Design of a Virtual Environment for Physiological and Subjective Monitoring of User Presence in VR

by

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Abstract

User presence is a natural construct of the human psyche that is central to VR development. If analyzed well, presence can indicate the effectiveness of VR settings on amplifying a user's sense of *'being'* in the environment. Consequently, allowing VR developers to save time and money. Several methods of measuring presence exist, and are classified as subjective or objective, with the latter being the most omnipresent. This paper discusses the process of designing a VR environment for subjective and objective presence measurement. The main physiological cue this study aims to inspect is grip-force, and its possible consistency with changes in other physiological responses, such as heart rate and respiratory response. In order to engender measurable variations in grip-force, the developed VE was designed to incorporate a gripping task for consistent grip-force feedback, and a virtual height stimulus to evoke objective physiological changes. The environment consisted of three stages: a training stage, a transition-to-stimulus stage, and a stimulus stage. Based on initial user testing, it was concluded that a virtual height situation with an environment disconnect between the training stage and the stimulus stage induced subjective stress.

Due to the COVID-19 outbreak, user testing was halted and we were unable to proceed with the experiment. We hope to resume our data collection once the outbreak ceases.

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I. Introduction

The rapid development of Virtual Reality (VR) has led to its prevalence in a panoply of applications grounded on the link between the virtual environment and the user interacting with it. Many engineers and researchers have utilized the concept of a user stepping into a three-dimensional (3D) virtual world for avenues such as entertainment, education, and therapy (Schuemie et al., 2001). For example, institutions have successfully integrated VR in rehabilitation for arachnophobia (Bouchard et al., 2006), public speaking (North et.al, 1998), and even for elderly populations for postural balance restoration (Chiarvono et al., 2015), proving VR to be a powerful tool for its applications.

When traced back to its earliest form, VR might have emerged for non-consumer applications such as displays for military and flight simulations (Lombard and Ditton, 1997). The first appearance of VR can be coined to the Ultimate Display in 1965 (Sutherland, 1965), albeit there were instances of stereoscopic consumer products that resulted in 3D illusions that VR can be regarded as a continuation for. Since the large advent of consumer-friendly head-mounted displays (HMD) like the Oculus Rift, HTC VIVE, and Windows Mixed Reality, the vast adoption of VR user experience development came along as a natural consequence. The readily available VR equipment facilitated the user-centric development of virtual environments across disciplines and increased efforts on how to optimally design a virtual environment.

As VR morphs the two major poles of “virtuality” and “reality”, the notion of the virtual environment (VE) as creating a sense of immersion and presence has become a key feature of virtual environments (Schwind et.al, 2019). This key characteristic of presence and immersion, which may be regarded as two different taxonomies (Slater, 2003), is what helps developers fathom the effectiveness of a virtual environment on users. In other words, we trouble ourselves with understanding presence because it is what enhances a VR experience, and can increase profitability for new technologies (Lombard and Ditton, 1997). In the context of VR, *user presence* is defined as a *transported sense of being* in the virtual landscape while being physically present in another (Schuemie et al., 2001).

Several common tools used to assess presence in VR are classified into three main groups: subjective measurements, behavioral measurements, and physiological measurements. Subjective measurement of presence can be achieved by means of standardized questionnaires given to the user proceeding VR exposure. Such questionnaires come in a myriad of flavors, but most omnipresent among them are Slater’s, Witmer and Singer’s, and IPQ. Behavioral measurements stem from analyzing user reactions to a VE. Whereas, objective physiological measurements are achieved by extrapolating results from physiological measures as validated results from standardized presence questionnaires. Several physiological measurements have been proposed as potential means for measuring the presence, such as heart rate, skin conductivity, and respiratory response (Meehan et al., 2002). However, significant changes in these measures often require sensitive medical equipment to be reliably detected. Consequently, due to the subjective nature of presence as the individual's perception of 'being' in the VE, presence questionnaires have emerged as a standard option for measuring presence.

In this study, we design a virtual environment around the notion of "grip force" as a new potential physiological measure for presence detection in VR. We illustrate the different stages the design process has progressed through, and future plans of testing the user's reported presence against changes in the environment's resolution, and the presence of feet in the virtual space. Participants of the study would also be asked to fill in presence questionnaires after each VR exposure, and results would be juxtaposed against objective measurement data.

II. Background

II.1 Presence & Immersion

Presence can be understood holistically as any mediated matter that provides the user with an experience that is “real,” “natural,” and “immediate” in reference to the ‘non-mediated world’ (Lombard and Ditton, 1997). Depending on the mediated channel, the degree to which presence is experienced can vary significantly. For example, non-interactive media like books and television are all instances that allow the user to feel presence, but to a lesser degree (Lombard and Ditton, 1997). VR distinguishes itself from other mediated forms through its multi-sensory involvement of the user (Schuemie et al., 2001). When a user steps into a VE through a head-mounted display, a 3D illusion of being in a new environment is achieved, and the user is capable of interacting with the virtual space through physical movement, sound, speech (Rickel and Johnson, 1999), and even smell (Serrano et al, 2016). There has been substantial literature discussing presence as a construct in a variety of research fields including psychology, cognitive science, and philosophy, in which its definition is often dictated by its applications within that specific field (Schuemie et al., 2001). Lombard and Ditton’s work (1997) is perhaps one of the earliest efforts to define presence across multiple disciplines. They describe presence through six different expositions of social richness, realism, transportation, immersion, social actor in medium, and a medium as a social actor (See Table 1). Today, presence can be generally understood as a three-dimensional construct of social presence, self- presence, and spatial presence.

Table 2.1: Summary of Lombard and Ditton’s six explications of the nature of presence

User-Presence in Virtual Environments	
Category	Description
Social Richness	The degree that the medium is perceived as intimate and warm
Realism	The degree at which events and objects are perceived as real
Transportation	The sensation of being there
Immersion	The degree of multi-sensory engagement in the medium

Social Actor in Medium	The extent of social interaction with a person figure in the medium
A Medium as Social Actor	The extent of social interaction with the medium (medium itself is seen as social)

For scholars in the field of communication, presence is often linked to Lombard and Ditton's first definition of social richness. In person-to-person interactions, the degree to which mediated and non-mediated contents are perceived as intimate, warm, or resonating with the other party becomes a key indicator of presence. Other social conceptualizations of presence in Lombard and Ditton's definition are related to presence as a social actor in the medium or as a medium as a social actor. The distinction between the former and the latter is that the latter is associated with the extent to which the user socially interacts with a 'person entity' in the space, while the former is related to the degree to which the space itself is regarded as a social agent. Generally, this definition of the social aspect of presence is referred to as social presence.

Another conceptualization of presence in Lombard and Ditton's definition is realism. Realism is mapped to how seemingly socially realistic objects and events are perceived through the media in question. Social realism, a nuanced version of realism, refers to the accuracy of mediated matter's representation of such cues according to experiences that the user regards as "real" in the non-mediated world. Self-presence, the second notable dimension of presence could be regarded as an extension of realism, as it is concerned with the user's perception of themselves in the VE as their actual selves (Tamborini and Skalski, 2006).

