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Stumbling into Virtual Worlds. How Resolution Affects Users' Immersion in Virtual Reality and Implications for Virtual Reality in Therapeutic Applications

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Stumbling into Virtual Worlds.

How Resolution Affects Users’ Immersion in Virtual Reality and Implications for Virtual Reality in Therapeutic Applications

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by Brianna I. Martinson 2020

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Declaration by student

I, Brianna Martinson, hereby declare that the work presented herein is original work done by me and has not been published or submitted elsewhere for the requirement of a degree program. Any literature date or work done by others and cited within this thesis has been given due acknowledgement and is listed in the reference section.

Brianna Ivette Martinson

Place: East Tennessee State University

Date: November 2, 2021

Certificate

Certified that the thesis titled “Stumbling into Virtual Worlds. How Resolution Affects Users’ Immersion in Virtual Reality and Implications for Virtual Reality in Therapeutic Applications” submitted by Ms. Brianna Martinson towards partial fulfilment for the Bachelor’s Degree in Computing (Honors-In-Discipline Scholars Program) is based on the investigation carried out under our guidance. The thesis part therefore has not been submitted for the academic award of any other university or institution.

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Abstract

Studies of how users experience Virtual Reality (VR) have thus far failed to address the extent to which rendering resolution and rendering frame rate affect users' sense of immersion in VR, including applications of VR involving simulators, treatments for psychological and mental disorders, explorations of new and nonexistent structures, and ways to better understand the human body in medical applications.

This study investigated if rendering resolution affected users' sense of immersion in VR. This was conducted by comparing the responses of two groups, relative to two measures of participant immersion: (a) participant's sense of presence and (b) participant's sense of embodiment. The treatment levels were (a) low 512 pixels per inch (ppi) and (b) high 2048 ppi rendering resolution. One potential moderating variable, game type, varied over three levels: narrative, objective, and situational. The participants were randomly assigned to a treatment level account for previous VR experience, neither participants nor the research observer knew the treatment level. Measurements were collected after each game via an Immersion tendency Questionnaire after each game. For each dependent measure, sample descriptive statistics—mean (M) and inter-quartile range (IQR) with a conventional significance level of 0.05—were evaluated to conclude the results. Data indicated that the rendering resolution did not affect user immersion, but the game type did affect immersion and the situational game type was determined to be significantly more immersive than the other game types.

Keywords: Virtual Reality, Immersion, Resolution, Therapeutic, Environment, Video Game

Dedication

This thesis is dedicated to my mom and dad; I am officially working with video games as part of my career like I always said I would. I am very thankful for the encouragement and support from my best friend, Hannah, for always being there for me, and for volunteering her time to be the study's equipment manager and creating the flyers for the study. I would also like to thank my mentor Mr. Mathew Desjardins for losing his mind with me during this process, couldn't have done it without him. Finally, I would like to acknowledge the encouragement to do this process from Dr. Dinah DeFord and Dr. Michelle Hurley from the Ronald McNair Post Baccalaureate Achievement program.

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I. Introduction

A. Overview and Motivation

Virtual reality (VR) is a medium that creates *virtual realities*: interactive, immersive simulated environments of real and imagined physical experiences. Virtual realities have been used as marketing tools for retail and automobile industries; entertainment platforms for sports, art, or video games; and training simulators for armed forces and medical training [1]; examples include “The Progressive LAKE DASH VR Trade Show Experience” [2]; a boat driving game that promotes Progressive Insurance; “Field Trip to Mars” [3], a VR experience field trip for elementary children; and “Walmart Academy” [4], a VR training simulator for Walmart employees. These realities are realized using a combination of hardware devices and software applications. VR devices include head-mounted displays, gesture-sensing gloves or controllers, speakers, and vibrotactile platforms; these allow for the stimulation of multiple senses and active exploration of the virtual environment. VR applications process and generate programmed, device-mediated responses to users’ actions in real-time. This delivery of real-time feedback helps create natural and intuitive experiences for users.

The medical community is using VR to implement novel therapies that classic therapies cannot deliver. Unlike traditional therapies, VR can immerse users in non-laboratory-like, tailored environments in their daily worlds, allowing them to feel more at ease and allowing practitioners to obtain more reliable observations [5]. According to Hoffman, “Researchers are finding that [v]irtual reality can ease pain, both physical and psychological” [6, p. 60]. 19% of the participants in a literature review on VR in psychiatric treatment who were unwilling to talk to a counselor in person about their issues expressed a willingness to use VR instead to access mental health care ([7], p. 104). Participants reported reduced anxiety due to there being no potential danger during the therapy.

North [8] found that Virtual Reality Therapy proved more effective and efficient in treating agoraphobia than in vivo treatment (p. 73). Other applications of therapeutic VR include Neuro Rehab VR, a library of physical and occupational therapies [9]; XRHealth, a VR Telehealth kit for acute and chronic pain management [10]; SnowWorld, a distractor for burn treatments [11]; Arachnophobia, a self-guided VR exposure therapy to treat the irrational fear of spiders [12]; and Virtually Resilient, an application to help nurses with work-related stress [13].

B. The Present Study

The potential value of configurable therapeutic simulations is suggested by gamers' experiences with VR. Virtual realities rely on software configurations to create a sense of immersion. People who play video games routinely configure their computer's hardware on a per-game basis in order to optimize their experiences for each game and argue over what configurations are more valuable for user experience. If an environment's attributes impact how gamers experience VR, these attributes should also be considered in therapeutic settings.

VR configuration, however, is not accounted for in current research and practice. This study explored how one aspect of VR configuration, rendering resolution, affects users' sense of immersion in VR environments. Two groups of participants were asked to play three single-person VR-based games, answer a questionnaire after each game, and participate in a semi-structured interview. The study's VR equipment presented each group with either low-resolution (512 pixels per inch (ppi)) or high-resolution images (2048 ppi) of these virtual environments, with choice of resolution determined at random. Neither the participants nor an observer who monitored these experiments were notified about this difference in image quality.

Participants were randomly split into two groups to account for previous VR experience. The participants' sense of immersion was gauged by measuring their sense of presence and embodiment. One potential moderating variable, game type, was varied over three different types of games: narratives, which feature story arcs involving conflict and resolution and interactive character(s) with a narrative or personality; objective games, which feature a clear goal(s) without a necessary narrative or reason behind said goal(s); and situational games, which, in lieu of objectives, enable users to experience the effect of actions that they choose in response to the game's situations.

Measurements were collected from a questionnaire after each game. For the study's two dependent measures, sense of presence and sense of embodiment, sample descriptive statistics—mean (M) and inter-quartile range (IQR)—were evaluated, with a conventional significance level of 0.05.

Specific research questions were as follows.

RQ1: Main effects: Does the resolution affect users' immersion?

RQ2: Interaction effects: Does the treatment effect vary with game type?

