5	1	2	3	6	6.14	3.43	0.64	15	4	1	3
40	2	20	3.74	2	6	1	3	1	3	6	1	21	5	1	2	3	6	4.07	1.74	1.08	15	4	0	2
40	3	15	0	2	6	3	3	2	3	6	1	21	5	1	2	3	6	-1.15	2.33	0.46	15	4	1	3
40	4	30	11.22	0	4	1	3	2	3	6	1	21	5	1	2	3	6	2.39	1.39	0.19	15	4	0	3
41	1	10	3.74	0	2	0	1	0	0	6	1	21	5	1	2	6	4	7.51	3.44	0.70	51	3	1	3
41	2	20	7.48	0	3	0	0	0	1	5	1	21	5	1	2	6	4	3.14	3.65	0.82	51	3	0	2
41	3	15	7.48	0	0	0	1	0	3	6	1	21	5	1	2	6	4	-0.43	2.18	0.45	51	3	0	1
41	4	30	18.7	0	2	0	0	0	3	6	1	21	5	1	2	6	4	-0.03	1.19	1.18	51	3	0	1
42	1	10	11.22	5	6	2	3	0	1	2	2	23	5	2	1	6	1	19.37	3.28	0.71	7	0	1	1
42	2	20	11.22	3	5	0	1	2	3	2	2	23	5	2	1	6	1	2.99	0.13	1.29	7	0	0	-2
42	3	15	18.7	3	6	0	0	2	2	1	2	23	5	2	1	6	1	2.81	2.65	0.63	7	0	1	-1
42	4	30	11.22	0	4	0	1	3	3	1	2	23	5	2	1	6	1	2.29	2.63	0.21	7	0	0	-2
43	1	20	18.7	5	6	2	2	2	2	6	2	21	2	1	1	6	2	0.01	0.43	0.80	29	5	0	6
43	2	30	22.44	6	7	2	2	2	2	6	2	21	2	1	1	6	2	8.84	0.30	0.70	29	5	1	7
43	3	15	11.22	7	7	2	2	3	3	7	2	21	2	1	1	6	2	-2.86	0.06	1.09	29	5	0	7
43	4	10	11.22	7	7	2	2	3	3	7	2	21	2	1	1	6	2	2.99	0.35	0.71	29	5	0	7
50	1	20	0	3	7	1	2	2	3	5	1	22	5	1	1	6	5	5.22	0.78	1.15	10	0	0	
50	2	10	0	0	6	1	3	1	3	4	1	22	5	1	1	6	5	3.76	0.11	0.69	10	0	0	
50	3	30	0	0	7	1	3	3	3	5	1	22	5	1	1	6	5	5.04	0.23	0.99	10	0	0	
50	4	15	0	0	5	1	2	2	3	5	1	22	5	1	1	6	5	-1.87	-0.13	0.55	10	0	0	
51	1	20	11.22	3	6	2	2	0	0	6	2	23	5	1	1	6	1	-0.29	1.50	0.41	48	10	0	3
51	2	10	18.7	5	7	1	1	0	0	5	2	23	5	1	1	6	1	5.04	3.12	0.75	48	10	0	3
51	3	30	18.7	6	7	1	3	0	3	6	2	23	5	1	1	6	1	3.25	2.23	0.53	48	10	0	3
51	4	15	18.7	7	7	1	1	3	3	6	2	23	5	1	1	6	1	3.16	1.89	0.39	48	10	0	3
52	1	20	11.22	7	7	3	3	2	3	6	1	20	5	1	1	7	6	3.30	2.97	1.38	27	2	0	3

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52	2	10	11.22	6	7	3	3	3	3	6	1	20	5	1	1	7	6	1.90	2.08	1.13	27	2	0	1
52	3	30	14.96	7	7	3	3	3	3	7	1	20	5	1	1	7	6	0.62	1.32	1.05	27	2	0	2