The Lambert and Ditton definition of presence as transportation refers to the capability of geographically sensing oneself and other objects in the medium. In the context of VR, presence is primarily coined to this. Lombard and Ditton's definition of "being there". That is, being teleported from the physical space to the virtual realm according to the subjective judgment of the user. It is important to note that other terms such as "co-presence" and "telepresence" surface alongside the definition of presence as transportation. "Co-presence" is a taxonomy reserved for instances where being in the virtual environment is done "together" with other entities (Schuemie et al., 2001). Whereas, "telepresence," which is a construct first defined by Minsky in 1980 (Minsky, 1980), is sometimes made more distinct by scholars, like Shreidan. According to Schreidan, presence stems from being in a computer-generated environment, while telepresence is a result of being in an actual remote location (Schreiden, 1992). For example, an instance of telepresence would be controlling a physical robot remotely through video, while an instance of presence would be interacting with an environment in VR. This definition of presence is often referred to as spatial presence.

It is important to note that scholars do not have a strict consensus on the nuanced definitions of presence in VR. Aside from Lambert and Ditton, scholars like Heeter distinguish presence on three different scales as personal, social, and environmental (Heeter, 1992), while Schloerb argues that presence is either subjective or objective (Schloerb, 1995). Fontaine, on the other hand, states that presence is all about the shift of one's focus.

Despite all these nuanced definitions, at their core, presence in VR stems from the subjective notion of a user's sensation of transportation to the virtual realm; whether the entity being transported is the user's focus, subconscious, or physical body.

Additionally, the term "immersion" is often used interchangeably with presence. One instance is Lombard and Ditton's identification of immersion as one of their six levels of presence. In Ditton and Lombard's explication, Immersion is coined to how much a user utilizes their senses in the environment. Other scholars, like Slater, defer to argue that presence and immersion are two separate taxonomies. Slater states that presence is a subjective measure of being in the virtual environment, whereas immersion is an objective description of the virtual environment's system such as resolution and field of view display (Slater, 2003). In this paper, we will be distinguishing between presence and immersion in accordance with Slater's definition.

II.2 Causes of Presence

There is substantial literature concerning the nature and sources of presence that span various fields. Regardless, we are primarily concerned with presence causes generated in VR.

A couple of channels have been proposed by scholars as sources of the construct based on empirical findings. While each scholar differs in their classifications of presence causes, the causes can be summed up as: characteristics of the system, and characteristics of the user in both the virtual and real realms.

In terms of system characteristics, scholars like Witmer and Singer, Usoh and Slater, Shreidan, and Lombard and Ditton all agree that the way information is displayed in the virtual environment can lead to presence when the information is presented in a rich, realistic and vivid sensorial means (Schuemie et al., 2001). One example that illustrates this is Usoh and Slater's finding that high-quality resolution and its consistency across all used displays create user presence in the environment (Slater and Usoh, 1993). Barfield and colleagues, also found a strong effect of update rate on user presence in a study conducted on eight subjects (Berfield et al., 1993). Additionally, Welch et al, found that realistic representation of pictures in the VE led to presence (Welch et al., 1996).

Another cause of presence that is related to the system's characteristics is the ability of the user to control the environment, and the degree of the environment's response to the user's modification in real-time. Such cause is known collectively as a virtual environment's interactivity and encompasses factors such as the response of the VE to Body movement (Slater et al., 1998), Head Tracking (Schubert et al., 2000), user's interaction (Welch et al., 1996), and feedback delay.

User characteristics are concerned with user portrayal in the VE and the user's personal tendencies in the real world. To further illustrate, Slater and Usoh (1993) have offered explanations on both. They describe the presence of a virtual body or avatar as one of the causes correlated with user presence in the virtual environment, and have experimentally established the effect of personal factors such as user field of dominance on presence in a VE. In their experiment, Usoh and Slater found that some participants had higher presence scores when auditory cues were added, while others had stronger visual preferences. These two findings were reflected in the users post-experience presence scores. By the same token, users have a tendency to interact differently to mediated forms from one another. For instance, some users have a higher tendency to suspend belief on the "realness of virtuality", while others don't. Bangay and Preston cement this notion through their study of a public VR ride on people around the age group of 10-20 and 35-45. Bangay and Preston found that the larger age group tended to score a lower presence score than the smaller age group (Bangay and Preston, 1998).

II.3 Importance of Presence

VR technology is becoming extremely ubiquitous these days. Despite the fact that VR was initially developed for military and flight simulations, the instances of VR have become characteristic of situations surpassing the realm they were first intended for. In medicine, doctors have utilized VR to train doctors on virtual surgeries (Ota et al., 1995), and have even used VR in rehabilitation for the elderly such as retrieving postural balance (Chiarvono et al., 2015). In the gaming industry, VR chat and VR games have also claimed their ways into consumer homes.

Being the central feature of VR environments that it is, presence is a natural construct of human psyche that allows us to gain insight on the effectiveness of a VR experience. If analyzed well, presence can indicate the causes of presence in a VE, what amplifies it, and what reduces it. Such analysis can help VR developers save time and money when it comes to developing virtual settings.

As far as the gaming industry is concerned, games are generally designed to manifest the sensation of “being there” in users. According to Tamborini and Skalski (2006), presence is a central determinant to explaining what captivates a person’s attention within the mediated realm. When a user feels “presence” in a video game or a VE, they would readily spend more time with the game resulting in increased game use, and consequently, the gaming industry’s profit (Tamborini and Skalski). Alongside this notion, the effect of user presence on enjoyment, especially in entertainment theory, has been closely scrutinized. And while a solid relationship between presence and enjoyment is yet to be scientifically established, entertainment theory states that it is certainly difficult to overlook the role of presence on user enjoyment in mediated channels (Tamborini and Skalski).

Additionally, in role-playing virtual experiences, spatial and self-presence (Section II.1) have been perceived to affect users' mental models in real life (Anderson and Dill, 2000). For example, violent games encourage aggressive behavior, and experiencing a virtual environment from a certain persona’s point of view can alter one’s perceptions on gender, self-portrayal, and even real-life decision-making skills (Anderson and Dill).

By the same token, altering mental models in clinical psychology was found extremely useful to treat phobia disorders such as arachnophobia, and fear of public speaking. Especially, since generating realistic environments that suspend user belief can aid users with overcoming certain anxieties.

II.4 Measuring Presence

Measuring presence is a pivotal means to gaining insight on the effectiveness of a virtual environment on the user. Presence can be measured in different ways through subjective standardized questionnaires, objective behavioral examination, and objective physiological measurements.

II.4.1 Subjective Measurement of Presence

Barfield and Warghof introduced one of the earliest means of measuring presence through questionnaires in 1993. They developed a 6 item questionnaire on a 1-7 Likert scale, for an experiment they conducted to measure the effect of varying a computer's update rate on users' sense of presence (Barfield and Warghof, 1993). Since then, other questionnaires have surfaced, and presence questionnaires have become the most omnipresent means of measuring presence. The advantage to using presence questionnaires is that the users can subjectively report their psychological response to a VR experience; what worked and what didn't work for them. However, the downturn is that because of the subjective nature of questionnaires, they are sometimes not entirely reliable. In recent years however, a couple of standardized questionnaires have been widely enforced for presence measurement.

The most commonly used validated questionnaires by presence researchers are Witmer and Singer, Slater Usoh Steed, and IPQ. These questionnaires differ in their set of questions based on their adopted theories on the nuanced nature of presence (**See Table 2**).