II. LITERATURE REVIEW

A. *Virtual Reality (VR) Systems*

According to Gandhi and Patel [14], VR is a low-risk means of immersing users in environments that are difficult or impossible to (re)create in the real world. Immersion is the degree to which participants believe they are in a virtual environment just as they believe they are in other physical locations. The low-risk encounters with problem stimuli that VR affords can be pivotal for therapy treatment.

In [7], Maples-Keller, Bunnell, Kim, and Rothbaum trace the development of VR, starting with the 1950s. Morton Heilig's Sensorama was the first system to use odors and vibration to create a 'multi-sensory experience'. In 1961, the Philco Corporation created Headsight, the first head-mounted display with motion tracking and dual monitor displays, for military training. In 1965, Ivan Sutherland created the Ultimate display; this allowed VR technology to use computer-generated interfaces, which helped improve real-time interactions for users.

Contemporary VR relies heavily on technology developed for recreational 2D gaming. In 2018, Gandhi and Patel [14] identified network capabilities, computer systems, processors, and cost as the key impediments to VR technology. Subsequently, Rizzo [15] discussed how advances in hardware have pushed VR technology to a 'second coming'.

Head-mounted devices (HMDs) are one of two principal components of most VR-systems. HMDs allow users to interact with a visual environment. Ideally, to create a sense of immersion, HMDs should generate sounds that correlate with users' visual orientation while allowing users to experience movement in their environments. The kinds of movement that an HMD can simulate depends on the degrees-of-freedom it provides [16]. Systems that provide 3 degrees-of-freedom (3DOF) display content in response to head movements but limit the viewer's viewpoint to a fixed point in VR space. Examples of 3DOF HMDs include Oculus Go, Google Cardboard, and the Samsung Gear. In 6-degrees-of-freedom (6DOF) VR, users also control their position in the virtual environment. Examples of 6DOF HMDs include Oculus Quest, Oculus Rift, Samsung Odyssey, HTC Vibe, and the HP Reverb. 3DOF VR is common in devices that are smartphone-based HMDs; 6DOF VR, which is harder to implement, is usually found in dedicated HMD either wired or wirelessly connected to a PC.

Controllers serve as input devices for HMDs, allowing users to interact with virtual worlds and objects. Controller layouts provide varying combinations of trackpads, buttons, triggers, and analog sticks. For example, the Samsung Odyssey's controllers have a trigger, touchpad, analog stick, menu button, and windows button on each controller. The Oculus Quest and Rift Touch controllers have two buttons, a menu or oculus button; two triggers; and an analog stick. The buttons' functions vary by controller and game. Hufnal [17] notes that different types of controllers have different impacts on user experience.

Rendering is the use of an image's description to realize that image in a visual format: e.g., through ray-tracing or luminosity. In contemporary VR systems, frames are rendered by a computer's graphics processing unit (GPU), based on information from a central processing unit (CPU). Each frame must be rendered twice, once per eye.

The capacity of a VR system's rendering component is typically characterized in terms of its rendering frame rate, refresh rate, and rendering resolution. *Rendering frame rate* (RFR) is the rate at which a CPU/GPU sends images to a screen. *Refresh rate* is the rate, measured in Hz, at which a screen refreshes its display; this is usually faster than the frame rate. *Rendering resolution* is the number of pixels per inch a CPU/GPU produces per frame. The higher the rendering resolution, the more a GPU/CPU has to work to produce one frame.

The quality of a VR system's images depends on its *display resolution*, measured in an image's pixels per inch (ppi), horizontal count by vertical count [18]. Display resolution depends on the quality of the device's display. Resolution can also affect RFR. High resolution can increase system *latency*—the delay between a user's action and a VR's reaction—if a CPU/GPU cannot produce frames quickly enough to preserve the illusion of presence. Increases in load, however, can be offset by lowering resolution at the cost of lower visual quality.

A GPU's and CPU's RFR, like a screen's refresh rate, depend on an HMD's connectivity. Wireless HMDs rely on their internal components to manage rendering. Wired HMDs rely on external, PC-based hardware and software. Wireless rendering is slower than wired rendering, which outperforms wireless rendering under higher CPU loads. For example, the wireless Oculus Quest has a refresh rate of 72 Hz and RFR of 72 frames per second, while the wired Oculus Rift has a refresh rate of 80 Hz and RFR of 80 frames per second [19]. The Oculus Go and the Oculus Rift S have LCD Displays with 1280x1440 resolution, while the Oculus Quest has an OLED display and 1440x1600 resolution.

VR displays use frame interpolation—also called *smoothing*—to generate missing frames between the RFR and the refresh rate. Missing frames are generated from preceding frames by a process called frame prediction. For example, for frame prediction, Oculus uses a built-in system called Asynchronous Spacewarp (ASW). ASW uses Timewarp, a VR technique that warps a rendered frame before it is displayed, to optimize and create a consistent frame rate and refresh rate [20], [21]. In order to reduce latency, Timewarp predicts frames using an HMD-captured image of a user's head position immediately before the rendered image is displayed. ASW uses animation detection, camera translation, and head translation from previous frames to predict its next frame. ASW automatically starts running when the RFR drops below 90 Hz. ASW directs the CPU/GPU to run at 45 FPS, while interpolating frames to assure a consistent 90 FPS. Since ASW and Timewarp ensure that the 90 Hz frame rate and refresh rate are constant, users should not notice a drop in a game's quality or response.

B. Virtual Reality in Therapeutic Contexts

VR has been used in medical education, in treatments for psychological and mental disorders, and in explorations of architectures for new and nonexistent structures [22].

Clinical roles: Psychiatrists first began to study VR's use in psychiatric treatment in 1989 when Jaron Lanier coined the term "virtual reality". According to Rizzo [15], VR was first used in clinical settings in the 1990s as exposure therapy for phobias such as heights, flying, spiders, and public speaking.

In [23], Difede and Cukor discuss the use of VR to treat participants with post-traumatic stress disorder (PTSD) from the September 11, 2001 attack on the World Trade Center. The study yielded clinically and statistically significant improvements for nine of the ten patients with severe PTSD, relative to a control group whose patients went untreated. VR treatment offered these nine patients a safe way to work through the trauma.

In [24], Anderson et al. reported significant improvement and reduced fear following VR treatments for participants who feared heights and flying. The authors attributed these results to VR's enabling participants to adapt to real-life exposures to these stimuli. The authors noted that VR exposure therapy was less expensive than paying for plane tickets.

In [7], Maples-Keller et al. present a meta-analysis of VR therapy applications for selected phobias, including social anxiety disorder, generalized anxiety disorder, panic disorder and agoraphobia; obsessive-compulsive disorder; schizophrenia; acute and chronic pain; addiction; eating pathology; and autism. Based on this analysis, the authors concluded that VR therapy was most effective for exposure therapy for anxiety disorders, cue exposure therapy for patients with substance use disorder, and distraction from acute pain caused by painful medical procedures. The authors acknowledged the need to repeat studies with larger sample sizes to validate these conclusions.