52	4	15	14.96	7	7	3	3	3	3	7	1	20	5	1	1	7	6	0.23	1.18	0.81	27	2	0	0
53	1	20	11.22	4	6	2	2	2	3	4	1	23	2	2	2	5	5	6.95	-0.28	0.51	32	4	0	0
53	2	10	14.96	3	7	3	3	1	3	5	1	23	2	2	2	5	5	2.35	0.10	0.49	32	4	0	0
53	3	30	18.7	3	7	2	3	2	3	4	1	23	2	2	2	5	5	7.79	-0.39	0.34	32	4	0	1
53	4	15	18.7	1	3	0	0	3	3	2	1	23	2	2	2	5	5	4.14	0.92	0.66	32	4	0	0
60	1	15	18.7	2	4	1	3	0	1	2	1	22	5	1	1	2	1	-0.20	10.98	2.12	16	2	0	2
60	2	20	14.96	2	5	1	3	2	3	4	1	22	5	1	1	2	1	-1.41	8.05	0.39	16	2	0	1
60	3	10	18.7	1	4	1	2	2	3	4	1	22	5	1	1	2	1	-1.23	5.92	1.89	16	2	0	1
60	4	30	11.22	2	6	1	2	2	3	3	1	22	5	1	1	2	1	1.57	8.03	0.68	16	2	0	2
61	1	15	14.96	1	1	0	0	0	1	4	2	21	3	1	1	6	1	-3.23	1.25	1.32	51	5	0	4
61	2	20	14.96	0	0	0	0	0	0	1	2	21	3	1	1	6	1	4.44	0.19	0.60	51	5	0	4
61	3	10	18.7	0	0	0	0	0	0	1	2	21	3	1	1	6	1	2.55	0.06	0.83	51	5	0	4
61	4	30	14.96	0	0	1	1	0	1	2	2	21	3	1	1	6	1	1.07	-0.10	0.87	51	5	0	3
62	1	15	7.48	3	6	0	1	3	3	5	1	20	5	1	2	6	5	12.91	3.62	0.60	17	2	0	0
62	2	20	3.74	3	6	1	2	2	3	4	1	20	5	1	2	6	5	16.53	3.47	0.54	17	2	0	0
62	3	10	7.48	5	6	1	1	1	3	6	1	20	5	1	2	6	5	5.80	3.41	0.76	17	2	0	0
62	4	30	7.48	2	6	1	1	3	3	5	1	20	5	1	2	6	5	2.85	4.20	0.58	17	2	0	0
63	1	15	0	1	4	2	3	0	0	2	1	30	5	2	1	6	1	0.93	5.61	0.58	24	1	0	7
63	2	20	0	3	5	2	3	0	0	2	1	30	5	2	1	6	1	2.73	3.29	0.29	24	1	0	2
63	3	10	3.74	0	0	1	1	0	0	4	1	30	5	2	1	6	1	3.76	4.21	0.36	24	1	0	2
63	4	30	7.48	0	2	1	3	0	0	3	1	30	5	2	1	6	1	5.57	3.02	0.14	24	1	0	3
70	1	10	26.18	4	4	3	3	2	2	5	1	21	2	1	1	7	4	10.54	1.80	0.87	54	15	0	5
70	2	15	26.18	5	5	2	2	2	2	5	1	21	2	1	1	7	4	11.18	-0.03	1.53	54	15	0	3
70	3	30	29.92	4	4	3	3	3	3	6	1	21	2	1	1	7	4	10.20	-0.19	0.31	54	15	0	2
70	4	20	29.92	4	5	2	2	3	3	6	1	21	2	1	1	7	4	11.08	-0.23	0.31	54	15	0	2
71	1	10	14.96	0	4	1	1	0	0	4	1	22	3	1	2	6	1	14.67	3.99	0.58	59	6	0	2