Table 2.2: Overview of common presence questionnaires based on Google Scholar citations for April 2020

Authors	Year	Google Scholar Citations	Number of Items in Questionnaire
Witmer & Singer (WS)	1998	4741	32
Usoh Slater Steed (SUS)	(1994)(2000)	(1140)(632)	(3)(6)
Schubert et al. (IPQ)	2001	1115	14
Lessiter et al.	2001	1014	44

Nowak & Frank	2003	739	9
Lombard & Ditton	2000	306	103
Nicholas et al.	2000	207	9
Lombard & Weinstein	2009	182	4-8

SUS Questionnaire

The SUS questionnaire is a result of several studies conducted by Slater, Usoh and Steed, making it collectively known as the Slater Usoh Steed Questionnaire (SUS), or most commonly as Slater's Questionnaire. In essence, the items in Slater's questionnaire aim to measure presence based on the user's sense of being in the Virtual Environment, the extent that the VE is the reality for the user, and the locality of the experience; whether or not the user regarded the VE as an actual place that they visited.

SUS consists of 6 items in total evaluated on a 1-7 Likert scale. To evaluate presence, a presence score, which is measured as the total number of items with a high user response, is calculated. SUS questionnaire items can be found in the Appendix A. .

Witmer and Singer

According to results from Google Scholar citations in April 2020 (Table 2), Witmer and Signer's questionnaire is noticeably the most widely-cited of the three prominent presented here. Essentially, the questionnaire is derived from the results of empirical findings that Witmer and Singer analyzed from 152 participants. Additionally, the questionnaire hinges on their explication of the nature of presence as indicative of immersion and involvement. From the questionnaire results of the 152 participants, Witmer and Singer selected the statistically significant factors from the reported user-presence responses to develop the final form of the questionnaire (Witmer and Singer, 1998) .

The final iteration is composed of 32 questions, and each item is conveniently answered on a Likert scale. The total presence score is calculated by summing the numerical responses to all items. Witmer and Singer's Questionnaire can be found in the Appendix B.

IPQ

Developed by Schubert and colleagues, Igroup Presence Questionnaire (IPQ) is the third most Google Scholar-referred to presence questionnaire. Fundamentally, IPQ is a combination of its antecedents, including the aforementioned two, and newly developed questionnaire items based on technological contexts (Schubert et al., 2001) . Initially, the questionnaire housed 75 items for the user to answer on a Likert scale, however, the current IPQ includes only 14 (Appendix C.). The developed questions serve Schubert and colleagues' conclusion that presence is generated from spatial presence, realness of the environment, and user involvement in the VE.

Despite the subjective nature of presence questionnaires, they are empirically proven to be sensitive enough to measure differences in presence. Regardless, Slater argues that relying on questionnaires is not a scientific basis for measuring presence, and that if researchers anticipate development in the field, then they should depart from subjective modes to concentrate on potential objective alternatives (Slater, 2004).

II.4.2 Behavioral Measurement

One alternative to subjective questionnaires can be achieved objectively through behavioral measurement of presence. Behavioral measurement hinges on the premise that user response to stimuli within the VE is a result of presence if similar to the user's real-world response to the same stimulus (Freeman et al., 2000).

Monitoring presence behaviorally encompasses multiple angles from analyzing user postural behavior and verbal reactions to overall cue reflex in the VE. In an experiment conducted by Freeman and colleagues (2000) , user postural reflexes to a stereoscopic and monoscopic display of a car hood traversing a track were observed. Upon the hood's in-track turns in the stereoscopic setting, participants inadvertently corrected their postures to match the changes in the hood's traversal. This observation of postural correction is an instance of behavioral measurement of user presence in VEs. Another example of presence-elicited behavioral responses is Slater's radio experiment, which monitored participant behavior of locating a real radio while being in a VE. In Particular, a physical radio was placed in real life, with a digital replica mapped to its initial position in VR. Initially, the user would locate the physical radio, and upon stepping into VR would find the digital substitute at the same location. Throughout the experience, the position of the physical radio would be altered, and the user would be requested to point at the perceived location of the physical radio accordingly. High presence was recorded when the user pointed at the virtual replica instead of the original radio. The objective behavioral measurement from this study was found positively correlated to the subjective result of the presence questionnaire used (Slater et al., 1995). Another example is Meehan and colleagues' pit room experiment, where users were instructed to drop items from a ledge overlooking a virtual height (Meehan et.al, 2002). When users moved closer to the ledge, it was observed that some took small steps in a similar gait as to how they would possibly react if placed in an analogous real-life setting.

The problem with behavioral measurement of presence in VR is that although it is of an objective nature, it is very limited in its applicable situations, which makes it difficult to substitute subjective questionnaires with.

Physiological

In another attempt to objectively measure presence, researchers have investigated physiological cues as possible indicators of presence in VR. Prior to their pit room experiment (Meehan et al., 2002), Meehan et al. attempted to measure presence through heart rate, skin conductivity, and skin temperature amongst 10 participants. Due to collected noise from the equipment used to measure heart rate, a correlation between heart rate and user presence was difficult to conclude. Similarly, due to the time dependency of skin temperature changes, establishing a relation between presence and skin temperature proved to be equally tricky. However, a correlation was found between skin conductivity and the user's subjective response to the environment (Schuemie et al., 2001). In a separate experimental setting by Wiederhold (1998), a correlation between skin conductivity and Slater's questionnaire was found under user exposure to a flight simulation.

Despite this fact, relying on physiological measurements alone is inadequate as such measures are direct results of specific stimuli rather than presence. For instance, skin conductivity is a measure of human arousal, and for both Meehan and Slater's experiments, a decrease in it was mapped to a higher arousal or higher user presence (Schuemie et al., 2001). However, in an experiment by Wilson and Sasse (2000), participants exposed to low frame rate video sequences consequently exhibited low skin conductivity despite lower frame rate resulting in lower user presence. This is because both arousal and stress are stimuli inducing low skin conductivity (Schuemie et al., 2001).

The difficulties associated with relying on physiological measurements as indicators of user presence can be summarized as two points. First, some physiological measurements require sensitive medical equipment to detect significant changes. The second, physiological measurements are not directly correlated to presence, which makes subjective questionnaires an pivotal addition to assessing the validity of physiological responses.

III. Previous Work

This section provides an overview of work previously done to measure user presence in VR. We present these to classify our approach as a continuum for their approaches and illustrate their influence on the design considerations for our developed virtual environment.

On the Relationship Between Presence, Anxiety, and Virtual height in VR

The ability of VR to simulate anxiety and fear is not a novel subject of investigation, especially in the context of user presence. Literature has illustrated how phobias tend to engender anxiety in VR when individuals are exposed to situations addressing their respective fears. Interestingly, in a study of the same line of reasoning on participants with reported specific phobias and without, Robilland et al. (2003) concluded that a strong correlation exists between experienced user presence and anxiety in a virtual setting. In different studies in VEs such as arachnophobia treatment (Bouchard et al.,2002), virtual height simulation (Schuemie et al., 2000), and subjective factor variations (Regenbrecht et al., 1998), a proportional relationship between presence and fear was further cemented.

The effects of anxiety and presence can also be found in instances of horror VR theme park attractions, and clinical rehabilitation such as overcoming fear of heights and spiders. It is due to the fact that the virtual environment is capable of genuinely generating a believable stress-inducing setting that users report fear and presence. These findings translate to the notion that fear or anxiety is a psychological construct that extends well in the virtual landscape for presence measurement purposes.

When looking at potential stimuli generating anxiety for presence studies, scholars have considered several non-threatening avenues, mainly those present in contexts of rehabilitation such as public speaking, and acrophobia. Perhaps one of the easiest stimuli to incorporate in VR to trigger anxiety is introducing virtual height. We present two past studies that cement this notion.