Empathy-building roles: In [25], Carey et al. argue that VR's immersive experiences can build empathy by engaging users in embodied thinking: a key component of empathy. The authors also noted a current lack of a unified approach to VR-based research on empathy-building. Carey et al. proposed a framework to establish VR testing environments for gathering data on the subjective empathic response of users in VR—which, they added, needed further validation.

Shin [26] investigates how the sense of immersion that VR creates affects users' sense of embodiment in a virtual environment and builds empathy for its characters. Shin defines immersion as the degree to which users perceive a story as real. He asserts that "the goal of VR storytelling is to tell a story that will stimulate emotions that will influence action"[27]. Shin's study used VR and a flat-screen TV to present content to the study's participants. Participants were divided into four groups, each with one characteristic empathy level (high or low) and one presentation medium (VR or flat-screen TV). He concluded that three cognitive processes determine how users empathize with and are immersed in VR stories: experience quality; presence, or immersion in a virtual space and association with the medium's technological features; and flow, or the experience of immersion during an action or performances [26, p. 67]. Shin further concluded that a VR experience needs high-quality content, enjoyable services, user engagement, and emotional involvement in order to influence cognition, engagement, and immersion.

Herrara et al. [28] describes two studies of VR's ability to create short- and long-term empathy. In the first, participants experienced a stimulus meant to increase empathy for the homeless population. Participants were randomly assigned to complete a narrative-based perspective-taking task or a VR perspective-taking task. A perspective-taking task asks people to imagine the perspective of someone else in a specific circumstance—in this instance, a homeless person. Data were collected immediately after the intervention and weekly over an eight-week period to gauge participants' empathy. Both groups' participants had similar degrees of increase in empathy for the homeless. However, participants from VR perspective-taking tasks had more positive, longer-lasting attitudes and took more initiatives towards helping the population than the narrative-based perspective-taking task group.

In the second study, participants did perspective-taking tasks to build empathy for homeless populations. Participants received information from either a desktop computer, a VR, or a traditional physical source of information; this latter served as the experiment's control. The researchers found that everyone in the first two groups of participants had significantly higher empathy and more connection to the homeless population than those who only received information from a traditional source. Both studies suggested VR improves the effects of empathy-building exercises.

Based on their review of several studies of VR's uses in building empathy, Bertrand et al. [29] propose a framework for empathic training in VR. This framework uses embodied virtual reality (EVR) with additional training to enhance empathic responses via EVR's ability to provide an illusion of body ownership. The training's targeted empathic responses include positive intergroup interaction and evaluation, awareness of the other and the self, empathic concern, and altruistic behavior. The training requires two users to wear EVRs with mounted cameras that broadcast the other participant's first-person perspective via live footage to the opposing user's EVR, thereby swapping the user's perspectives with the others.

Ecological validity in therapeutic roles: Bronfenbrenner defines ecological validity as "the extent to which the environment experienced by the subject in a scientific experiment has the properties it is supposed to have by the investigator" [30, p. 516]. Regarding environments that exhibit ecological validity, Rizzo writes, "VR-derived results could have greater predictive validity and clinical relevance for the challenges that patients face in the real world" [31, p. 122].

C. Immersion

Definition: VR-related studies routinely claim that their environments create immersive experiences for their users. For example, according to Anderson, Rothbaum, and Hodges, "The sense of immersion is achieved by an integration of real-time computer graphics, body-tracking devices, visual displays, spatial audio (sound coming from different locations), and other sensory input." [24, p. 79]. Unfortunately, none of the authors whose work is cited here provide a clear, unambiguous definition of "immersion". According to Shin and Biocca [32], the term "immersion", though " widely used … has not been precisely defined or explained with users. This term has become even more ambiguous in the emerging domain of VR storytelling" [26, p. 64]. Shin and Biocca, like Bangay and Preston [33], equate immersion with sense of presence. Other studies, however, define presence as a completely different concept than immersion. In a discussion of ambiguous characterizations of players' interactions with virtual worlds, Grimshaw observes, "… the two terms [presence and immersion] are used in various fields and have been discussed for three decades, there seems to be a lack of consensus as to what either of them actually refers to…" [34, p. 222].

Framework for immersion: Studies by Shin et al. used four psychometrically based questionnaires to help users articulate their experience of story presentations [35], [36], [32], and [26]. Using data from these questionnaires, Shin et al. developed models that account for how VR creates immersive experiences. These models use four experience factors to account for users' evaluations of their experiences [32]:

- Embodiment –The "[degree to which] users feel their story with their entire body... [and] create the sensation of personally having the experience in VR" (p 2807).
- Empathy –The "[degree to which users] comprehend another person's subjective experience and environment" (p. 2807).

- Immersion – a “sub-optimal experience” that “occurs at one moment in time, similar to engagement, engrossment, and total immersion” (p. 2809).
- Presence – The degree to which “two people interacting via a technological medium feel as if they are together” and "fee[l] connected with other social users” (p. 2809).

The authors’ questionnaire was shown to be reliable and internally consistent using a confirmatory factor analysis, all giving evidence that the following questions likely operationalize their constructs. Shin measured embodiment on a Likert scale of 1 to 7 using the three questions below:

- EMB1: How much did you feel that the object and entity in the VR news was your body?
- EMB2: To what extent did you feel that you could reach into the VR news through your avatar?
- EMB3: When something happened to your avatar, to what extent did it feel that it was happening to any part of your body?

Shin measured presence similarly using these three questions:

- PEQ1: How compelling was your sense of things moving through space?
- PEQ2: How much did your experiences in the VR news seem similar to your real-world experiences?
- PEQ3: How compelling was your sense of moving around inside the VR news?

D. Ecological aspects of Immersion into VR

In order to assure a study’s ecological validity, Bronfenbrenner [30] states research must account for how experimental outcomes could be influenced by reciprocity, or the effect of A on B and B on A; participants’ recognition of the social system in the research setting; the systems’ settings; the participants’ backgrounds; and the physical environment. If a VR environment is intended to help individuals in therapeutic situations, the ways in which the environment’s users are expected to move through, interact virtually with, and develop in that environment should be understood, much as is required of real environments.

In [30], Bronfenbrenner presents a “systems” framework for studying user interactions with virtual environments. This framework organizes an individual’s environment into four nested systems. The most immediate, the “microsystem”, is the “complex of relations between the developing person and environment in the immediate setting containing that person”. Here, setting denotes “a place with particular physical features in which the participants engage in particular activities in particular roles” [30, p. 514].

Looking at the VR environment as a “microsystem” highlights the importance of the settings’ physical features and users’ activities and roles when measuring how technical features affect a user’s psychological experiences. These features include a VR’s situational context. How a VR environment implements a simulation may influence a user’s sense of being in the environment. The effect of factors like rendering rate and resolution on a user's sense of immersion could vary, depending on the game and situation being simulated.