71	2	15	14.96	0	0	0	0	0	2	3	1	22	3	1	2	6	1	11.48	1.50	0.34	59	6	0	1
71	3	30	11.22	1	5	1	1	2	3	4	1	22	3	1	2	6	1	11.61	0.14	0.59	59	6	0	1
71	4	20	18.7	2	4	0	0	2	3	4	1	22	3	1	2	6	1	9.35	-0.12	0.92	59	6	0	1
72	1	10	26.18	5	6	2	2	1	2	4	1	21	3	1	1	7	2	9.08	2.23	1.54	25	3	1	5
72	2	15	52.36	5	7	2	2	2	3	2	1	21	3	1	1	7	2	10.27	0.20	0.23	25	3	0	7
72	3	30	52.36	6	7	2	2	0	3	2	1	21	3	1	1	7	2	7.50	-0.01	0.32	25	3	0	5
72	4	20	48.62	4	7	1	2	0	1	3	1	21	3	1	1	7	2	5.74	-0.02	0.56	25	3	0	3
73	1	10	3.74	1	2	0	2	2	3	4	1	33	4	2	1	7	2	5.02	0.46	1.41	15	5	0	3
73	2	15	3.74	1	2	1	2	2	3	4	1	33	4	2	1	7	2	5.40	0.82	0.63	15	5	0	3
73	3	30	0	0	1	1	2	2	2	2	1	33	4	2	1	7	2	5.09	1.30	0.55	15	5	0	3
73	4	20	0	1	2	1	2	2	3	3	1	33	4	2	1	7	2	7.54	1.20	0.80	15	5	0	3
80	1	15	11.22	2	5	1	2	0	2	2	1	20	5	1	2	7	5	7.77	1.94	0.55	8	0	0	2
80	2	30	26.18	1	4	0	1	0	0	1	1	20	5	1	2	7	5	4.89	1.38	1.14	8	0	0	3
80	3	20	37.4	0	0	0	0	0	0	2	1	20	5	1	2	7	5	-2.96	0.89	0.53	8	0	0	2
80	4	10	37.4	0	2	0	0	0	0	1	1	20	5	1	2	7	5	3.30	0.55	0.94	8	0	1	2
81	1	15	3.74	4	7	1	2	1	3	4	2	23	5	2	1	7	4	1.87	2.02	1.60	20	2	0	3
81	2	30	3.74	4	7	1	2	3	3	6	2	23	5	2	1	7	4	8.82	1.93	1.97	20	2	0	1
81	3	20	0	7	7	1	3	3	3	5	2	23	5	2	1	7	4	7.48	2.25	0.92	20	2	0	1
81	4	10	0	1	6	0	3	0	0	4	2	23	5	2	1	7	4	8.13	2.88	1.23	20	2	1	3
82	1	15	0	3	5	2	3	1	3	6	1	20	2	1	1	7	7	6.93	2.01	0.61	8	1	1	3
82	2	30	7.48	0	4	1	3	2	3	6	1	20	2	1	1	7	7	6.26	1.34	0.40	8	1	0	2

82	3	20	11.22	2	4	1	3	2	3	7	1	20	2	1	1	7	7	4.91	0.94	0.68	8	1	0	1
82	4	10	18.7	0	4	0	2	3	3	7	1	20	2	1	1	7	7	2.33	1.13	0.57	8	1	0	2
83	1	15	11.22	5	6	3	3	2	3	4	1	20	2	7	1	6	4	8.56	4.50	0.45	16	9	0	2
83	2	30	0	4	6	2	2	0	2	5	1	20	2	7	1	6	4	4.78	2.94	0.31	16	9	0	2
83	3	20	0	1	5	2	2	2	3	4	1	20	2	7	1	6	4	7.26	1.45	0.15	16	9	0	2
83	4	10	0	2	5	2	2	0	3	4	1	20	2	7	1	6	4	0.20	2.58	0.48	16	9	0	2

Table C.4. Table of data for Frame Rate.