In a pilot investigation conducted by Hodges et al. (1999), 10 participants with acrophobia were placed in different settings of virtual height such as an open elevator, a balcony, and a bridge overlooking a river. The participants were placed in these mediated situations as an attempt to evaluate the effect of virtual high exposure on acrophobia therapy. Proceeding the VR exposure, participants were asked to fill in a subjective questionnaire, and results revealed a correlation between fear of heights and user presence in the VE. Still, no significant correlation between presence and reduction of acrophobia in the users was concluded.

In Meehan and colleague’s second attempt to measure physiological cues as indicators of presence through heart rate, skin conductivity, and skin temperature (Meehan et al., 2002), virtual height was decided as the stimulus of the experience. The design of the VE housed two rooms: a training room and a pit room (Figure 3.1). The total environment area was 5.5x 9.7 meters-squared, and the 52 participating users, wearing HMDs, started the experience in the training room. In the training room users practiced walking in the VE, as well as picking and dropping items. The users were then instructed to carry items from the training room to the pit room so as to release them from a ledge overlooking a 6-meter drop. When the users approached the virtual height, some reported motion sickness, and others refused to walk on the ledge. However, a few did boldly traverse the ledge, and even stood on the pit overlooking the void. Such behavioral observation illustrates how users have different tendencies on what they perceive as ominous, as explained earlier in Section II.4.

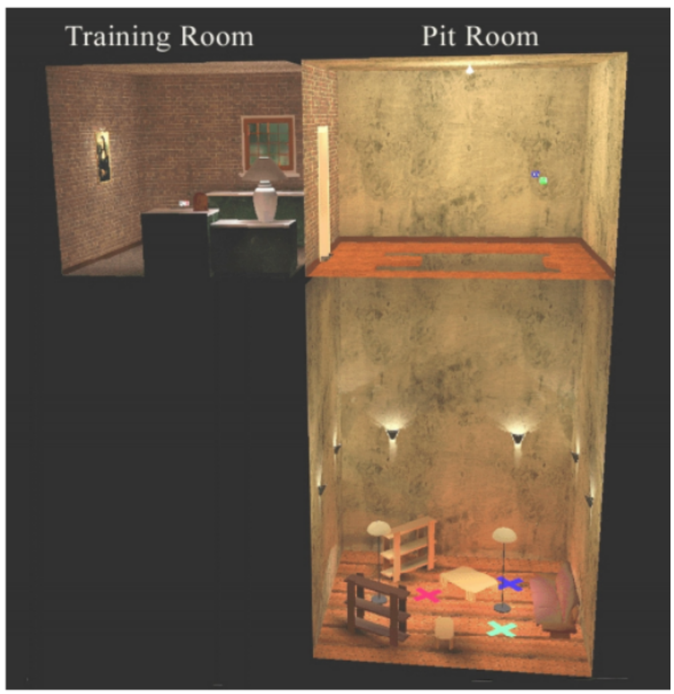

Figure 3.1: Side view of Meehan and colleagues' virtual environment design. Participants start in the room and then move to the pit room

Meehan and colleagues had the participants undergo repeated exposure of the VR stimulus. With every exposure, the environment consistently evoked user stress 90% of the time. However, as repeated exposure increased (2-12 sessions), the novelty of the VE diminished for the participants, which translated into a slight decrease of physiological changes of heart rate, reported user presence, and behavioral presence amongst others. The experiment also attempted varying aspects of the VE such as frame rate, and haptic feedback embodied in the form of a 15” wooden ledge for participants to walk on. Although the presence of the ledge did invoke a higher subjective user presence, the environment was still conducive to stress and physiological changes even in the absence of the haptic form.

IV. Methodology

In the following section, we introduce the virtual environment designed for our proposed grip force measurement. We start by first describing the design considerations and inspirations, and then explain the four different iterations that the design evolved from and to.

IV.1 Virtual Environment Design:

IV.1.1 Environment Considerations and Inspirations

The virtual environment was developed with the Unity Game Engine for use on an HTC VIVE headset. The primary purpose of the VE is to serve as a medium for inducing measurable physiological responses to be correlated with the user's subjective presence in the VE.

The key physiological response this study aims to inspect is grip-force, and its possible consistency with changes in other physiological responses, such as heart rate and respiratory response. As explained in Section II.4.3, in order to engender measurable variations in physiological cues, the presence of a stimulus is a requisite. Based on these two conditions, the VE developed for this study was designed to: incorporate a nonintrusive method for consistent user grip-force feedback, and a stimulus evoking objective physiological changes. To consistently measure grip force, a gripping task was introduced for the users to perform in a pre-stimulus stage, and during the presence of the stimulus. Additionally, Virtual height was selected as the stress inducer.

The main inspiration for the environment design was the virtual height situation introduced in Meehan's pit room experiment (Section III), and VR theme park attractions. In Meehan's experiment, a user engages with the VE through two rooms by carrying items from the first to the second. The first room served as an avenue for user practice on lifting objects in the VE and measuring baseline data, while the second exposed the user to the stimulus, in which users were told to release items from a ledge overlooking a drop.

Consequently, we decided for our environment design to echo three main stages: the training stage, the transition-to-stimulus stage, and finally, the stimulus stage. The first stage, which we refer to as the training stage, is concerned with accustoming users to the possible novelty of VR-environment control. Here, the user would practice grabbing items in VR, and we would measure a baseline reading for the user's pre-stimulus grip force.

The transition-to-stimulus or exposure to stimulus state is where the user experiences first hand environment change from the training room to the stimulus room. We echo this transition through a door-opening from the training room to the stimulus room. Finally, the stimulus stage is where the user is requested to complete a gripping task under the influence of the stimulus. The three stages of our environment design are summarized in Figure 4.1. The actual gripping task in the VE is for users to transport a single item, a teapot, from the training stage to the stimulus stage.

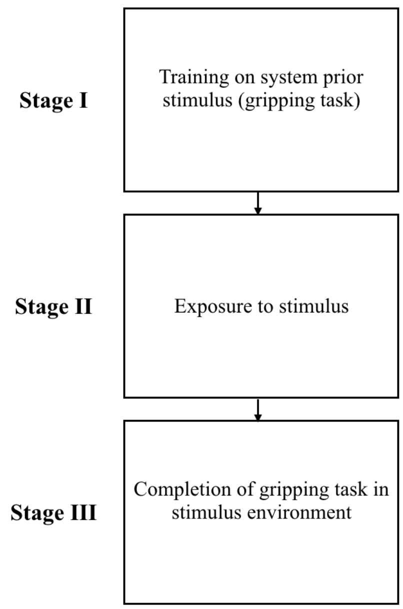

Figure 4.1: The three design stages of the proposed VR environment design. The stimulus in question was decided as virtual height

The difference between Meehan's experimental design and this study is that grip force is the main physiological response under speculation. In Meehan's experiment, the physiological responses scrutinized were heart rate, skin conductivity, and skin temperature. Moreover, part of Meehan's experimental variations included a physical ledge for users to step on. However, even with the absence of the physical ledge stress and subjective presence were reported. We decided to implement our environment without a haptic form.

IV.1.2 Design Iterations

The VE environment in this study is 6 meters in length and 3 meters in width; it was designed to fit the space of the MIT Nano Immersion Lab, and the user testing room provided by the MIT Clinical Research Center (CRC). In general, the design of the VE underwent four different iterations based on informal user feedback and testing at CRC and the Immersion Lab.