Another factor that affects immersion is a game's use of diegetic and non-diegetic elements. Diegetic elements communicate information through a game's intrinsic elements: i.e., its maps, compasses, watches, and the screen going red to show damage instead of a health bar [37]. Diegetic elements add to the player's immersion and help them identify with the avatar they are controlling. Non-diegetic elements are the parts of the game outside the narrative, meaning only the player can see them. These typically make it easier for players to monitor their status, but detract from a user's sense of immersion [37].

Fricker [38] observed how different first-person shooter games attributes affect the player's experience. She suggested that non-diegetic elements help users take in more information faster, reducing their memory load. Fast-paced games like first-person shooters might benefit from non-diegetic elements though they are not as immersive as diegetic elements.

E. Technology's Impact on Immersion in VR

Controllers: Hufnal et al. [17] determined that differences between the Xbox One and Oculus Touch controllers affected users' sense of immersion. While the two controllers afforded comparable experiences and sense of presence, the Oculus Touch controllers were perceived to be more natural than the Xbox controllers.

Rendering resolution: In [39], Bracken determined that users' sense of presence, defined as "a psychological state or subjective perception created by technology in which all or part of an individual's perception fails to accurately acknowledge the role of technology", was affected by display resolution while watching television. The study showed a common stimulus to two different groups of participants, at a resolution of 1080 pixels to one group and to the other at 480 pixels. The group that viewed the better-quality images reported a stronger sense of presence, as measured by all of the study's variables for evaluating presence. Bracken noted that this result confirmed previous studies done by Lombard et al. and Lombard and Ditton.

Similarly, Bangay and Preston [33] found that an image's quality affects a user's sense of immersion, defined as "a sense of presence." This study immersed users in interactive VR environments that featured swimming with dolphins and a virtual roller coaster. Bangay and Preston concluded that environments that offer exciting experiences, comfortable peripherals, a comfortable environment, and realistic sounds and images tend to increase participants' sense of immersion and excitement; that older participants tend to register lower scores for immersion and excitement; and that simulator sickness, control, excitement of the experience, and desire to repeat the experiment have no effect on these sensations.

Members of the gaming community differ as to the importance of resolution on UX. In a debate on Reddit.com, the community for social news and general discussion forums [40], one contributor argued that running a game on a lower resolution might result in smoother picture quality. One user stated that "resolution is the utmost important quality setting," while another stated a preference for lower resolution because it can improve frame rate. Others replied that the setting does not matter and users should always use the native setting; still others specified preferred resolution settings.

Rendering frame rate (RFR): Choppy frames degrade UX. The Guidelines for VR Performance Optimization Oculus page for developers [41] advises that "Dropped frames that cause discomfort are not worth better quality graphics" [41]. Similarly, an article by Windows Central [42] states, "Choppy graphics, lagging audio, slow load times all contribute to a bad time" [42].

The video game community has long debated whether RFR affects gameplay and UX. One 1,100+-member Reddit.com group, r/FPS, is devoted to discussions of how frames per second affect video games [43]. One point of view that holds that RFR matters is typified by the following comment: "This is an ongoing debate, because some people swear that the human eye can only see around 40 frames per second… Regarding framerate for gaming, higher framerates make the gameplay appear smoother, with less blurring and more crisp transitions." [44]. This contrasts with posts like the following: "I understand more frames make gameplay feel less choppy and smoother, but me and my console friend were arguing about how much frames affect gameplay… If my friend is on 60 FPS and I'm on 120 FPS, how is my gameplay affected compared to his?" In response to this comment, one person claimed they earned a new high score after switching from 60 FPS to 120 FPS, while others argue it is the monitor or the controller [45].

Other aspects of VR that influence a gamer's experience of immersion, according to Wilde [46] include anti-aliasing and screen tearing.

F. Observations

The studies reviewed here fail to specify the characteristics of their hardware in their reports, including image resolution. At face value, the fact that developers often allow users to change a game's resolution suggests that resolution affects a user's quality of experience. Moreover, disagreements among the gaming community on the impact of RFR on user experience suggest a need to address the impact of potential confounding technical variables in studies of immersion in VR and therapeutic applications.

Waltemate [47] discusses the impact of a player's in-game avatar on the player's sense of immersion. In the study, participants enter a virtual environment where they can see their virtual avatar in a mirror. More realistic features like the body's appearance, the clothing, and the quality of rendering positively affected the degree to which participants felt "immersed" in their avatars. This study shows another confounding variable that could arise in this research: if participants can see their avatar in an experiment, it could affect the results of users' immersion.

Shin's conceptualization of "embodiment" is reasonable [27]. His study, however, fails to address whether users feel presence and flow while immersed, if immersion influences behavior, and how immersion affects UX [26, p. 64]. The "presence" factor is particularly troubling, since no question refers to others or social experiences. Both factors can arguably be components of immersion. Immersion is defined differently by authors and the components of immersion also have ambiguous definitions.

III. METHODOLOGY

This study investigated how rendering resolution impacts VR users' sense of immersion. *Immersion* was defined as the degree to which a user treats a virtual environment as realistic: i.e., the extent to which rendering resolution influences a user's sense that the environment's virtual stimuli are real, natural, and intuitive; that its objects appear to be real; and that the user's interactions with the environment are real.

Two factors from Shin et al.'s models of user experience ([35], [36], [32], [26]), embodiment and presence, formed the bases for measuring immersion. They were, however, be conceptualized differently. *Presence* was defined as the degree to which users feel they are experiencing a real and reactive environment. *Embodiment* was defined as the degree to which users feel that their body is naturally inhabiting the avatar in the virtual environment. Presence and embodiment were operationalized using Shin et al.'s questions, with the word "News" in EMB2 replaced by the more general word "experience."

The study accounted for the potential effect of situational context on users' sense of immersion. This included a user's role and relation to others in the environment. It used objective, situational, and narrative games because the experience that a game creates correlates with its usability: the better the environment's usability, the easier it is for a player to feel immersed in the game's experience. An objective type game has a clear goal(s) that needs neither a narrative nor a reason for its goal(s). A situational type game has no clear objective or purpose; it puts a user in situations to which a user is expected to respond. A narrative type game has a story arc involving conflict and resolution and interactive character(s) with a narrative or personality. These game types create an environment and ecology for users' situational context.

The study's experiment compared the responses of two groups relative to two measures of participant immersion: (a) sense of presence and (b) sense of embodiment. Immersion was measured and compared relative to two levels of resolution, one higher than the other, to determine the effect of rendering resolution. One potential moderating variable, game type, was varied over three levels: narrative, objective, and situational. A potentially confounding variable, rendering frame rate (RFR), was fixed by Virtual Reality's built-in ASW and Timewarp systems. Another potential confounder, a participant's prior VR experience, was controlled by stratifying the sample at two levels of experience and assigning these equally to treatment groups. Demographic data included participants' ages, genders, prior experience with VR, and prior experience with gaming. Inclusion criteria were current college enrollment, physical presence in the United States, and willingness to observe East Tennessee State University's COVID-19 safety protocols. Exclusion criteria included acrophobia, epilepsy, and motion sickness.