The first iteration of the VE design closely mimicked Meehan and colleagues' VR environment. The VE consisted of two rooms: a training room and a stimulus room, and a ledge overlooking a void (Figure 4.2).

The Training room is furnished with grabbable items (teapot, books, flower vase) for the user to grab and train on. The purpose of the training is to make sure that the user is accustomed to grabbing items with the VR controller in the Virtual Environment and to eliminate possible physiological changes induced from the novelty of gripping items in the VE.

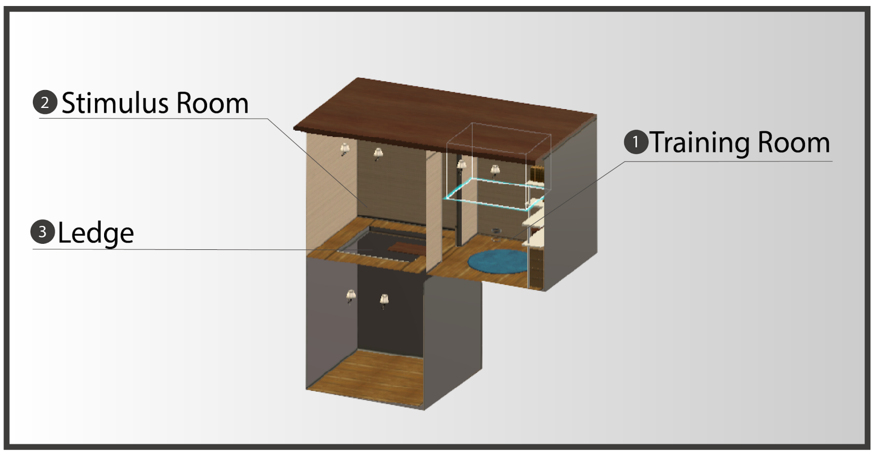

Figure 4.2: Isometric view of the first iteration of the VE design. The user starts at the training room then moves the stimulus room

The stimulus of this design is the virtual height experienced through the ledge (Figure 4.3b). After the training stage, a door opens, and the user is instructed to move items to the stimulus room to drop into the void. It was anticipated that the height difference would induce a physiological change.

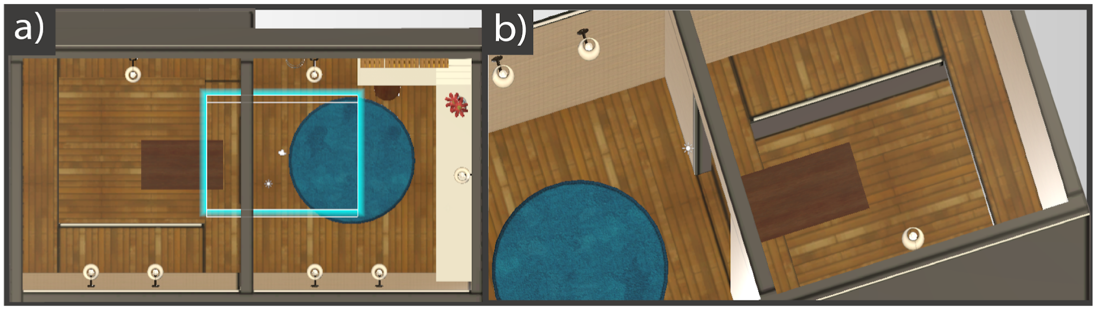

Figure 4.3: Visualization of the top view of first VE design (a) and the stimulus room ledge (b)

In its first experimental evaluation, the design was tested on two MIT students: one with reported acrophobia, and one without. The initial users were verbally asked whether the VE prompted feelings of anxiety or excitement. Subjective reports from the users revealed that neither experienced excitement or anxiety from the virtual height setting. There were several plausible explanations to why the environment might have not been conducive to promoting stress, like:

1) The environment did not mimic *user-preferred* lighting conditions
2) The ledge design did not allow much space for the users to experience the virtual height difference
3) Uniformity between the Stimulus Room and the void's flooring made it hard to distinguish between the two

As a consequence of our initial informal testing, the question on how can we further increase the effect of the stimulus arose. As in the first iteration, the second environment design consisted of two rooms serving their aforementioned purposes (Figure 4.4). The changes introduced were based on prior knowledge of presence factors in a VE such as level of detail and richness of display, and the user feedback. To address the first item from the informal experimental feedback, we rearranged the lighting configuration in the scene and used baked light settings. Baked lighting is a technique that grants ambient occlusion to static objects in the VE by overlaying a rich texture of shadows and highlights. It is important to note, however, that subjective feedback on lighting conditions, according to Flynn (1975) is a function of lighting itself, and not of the environment design. Specifically, in an experiment on varying lighting across a physical and a virtual room, user-preferred lighting arrangements were consistent across the two. In another separate study, Mania outlines that lighting is not necessarily correlated to user presence in VR as much as it is correlated to the user's subjective judgment (Mania and Robinson, 2004). Regardless, the lighting conditions in this iteration were altered to serve an additional role. They were utilized to intentionally focus the user's attention on the three pedestals in the environment as seen in Figure 4.5. The pedestals served as guiding stations to lift the teapot from and to. After ensuring user baseline measurement of grip force, the user would be instructed to move the teapot from the first pedestal (Figure 4.5a) to the second pedestal (Figure 4.5b). Upon moving to the second station, the user gains access to the stimulus room, where the gripping task is completed upon placement of the teapot on the final base (Figure 4.5d) .

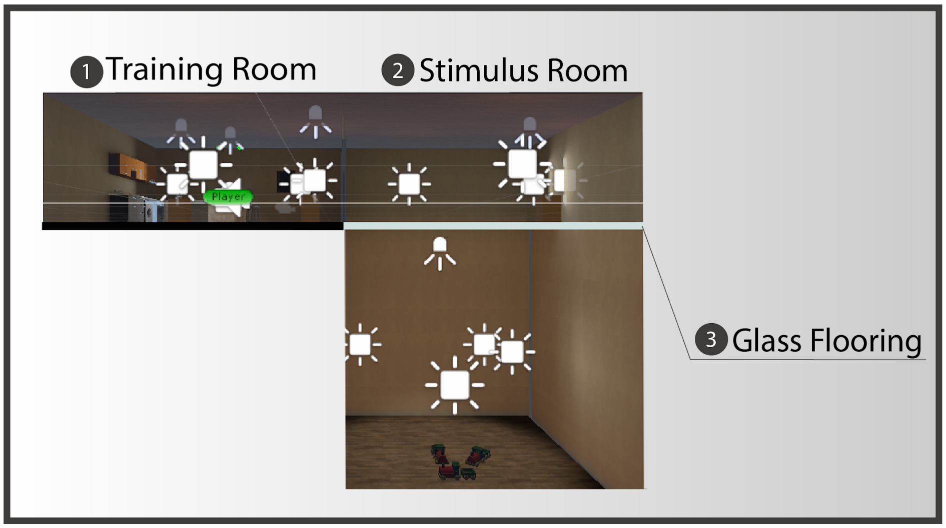

Figure 4.4: Side view of second VE design iteration.

Figure 4.5: Stage by stage representation of user grip task in second VE iteration. a) shows the initial location of the teapot, b) the second pedestal, and c) the final pedestal in the stimulus room. The ledge is substituted with a glass flooring

To address the second and third feedback items, the area of virtual height exposure was increased by implementing a glass flooring in the stimulus area (Figure 4.5d) . This iteration was tested with four initial users: two MIT students who tested the previous design, and two MIT staff and faculty members with one reporting acrophobia. Again, users were asked for their verbal feedback upon exposure to the VR setting. The general subjective consensus was that the glass flooring did not induce stress as was anticipated. This was mainly due to the granularity of the glass flooring, which interfered with the visual clarity of the void beneath the stimulus room. Additionally, one of the users stated that the lack of reference, like furniture, on the glass flooring made it difficult to tell that they were standing below a void. In the same user feedback session, the glass flooring was eliminated altogether, and users were asked to cross the virtual scene. The elimination of the glass flooring did not contribute to an increase in the reported excitement or anxiety of the initial testers; however, the introduction of a plank across the room did beget positive feedback.

This positive feedback was taken into consideration when creating the third iteration. The change introduced was the substitution of the glass flooring with a plank that still spanned the same area of virtual height exposure. Similarly, this design was tested and reported feedback led to the conclusion that an environmental variation between the training room and the stimulus room triggers a more lasting sense of excitement or anxiety.

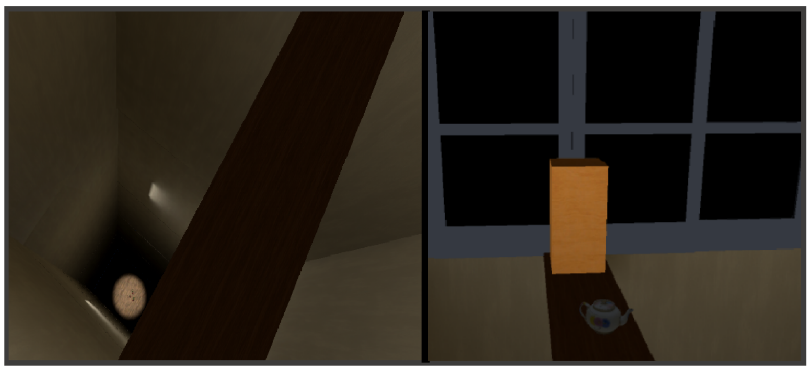

Figure 4.6: Visualization of third VE design iteration.
The glass flooring is substituted with a wooden plank.

For the fourth and final iteration, the concept of the stimulus room was substituted with a plank overlooking a detailed modern city (Figure 4.7). The purpose of the training room remained unchanged, but the number of pedestals was reduced to two: the first as an initial teapot station, and the second to activate the door leading to the plank (Figure 4.8).

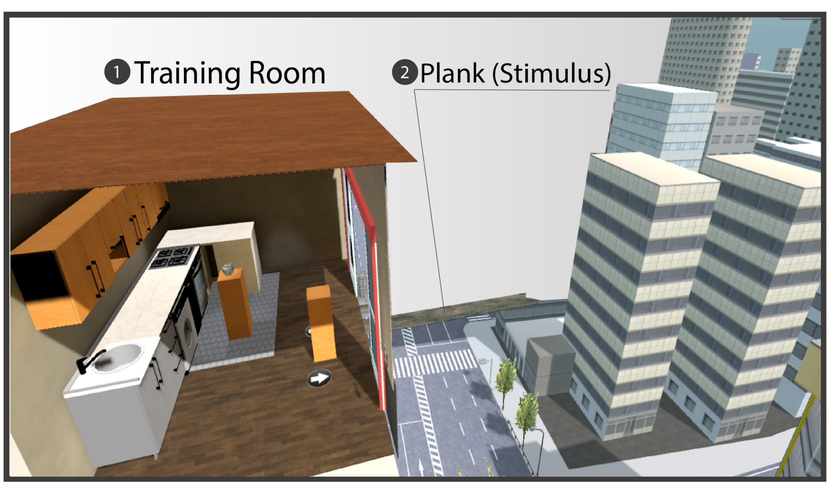

Figure 4.7: Side view of the final VE iteration.

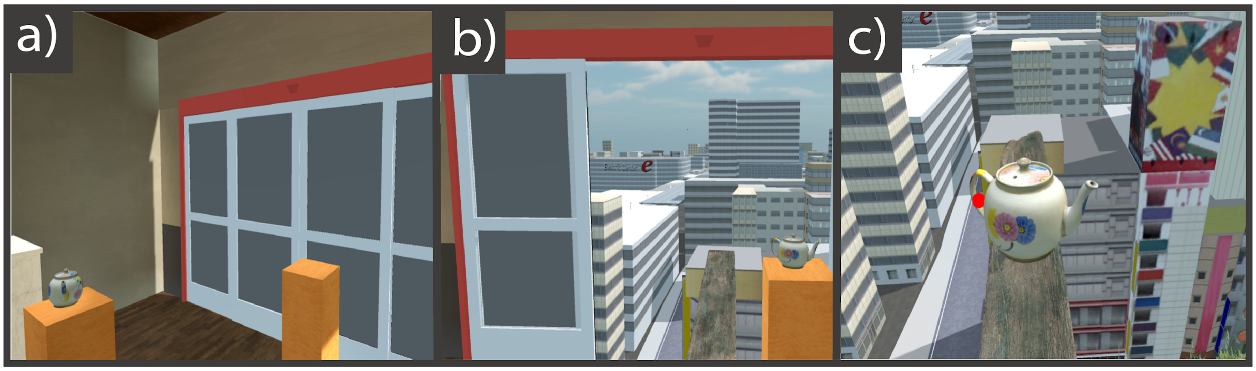

Figure 4.8: Stage by stage representation of user grip task in the third VE design. a) shows the initial location of the teapot, b) the teapot triggering access to the plank, and c) the teapot carried along the plank..

According to the environment testers, the disconnect in the environment between the plank and the apartment training room contributed to a sense of 'surprise'. This characteristic outcome is not germane to this study, since change and contrast are deemed as surprise-inducing factors in the general human psyche (Louis 1980). Laurent and Baldi (2009) theorize that surprise hinges on the presence of two elements: unpredictability, and relative subjective expectations. To speak loosely, the unpredictability of a plank being housed outside of the apartment room, and the scenic disconnect between the apartment room, the city environment, and the wooden plank appeared as effective conditions to evoking user positive stress (excitement) or negative stress (anxiety).

IV.2 Presence Questionnaires

To assess the degree of reported subjective user presence in the VE environment, we have used a combination of the IPQ and Slater Questionnaires to ask participants to report how present they were in the VE. We did not use Witmer's questionnaire due to its length (32 items), which is difficult to implement with studies of repeated user exposure. Each question was assessed on a Likert scale from 1-7, and there were a total of X number of questions as can be seen in Appendix D. .

Additionally, prior to the presence questionnaire, a pre-questionnaire was designed to assess the user's experience with VR, their age, gender, and educational background in an attempt to investigate if the effect of the user's personal factors on presence in the VE, as was discussed in Section II.2. The pre questionnaire is shown in Appendix E. .

V. Future Work

V.1 Environmental Variations

In trials to follow, we aim to explore minimum combinations of the designed system to trigger user presence. What system characteristics can we trade-off, and what are essential to the experience?

Some aspects of the VE that we anticipate to initially test are :

1) Rendering quality (number of pixel columns and rows displayed on the HMD)
2) Presence of virtual feet

Based on these prospective variations, each user would experience the VE three times at a randomized sequence, with one control factor altered in each setting. The aim is to gauge the significance of the control factors on affecting user presence in the VE. All three environment settings and their varied metrics are summarized in Table 5.1.