Participants and research administrator were blind to the treatment group to which they were assigned; the equipment manager was not. Demographic data was collected prior to group assignment to assure stratification by prior VR experience. Response variables were measured immediately after each VR experience with self-reporting using a questionnaire administered by the research observer. After a participant's VR experiences were finished, a research observer conducted a semi-structured interview with that participant. The observer discussed the study's significance, noted the importance of participant's volunteered time, and gave each participant resources to learn more about the study via the researcher's information and the school's counseling.

A. Population and sample

The general population of interest was "pre-professional" college students: non-minors, ranging 18 to 30 in age. This age range was selected because of that age group's familiarity with computer technology.

1. Sample: Participants were recruited with fliers that offered participants a free experience of three different games in VR with the Oculus Quest. These fliers, distributed around East Tennessee State University's campus, attracted students from different academic backgrounds with different personalities. The fliers had a QR code or link to an online form, via Typeform, to screen potential participants for eligibility while preserving participants' confidentiality, specifically identity and privacy.

2. Ethical treatment of participants: All methods, recruitment materials, measurement instruments, and debriefing procedures were approved in advance by the Institutional Review Board of East Tennessee State University. Participants' anonymity was protected by assigning each a random ID prior to data collection. All data was identified by this ID only.

Because some VR treatments could produce intense personal experiences, treatments were administered according to protocols that encouraged the participants' agency, limited their exposure to disturbing scenarios, and gave them clear avenues to opt out or leave the study entirely. This included people with a phobia of heights because of the nature of Richie's Plank Experience and people with epilepsy and extreme sensitivity to motion sickness because of the nature of VR technology.

3. Justice: Participants received equal opportunities and treatment in the study. Anticipated benefits from participation were a feeling of contribution to science and one's community and an interesting experience outside of one's routine.

B. Demographic data

Before being sent to a demographic questionnaire, prospective participants were screened for exclusion criteria, including acrophobia, epilepsy, and motion sickness. All data for prospective participants who were disqualified from the study on any of these accounts were immediately discarded. The questionnaire asked for a user's, age, gender, level of prior video game experience (none, very little, moderate, often), level of prior VR experience (none, very little, moderate, often), and contact information; the latter was used to tell prospective participant if they could partake in the study.

C. Treatment

The HMD for this research was the Oculus Quest 2 (Fig. 1). This is a 6DOF VR system that allows a user's body movement to be integrated into the experience. It is an all-in-one HMD that does not require a PC. Its specs [48] include a Single Fast-Switch liquid-crystal display, 1832x1920 ppi resolution per eye, 72 hertz per second refresh rate, built-in speakers with an optional 3.5 mm audio jack for headphones, 64 gigabytes or 128 gigabytes internal hard drive storage, a Qualcomm® Snapdragon XR2 Platform CPU, and an additional optional buffer piece for users with glasses.

The Quest features two Oculus Touch Controllers. The controllers, a left- and a right-hand controller, track a user's hand movements and gestures to integrate into the experience. Each controller has a joystick; two buttons on the front of each controller; an 'A' and 'B' on the right side; an 'X' and 'Y' button on the left; and two trigger buttons, one on top for the index finger and one on the back for the middle finger, to provide for a natural grip. The right-hand controller has an Oculus button and the left-hand has a menu button. The circle above the controller uses motion tracking to communicate its user's hand position to the HMD. Each controller is powered by one AA battery.

Figure 1. Oculus Quest 2 with its two Oculus Touch Controllers. Both this system and its controllers use 6DOF tracking without the need for any external sensors or wires.

The study's two levels of rendering resolution, low (512 ppi) and high (2048 ppi), were established before starting treatments. They were determined by studying how game type and resolution affect RFR, by running each game with a HUD that displays the game's FPS.

D. Game experience management

Each participant participated in each of the following three VR games:

- *Oculus First Contact* is an objective game by developer Oculus. The game is designed to introduce users to VR. In it, a user sees a robot guide who encourages the user to interact with and pick up objects in the environment. Small hints from on-screen graphics and suggestions from the robot guide are used to direct the user's actions. While the game lacks a storyline, it asks users to complete small goals and tasks.
- *Richie's Plank Experience* is a situational game by developer Toast. It puts users in front of an elevator, allowing them to choose to enter it. The elevator, if entered, takes users to a plank looming 80 stories above the ground. Users can then choose to walk out onto the plank and look around the city below them.
- *Ghost Giant* is a narrative game by developer Zoink. Users are a giant ghost that helps a young lonely boy named Louis by interacting with the world to solve puzzles. Louis is the only character that is aware of the user's presence in the world. The game's story arc presents a conflict and provides a resolution to the conflict. It also has several characters in the town of Sancourt who have a progressive narrative throughout the game; Louis, the main character, particularly grows a bond with the player.

1. Game Order: Each participant played through a tutorial to give participants more confidence to maximize potential UX before playing the three games. The order of the three games was predetermined randomly by the equipment manager and was kept confidential to the research administrator and participant.

2. Facilitation Protocols: A facilitation protocol, involving a research administrator (RA) and an equipment manager (EM), was used to ensure consistency across participants, constrain the experience, and allow participants to opt-out and exit treatment.

The EM manipulated the VR equipment and was alerted to the treatment condition. The EM also cleaned the equipment between participants following COVID-19 safety protocols.

The RA attended to the participant's behaviors and engaged the participant directly during the VR experience to help assure the participant's engagement. The RA was instructed to avoid prompting participants to behave in any particular way and to avoid pressuring them to move past where they wanted to; rather, the RA was merely directed to prompt them to stay engaged in the game as long as they were comfortable.

For example, with Plank,

- If a participant were to say, "I can't do this" when the elevator door opens, the RA was instructed to say, "OK, take a breath, tell me what the problem is." If the participant wanted to end the game, the RA was instructed to say, "OK, press the elevator door button and go back down and take off the headset."
- If a participant were to begin to describe their thoughts, the RA was instructed to say, "OK, I get that; remember the game is meant to encourage you to interact with the world in some way. Can you interact with this game in some way you are comfortable with?" If a participant were to then refuse to act, the RA was instructed to say, "OK, we will end the game. Press the elevator door button and go back down and take off the headset."

If, after some initial hesitancy, a participant began to interact with a game's environment, the RA was to return to standard protocol. This included saying nothing to remind participants of their presence in a virtual world or video game to avoid interfering with their sense of immersion. The RA was also required to refrain from saying anything to suggest the experience should feel real to prevent bias.

For all three games, the RA was tasked with ending gameplay and debriefing participants.

The RA brought participants into the room in which the study was conducted, introducing them to the equipment, and guiding them through the study procedure. The RA was blind to the treatment condition and did not interact with the VR equipment. After each game type, the RA gave each participant a questionnaire. After playing all three games, the RA conducted the final short semi-structured interview to enable them to describe their VR experiences and wind down from the study. At the study's conclusion, the RA led the participants out of the facility.