Table 5.1: Set of control factors and variants to the three VE experiments proposed

VE Experiment	Rendering Quality	Feet presence
1 -- *Base*	High	No
2 -- *Resolution*	Low	No
3 -- *Feet*	High	Yes

By default, the rendering quality would be set to high, and virtual feet to absent.
To achieve changes in the VR environment resolution, the steam VR in-game settings would be altered between the default 100% (high) and 512x512 resolution per eye (low).

To integrate virtual feet in the environment, two VIVE VR trackers (figure) would be used and strapped to the users ankles for convenience of mobility. The VIVE trackers were mapped to virtual feet in the VE, and through tracking of user ankle movement would update the position of the virtual feet in real-time. Unfortunately, due to the COVID-19 outbreak, pictures were not taken of this setup.

V.2 Sensors

Because the user's physiological responses would be monitored, we have decided to use Equivital vests for physiological measurement. The Equivital vest sensors were supplied from MIT's Clinical Research Center, and will be used to measure heart rate and respiratory response in this experiment. Each user would have to have a vest fastened around their chest in which the sensor is housed. The sensor works through Bluetooth for data transmission, hence, users would not be tethered to a computer desktop unit. The only tethering occurs through the HMD to the computer unity, but a 5-meter cable connecting the HMD to the computer will be used so that the mobility in the VE won't be restricted. Additionally, one of the experiment facilitators is in charge of ensuring that the long cable will not tangle upon participant movement. One concern with using many wearable sensors is that user presence might be disrupted. However, in our case, the Equivital vest does not pose as an obstruction, and the grip force sensors that we have developed are housed on the VR controllers; not the user.

Figure 5.3: Equivital vest and sensor for physiological data measurement

V.3 Experimental Procedure

Unfortunately, due to MIT Campus Closure, we could not proceed with user testing. We anticipated each user setting to take around an hour to complete. The order at which the users would be exposed to the experiments of varying display resolution and presence of feet would be randomized. Additionally, the experiment would be executed by two researchers: One to run the VR environment and monitor physiological data collection, and the other to ensure the safety of the user and facilitate the subjective aspect of the experiment.

We have already received IRB approval to conduct our study. The participants would have been predominantly MIT students, faculty, and staff, and users with reported instances of motion sickness would be filtered from the recruitment process. In the recruitment stage, prospective participants would be asked to supply cloth size for Equivital belt fitting.

Proceeding user consent, users would be assisted to wear the Equivital belt, then requested to fill in the pre-questionnaire. After a short debrief on the game mechanics, users would experience one of the three experiments at a randomized order. Upon the completion of the VE task, users would be asked to fill in the post experience questionnaire. Accordingly, users would complete the second and third VE experiences. User data will be encrypted through RedCap, a medical platform provided by CRC.

Conclusion

Developing a virtual reality environment with the ability to create user presence is extremely important, however, measuring presence is more crucial especially when achieved in objective terms. Designing a VR setting to invoke user stress for objective presence measurement proved to be harder than anticipated, since users have varying subjective tendencies on what they deem as stressful. We were able to successfully receive positive feedback from initial users when our design environment included elements of surprise, such as environment disconnect and contrast, as well as exposure to a larger area of virtual height. While we have developed the VE, we still have not tested its credibility on inducing the desired physiological changes we anticipate, mainly grip force. Once MIT Campus resumes research activities, we hope to test our environment in our next round of data collection to validate our hypotheses.

APPENDIX A.

SLATER-USOH-STEED QUESTIONNAIRE (SUS)

1. Please rate your *sense of being in the* virtual environment, on a scale of 1 to 7, where 7 represents your *normal experience of being in a place.*

2. To what extent were there times during the experience when the virtual environment was the reality for you?

3. When you think back to the experience, do you think of the virtual environment more as *images that you saw* or more as *somewhere that you visited*?

4. During the time of the experience, which was the strongest on the whole, your sense of being in the virtual environment or of being elsewhere?

5. Consider your memory of being in the virtual environment. 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 environment, whether that memory is in colour, 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.

6. During the time of your experience, did you often think to yourself that you were actually in the virtual environment?

APPENDIX B.

WITMER & SINGER QUESTIONNAIRE

1. How much were you able to control events?
2. How responsive was the environment to actions that you initiated (or performed)?
3. How natural did your interactions with the environment seem?
4. How completely were *all* of your senses engaged?
5. How much did the visual aspects of the environment involve you?
6. How much did the auditory aspects of the environment involve you?
7. How natural was the mechanism which controlled movement through the environment?
8. How aware were you of events occurring in the real world around you?
9. How aware were you of your display and control devices?
10. How compelling was your sense of objects moving through space?
11. How inconsistent or disconnected was the information coming from your various senses?
12. How much did your experiences in the virtual environment seem consistent with your real-world experiences?
13. Were you able to anticipate what would happen next in response to the actions that you performed?
14. How completely were you able to actively survey or search the environment using vision?
15. How well could you identify sounds?
16. How well could you localize sounds?
17. How well could you actively survey or search the virtual environment using touch?
18. How compelling was your sense of moving around inside the virtual environment?
19. How closely were you able to examine objects?
20. How well could you examine objects from multiple viewpoints?
21. How well could you move or manipulate objects in the virtual environment?
22. To what degree did you feel confused or disoriented at the beginning of breaks or at the end of the experimental session?
23. How involved were you in the virtual environment experience?
24. How distracting was the control mechanism?
25. How much delay did you experience between your actions and expected outcomes?
26. How quickly did you adjust to the virtual environment experience?
27. How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?
28. How much did the visual display quality interfere or distract you from performing assigned tasks or required activities?

29. How much did the control devices interfere with the performance of assigned tasks or with other activities?
30. How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?
31. Did you learn new techniques that enabled you to improve your performance?
32. Were you involved in the experimental task to the extent that you lost track of time?

APPENDIX C.

IPQ QUESTIONNAIRE

English IPQ Items

Number	PQI/II Nr. (internal)	IPQ item name	shortcut	loading on ...	English question	English anchors	Copyright (item source)
1	s62	G1	sense of being there	PRES	In the computer generated world I had a sense of "being there"	not at all--very much	Slater & Usoh (1994)
2	s44	SP1	sense of VE behind	SP	Somehow I felt that the virtual world surrounded me.	fully disagree--fully agree	IPQ
3	s30	SP2	only pictures	SP	I felt like I was just perceiving pictures.	fully disagree--fully agree	IPQ
4	s28	SP3	not sense of being in v. space	SP	I did not feel present in the virtual space.	did not feel--felt present	???
5	s31	SP4	sense of acting in VE	SP	I had a sense of acting in the virtual space, rather than operating something from outside.	fully disagree--fully agree	IPQ
6	s33	SP5	sense of being present in VE	SP	I felt present in the virtual space.	fully disagree--fully agree	IPQ
7	s64	INV1	awareness of real env.	INV	How aware were you of the real world surrounding while navigating in the virtual world? (i.e. sounds, room temperature, other people, etc.)?	extremely aware-moderately aware-not aware at all	Witmer & Singer (1994)
8	s37	INV2	not aware of real env.	INV	I was not aware of my real environment.	fully disagree--fully agree	IPQ
9	s40	INV3	no attention to real env.	INV	I still paid attention to the real environment.	fully disagree--fully agree	IPQ
10	s38	INV4	attention captivated by VE	INV	I was completely captivated by the virtual world.	fully disagree--fully agree	IPQ
11	s48	REAL1	VE real (real/not real)	REAL	How real did the virtual world seem to you?	completely real--not real at all	Hendrix (1994)
12	s7	REAL2	experience similar to real env.	REAL	How much did your experience in the virtual environment seem consistent with your real world experience ?	not consistent-moderately consistent-very consistent	Witmer & Singer (1994)
13	s59	REAL3	VE real (imagined/real)	REAL	How real did the virtual world seem to you?	about as real as an imagined world--indistinguishable from the real world	Carlin, Hoffman, & Weghorst (1997)
14	s47	REAL4	VE wirklich	REAL	The virtual world seemed more realistic than the real world.	fully disagree--fully agree	IPQ

APPENDIX D.

PRE-EXPERIENCE QUESTIONNAIRE

Gender *

- ◯ Female
- ◯ Male
- ◯ Prefer not to say
- ◯ Other...

Age *

- ◯ 17 or younger
- ◯ 18-20
- ◯ 21-29
- ◯ 30-39
- ◯ 40-49
- ◯ 50-59
- ◯ 60 or older

Status *

- [ ] Undergraduate student
- [ ] Masters student
- [ ] PhD student
- [ ] Research Assistant/Research Fellow
- [ ] Staff member - systems/technical staff
- [ ] Faculty
- [ ] Administrative staff
- [ ] Other...

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

	1	2	3	4	5	6	7	
Not at all	○	○	○	○	○	○	○	Very much so

Have you experienced "virtual reality" before? *

- ○ 0 times
- ○ 1-5 times
- ○ greater than 5 times

Which is your dominant hand? *

- ○ Left
- ○ Right

APPENDIX E.
POST-EXPERIENCE QUESTIONNAIRE

The current resolution can still make you tell that you are in a room and on a plank

◯ Yes

◯ No

Please rate your sense of being in the virtual environment, on a scale of 1 to 7, where 7 represents your normal experience of being in a place.

1. Please rate your sense of being in an apartment-city environment, 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 there" in the apartment-city environment: *

	1	2	3	4	5	6	7	
Not at all	◯	◯	◯	◯	◯	◯	◯	Very much

2. To what extent were there times during the experience when the apartment-city environment was the reality for you?

There were times during the experience when the apartment-city environment was the reality for me... *

	1	2	3	4	5	6	7	
At no time	◯	◯	◯	◯	◯	◯	◯	Almost all the time

3. When you think back about your experience, do you think of the apartment-city more as images that you saw, or more as somewhere that you visited?

The apartment-city seems to me to be more like... *

	1	2	3	4	5	6	7	
Images that I saw	◯	◯	◯	◯	◯	◯	◯	Somewhere that I visited

4. During the time of the experience, which was strongest on the whole, your sense of being in the apartment-city, or of being elsewhere?

I had a stronger sense of... *

	1	2	3	4	5	6	7	
Being elsewhere	○	○	○	○	○	○	○	Being in the apartment-city

5. Consider your memory of being in apartment-city environment. 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 roller coaster park space, 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 apartment-city space as a place in a way similar to other places that I've been today... *

	1	2	3	4	5	6	7	
Not at all	○	○	○	○	○	○	○	Very much so

6. During the time of the experience, did you often think to yourself that you were actually in the apartment-city?

During the experience I often thought that I was really in an apartment-city environment... *

	1	2	3	4	5	6	7	
Not very often	○	○	○	○	○	○	○	Very much so

1. In the computer generated world I had a sense of "being there" *

	1	2	3	4	5	6	7	
Not at all	○	○	○	○	○	○	○	Very much

2. Somehow I felt that the virtual world surrounded me. *

	1	2	3	4	5	6	7	
Fully disagree	○	○	○	○	○	○	○	Fully agree

3. I felt like I was just perceiving pictures. *

	1	2	3	4	5	6	7	
Fully disagree	○	○	○	○	○	○	○	Fully agree

4. I did not feel present in the virtual space. *

	1	2	3	4	5	6	7	
Did not feel	○	○	○	○	○	○	○	Felt present

5. had a sense of acting in the virtual space, rather than operating something from outside. *

	1	2	3	4	5	6	7	
Fully disagree	○	○	○	○	○	○	○	Fully agree

6.I felt present in the virtual space. *

	1	2	3	4	5	6	7	
Fully disagree	○	○	○	○	○	○	○	Fully agree

7. How aware were you of the real world surrounding while navigating in the virtual world? (i.e. sounds, room temperature, other people, etc.)? *

	1	2	3	4	5	6	7	
Extremely aware	○	○	○	○	○	○	○	Not aware at all

8. I was not aware of my real environment. *

	1	2	3	4	5	6	7	
Fully disagree	○	○	○	○	○	○	○	Fully agree

9. I still paid attention to the real environment. *

	1	2	3	4	5	6	7	
Fully disagree	○	○	○	○	○	○	○	Fully agree

10. I was completely captivated by the virtual world. *

	1	2	3	4	5	6	7	
Fully disagree	○	○	○	○	○	○	○	Fully agree

11. How real did the virtual world seem to you? *

	1	2	3	4	5	6	7	
Completely real	○	○	○	○	○	○	○	Not real at all

12. How much did your experience in the virtual environment seem consistent with your real world experience ? *

	1	2	3	4	5	6	7	
Not consistent	○	○	○	○	○	○	○	Very consistent

13. How real did the virtual world seem to you? *

	1	2	3	4	5	6	7	
About as real as an imagined world	○	○	○	○	○	○	○	Indistinguishable from the real world

14. The virtual world seemed more realistic than the real world *

	1	2	3	4	5	6	7	
Fully disagree	○	○	○	○	○	○	○	Fully agree

How excited did moving the teapot in the apartment make you feel? Please rate from 0 to 4 *

	0. I didn't feel excited	1. Somewhat excited	2. Moderately excited	3. Very excited	4. Extremely excited
I felt	○	○	○	○	○

How anxious did moving the teapot in the apartment make you feel? Please rate from 0 to 4 *

	0. I didn't feel anxious at all	1. Somewhat anxious	2. Moderately anxious	3. Very anxious	4. Extremely anxious
I felt	○	○	○	○	○

How excited did the door opening make you feel? Please rate from 0 to 4 *

	0. I didn't feel excited	1. Somewhat excited	2. Moderately excited	3. Very excited	4. Extremely excited
I felt	○	○	○	○	○

How anxious did the door opening make you feel? Please rate from 0 to 4 *

	0. I didn't feel anxious at all	1. Somewhat anxious	2. Moderately anxious	3. Very anxious	4. Extremely anxious
I felt	○	○	○	○	○

How anxious did walking on the plank make you feel? Please rate from 0 to 4 *

	0. I didn't feel anxious at all	1. Somewhat anxious	2. Moderately anxious	3. Very anxious	4. Extremely anxious
I felt	○	○	○	○	○

How excited did walking on the plank make you feel? make you feel? Please rate from 0 to 4 *

	0. I didn't feel excited	1. Somewhat excited	2. Moderately excited	3. Very excited	4. Extremely excited
I felt	○	○	○	○	○

Did you feel any of the following during the experience?

- ☐ Nasueous
- ☐ Dizzy
- ☐ Fatigued
- ☐ Disoriented

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