E. Rendering frame rate

Two RFR-preserving resolutions levels, 512 ppi for low and 2048 ppi for high, were chosen to assure consistency of treatment. This choice mitigated the potential confounding impact of varying rates of RFR on the study's treatment variable, relative to users' sense of immersion. To ensure frame rate consistency, each game was run with a HUD displaying the FPS of the game rendering before working with participants. Resolution levels were changed, and the game's average FPS were recorded to ensure that it remained constant across game types and treatment variables.

F. Dependent measures

Immersion was measured on two constructs, the users' sense of presence in an environment and the users' sense of embodiment in the environment. Each was measured by three Likert scale questions on a scale of 1 to 7, adapted from Shin [32], with 1 meaning "very little" and 7 meaning "very much". The survey's questions and the definitions upon which they were based are given below:

1. Presence: How much a user feels they are experiencing a real and reactive environment.

PEQ1: How compelling was your sense of things moving through space?
PEQ2: How much did your experiences in the VR news seem similar to your real-world experiences?
PEQ3: How compelling was your sense of moving around inside the VR experience?

2. Embodiment: How much a user feels their body is naturally inhabiting the avatar in the virtual environment.

EMB1: How much did you feel that the object and entity in the VR experience was your body?
EMB2: To what extent did you feel that you could reach into the VR experience through your avatar?
EMB3: When something happened to your avatar, to what extent did it feel that it was happening to any part of your body?

G. Facilities

The study was conducted in 28.5' x 19' room, which exceeded the recommended 6.5' x 6.5' the space that Oculus recommends for the play area. The room was devoid of furniture and other objects. Since the study's three games required relatively little movement, it was thought that this amount of space would guarantee that users did not encounter Oculus's "guardian boundary": a virtual grid fence that limits users to the play space and ensures user safety.

Participants' privacy was ensured by allowing no one to enter or exit the testing space once an experiment began.

H. Procedures

Volunteers who passed the initial online screening were sent an email by the research administrator (RA) and offered a time slot to volunteer for the study. The equipment manager (EM) prepared a study's resolution on the VR HMD, while keeping this secret from the participant and the RA. Participants first encountered the EM and were asked to acknowledge and agree to safety protocol. Each successive participant was then introduced to the RA and brought into the study's room. The RA gave the participant a general idea of the study, introduced them to the equipment, informed the participant that they could ask for assistance if needed, and offered help with putting on the HMD.

During gameplay, the RA observed a participant's actions. The RA used the following verbal prompts during each game:

- Oculus First Contact: "When you put on the VR, you will be standing in a room. Feel free to interact with and pick up objects in your surroundings."
- Ghost Giant: "When you put on the VR, you will see prompts to follow to set up the game."
- Richie's Plank Experience:
    - Initially: "When you put on the VR, you will see an elevator. Feel free to look around the area. When you are ready, please walk into the elevator and press the button labeled 'Plank' on your right."
    - When the sound of the elevator door opening on the top floor plays: "Feel free to walk out onto the plank and look around the cityscape. If you feel uncomfortable, remember you can always reenter the elevator and use the button labeled 'Ground' to return to ground level."
    - For participants who showed lots of discomfort or fear: "Remember, you can remove the headset if you feel too overwhelmed but also remember you are in no real danger."

The RA was instructed to remind participants who asked for help about the game's controls and ask them to try interacting with the environment; this was seen as a non-biasing way to assist the participant. The RA was to encourage participants to stay in the game as long as possible by reminding them of the game's purpose or suggesting that they interact with the environment in any way they felt comfortable. The RA was also instructed to avoid suggesting any strategies that made participants uncomfortable and allow each participant to stop playing the game and end the study at any time.

After the participants played each game, the RA gave them a questionnaire that measured the study's dependent variable. After the participant completed the last questionnaire, that participant was offered a brief break, then interviewed by the RA.

I. Debriefing and follow-up

After the participant played all three games, the RA conducted the final short semi-structured interview. This interview enabled the participant to describe their VR experiences and wind down from the study. The RA first told each participant that "The study's overall purpose is to explore whether 'gaming technicalities' need to be taken into account in therapeutic uses of virtual reality.” Then the interview proceeded with questions as “How are you feeling?” and “How did you feel in the games?” This naturally led the dialog of the next questions: “What did you like/dislike about the games?”, “What made you feel immersed/not immersed in each game?”, and “Any particular element in the experience made you feel immersed/not immersed?” The researcher made brief anonymized notes from the responses. To ensure that each participant was comfortable before leaving the study, the RA’s last two questions were always “Were there any experiences that bothered or unsettled you that you would like to discuss?” followed by “Is there anything else from your experiences today that you would like to share with me?” The RA then thanked the participant for their time and sent them home with the RA’s contact information and the ETSU’s school counseling contact information. There was no follow-up contact with the participants.

IV. ANALYSIS

A. Sample Descriptive Analysis

1. Summary statistics: For the dependent measure, overall and per-game-type sample descriptive statistics—mean (M) and inter-quartile range (IQR)—were tabulated by treatment level (Table 1).

Table 1. Descriptive sample statistics for response variables

Treatment Level	Game Type	Immersion	
		M(Average)	IQR(Q3-Q1)
Low	Overall		
	Situation		
	Objective		
	Narrative		
High	Overall		
	Situation		
	Objective		
	Narrative		

2. Distributions: To visualize main effects, density models and boxplots of overall distributions of each response variable were paneled by treatment level to visualize how resolution affects the distribution of users' sense of immersion.

Density models and boxplots of each response variable's conditional distributions relative to game type were clustered by treatment level and paneled by game type to visualize how treatment effects on distributions of responses change with game type. In addition, interaction plots for each response variable were plotted, showing how conditional means and medians change with game type, using conditional standard deviations for error bars. The center and spread of response distributions revealed how immersion measures are distributed and vary across controlled variables. This analysis demonstrated effect sizes and helped guide new hypotheses about users' sense of immersion and guided what kind of assumptions can be made about the distributions of response measures.

3. Research questions: RQ1 was addressed by analyzing differences between low- and high-resolution VR experiences in summary statistics and distributions of overall presence and embodiment scores.

RQ2 was addressed by analyzing differences between high- and low-resolution VR experiences in summary statistics and distributions of immersion scores across game-type conditions. RQ2 was also addressed by looking for different patterns of means and medians between treatment levels in the interaction plots.

B. Inferential analysis

1. Overall resolution statistical significance and effect sizes: The results from the low- and high-resolution treatment levels were compared using a T-test:

T-test formula: $t = \frac{m - \mu}{s \,/\, \sqrt{n}}$

A T-test produces a result, a p-value, that indicates the likelihood that an experiment's outcome was due to random chance; the lower the p-value, the greater the statistical significance. For this study, a p-value that was less than or equal to 0.05 would indicate that the difference in resolution significantly affected a participant's sense of immersion. The T-test between the low- and high-resolution results concluded if the rendering resolution is an aspect that affects user's immersion.

2. Game variance statistical significance: Each game type's immersion results were compared using T-tests to test for a significant effect via the computed p-value. These comparisons did not account for the rendering resolution; rather, they focused on the second treatment level, game type. The following comparisons were made with the resulting data: situational versus objective, situational versus narrative, narrative versus objective. The T-test between the game types concluded if the game type is an aspect that affects users' immersion.

V. RESULTS

Four demographic variables, two controlled variables, and one dependent variable were collected for each participant. The dependence variable, immersion, was collected from each participant for each VR game through the measurements of the *Immersion tendency Questionnaire* (Appendix B). This questionnaire featured ten questions, each of which asked users to indicate the strength of their feelings about some aspect of their experiences, using a scale that ranged from 1 ("NEVER") to 7 ("OFTEN"). These scores were then averaged to obtain a score for immersion.

Sixty-one people followed the link to the online Typeform consent page. There was a 19.67% rejection rate; the consent page eliminated twelve people who failed to meet one or more of the following criteria:

- between 18 and 30 years old
- can read and speak English
- can be physically present in the study's location
- can volunteer 2 hours of time
- will adhere to ETSU-mandated COVID-19 safety measures
- have no condition of epilepsy
- are not prone to motion sickness or vertigo
- have not experienced any recent migraine headache, head concussions, or other injuries that could impact thinking or emotional experiences.

On completion, the consent page redirected eligible individuals to a demographic survey. This survey anonymously asked for their age, gender, and VR and video game experience: the latter on a scale of 1-4, 1 meaning none and 4 meaning often. Figures 2, 3, 4, and 5 reflect the forty-three responses to the Demographic Survey.

A total of 31 participants volunteered for the study. 30 of the 31 participants' questionnaires were retained. The remaining participant's responses were excluded because that participant failed to complete the backside of the questionnaires immediately following the games. While one participant was too scared to step out onto the plank in Richie's Plank Experience, none of the participants experienced emotional discomfort or required verbal prompts to take off the headset prematurely.

Due to technical difficulties outside of the research staff's control, the Oculus Quest 2 would sometimes recalibrate the games' environments and some participants saw or ran into the guardian boundary grid.

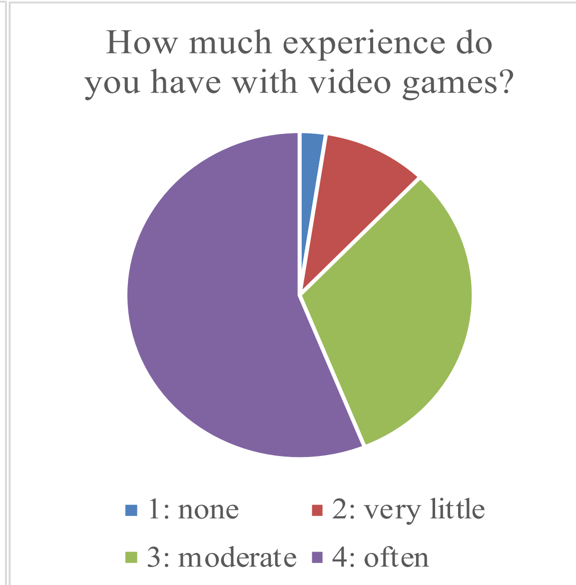
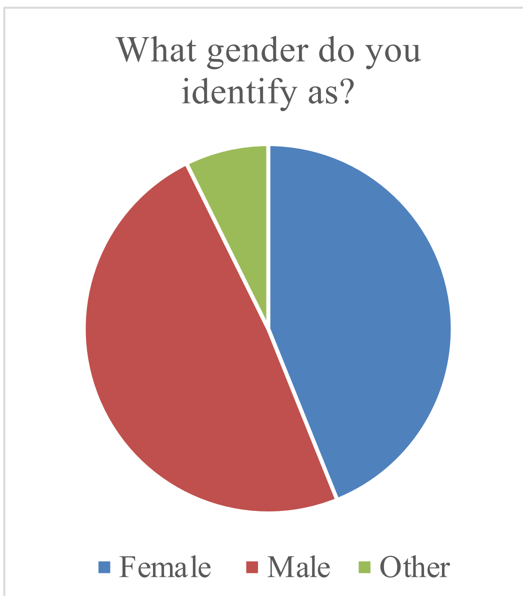


Figure 2. VR Experience Demographic

Figure 3. Video Game Experience Demographic



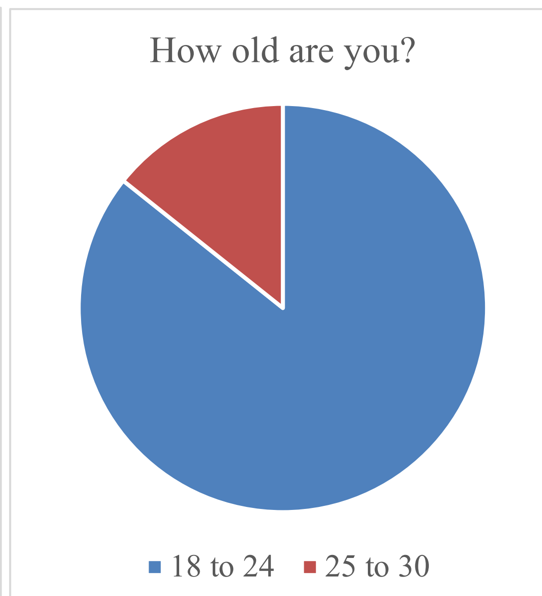


Figure 4. Gender Demographic

Figure 5. Age Demographic

There has not been any follow-up contact from the participants. Table 2 summarizes the participants' data.

Table 2. Descriptive sample statistics for response variables			
Treatment Level	Game Type	Immersion	
		M(Average)	IQR(Q3-Q1)
Low	Overall	5.39	3.00
	Situation	5.51	1.65
	Objective	5.18	1.45
	Narrative	5.33	1.80
High	Overall	5.16	3.00
	Situation	5.40	1.35
	Objective	5.35	1.43
	Narrative	4.73	1.40

Table 3 gives the results of T-Tests that compare the high- and low-resolution groups. An overall p-value of 0.71 was computed from the T-test.

Table 3. T-Test: Two-Sample Assuming Equal Variances		
	Low Resolution (LR)	*High Resolution (HR)*
Mean	5.341543514	5.22044335
Variance	1.092815199	0.474704638
Observations	14	16
Pooled Variance	0.761684542	
Hypothesized Mean Difference	0	
df	28	
t Stat	0.379158279	
P(T<=t) one-tail	0.353715279	
t Critical one-tail	1.701130934	
P(T<=t) two-tail	0.707430559	
t Critical two-tail	2.048407142	

Figure 5 reflects the same data, comparing the low- and high-resolution groups, illustrating the distribution.

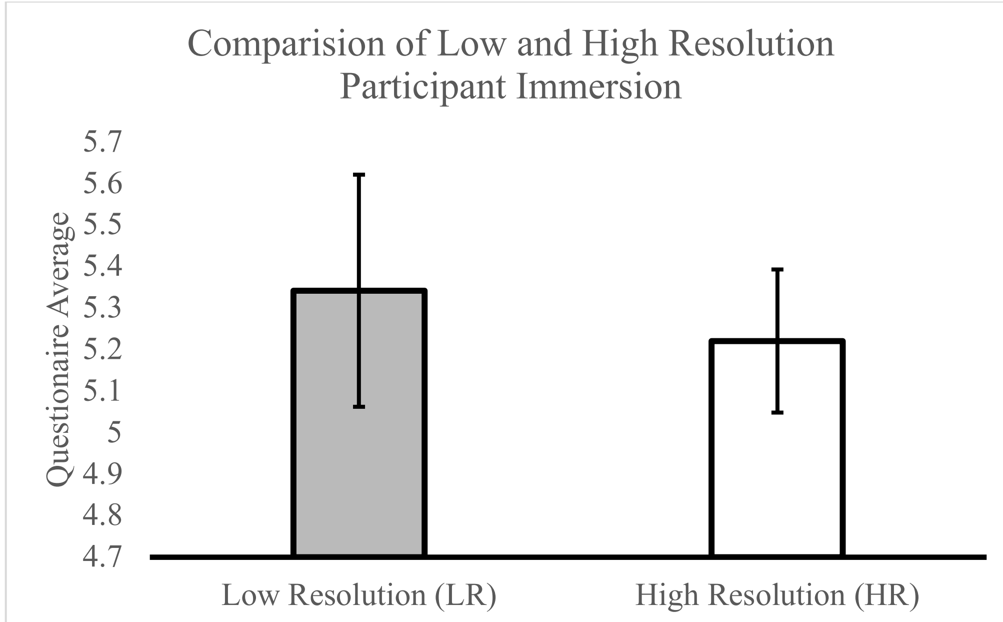


Figure 5

Table 4 illustrates a T-Test comparing the situational game, Richie's Plank Experience, and the narrative game, Ghost Giant. A p-value of 0.01 was computed from the comparison. Figure 2 reflects the same data, comparing the averages from the two games, illustrating the distribution. Comparisons among the other games—situational versus objective or objective versus narrative—yielded no significant results.

Table 4. T-Test: Paired Two Sample for Means		
	Richie's Plank Ex.	*Ghost Giant*
Mean	5.521851852	5.027222222
Variance	0.97995303	1.233380907
Observations	30	30
Pearson Correlation	0.567031937	
Hypothesized Mean Difference	0	
df	29	
t Stat	2.755668793	
P(T<=t) one-tail	0.005008655	
t Critical one-tail	1.699127027	
P(T<=t) two-tail	0.01001731	
t Critical two-tail	2.045229642	

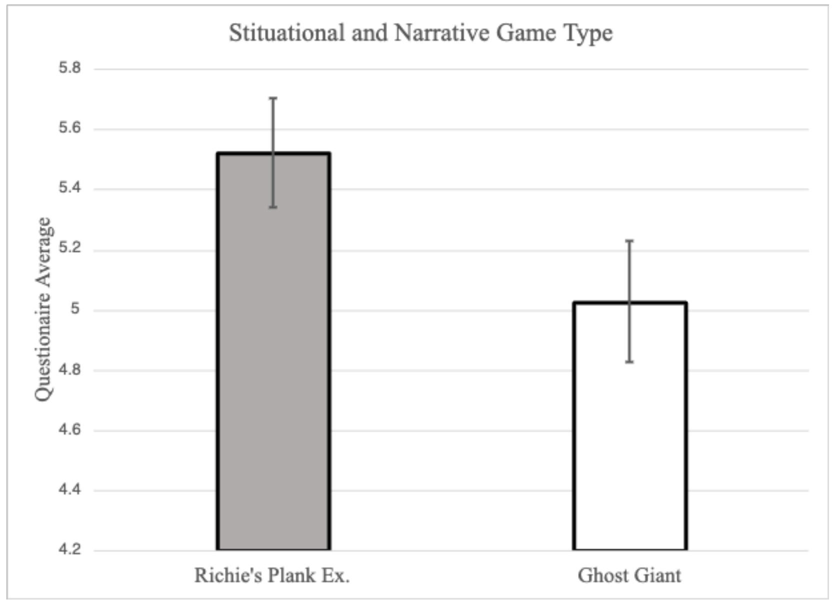

Stituational and Narrative Game Type
Questionaire Average
5.8
5.6
5.4
5.2
5
4.8
4.6
4.4
4.2
Richie's Plank Ex.
Ghost Giant

Figure 6

VI. DISCUSSION

The p-value of 0.71 from the T-Test comparing the low- and high-resolution groups shows no statistical significance since it is greater than 0.05. Accordingly, the null hypothesis for RQ1 cannot be rejected; the change in resolution used as a basis for these experiments, relative to the chosen degrees of resolution, does not appear to affect users' sense of immersion. The increased variance in the low-resolution compared to the high-resolution group could suggest that the quality of resolution effect merits further study.

The p-value of 0.01 from the T-Test that compared the situational game, Richie's Plank Experience, to the narrative game, Ghost Giant, shows statistical significance since it is less than 0.05. Accordingly, the null hypothesis for RQ2 is rejected; the situational game type was more immersive than the narrative game type. The increased immersion could be due to Richie's Plank Experience being the most realistic of the games. Richie's Plank Experience puts users into a life-like situation to explore at their pace while Ghost Giant and Oculus First Contact feature imaginary creatures, i.e., an animated robot in Oculus First Contact and a cartoon cat in Ghost Giant. This significant data point shows the context and various elements, e.g., diegetic and non-diegetic elements as mentioned in Fricker [38] investigation of first-person shooters, of the situation is an important aspect of immersion for VR users.

A. Research Questions

I anticipated that gaming technicalities would affect users' sense of immersion in the VR experience. I also anticipated that there would not be a change in this effect over the types of games. Below, I give a "no effect" (Null) hypothesis, the expected, and the actual hypothesized effect for each research question.

RQ1: Does resolution effect the participant's sense of immersion?

Hypothesis: Higher resolution will increase all measures of the user's sense of immersion.

Null Hypothesis: Resolution won't materially affect any measures of a user's sense of immersion. In other words, the difference between the average immersion values for low-resolution and high-resolution experiences will be insignificant.

Actual Findings: The calculated p-value of 0.71 shows no statistical significance, so we cannot reject the null hypothesis.

RQ2: Does the treatment effect vary with game type?

Hypothesis: Treatment effect will vary by game type.

Null Hypothesis: Treatment effect will not vary by game type. In other words, Richie's Plank Experience would be affected the same by resolution changes as in Ghost Giant or Oculus First Contact.

Actual Findings: The calculated p-value of 0.01 shows statistical significance, so we can reject the null hypothesis.

VII. CONCLUSION

A. Overall

This study investigated the potential effect of rendering resolution on the immersive nature of Virtual Reality. Results were determined from 30 participants who were assigned to play an objective game (Oculus First Contact), a situational game (Richie's Plank Experience), and a narrative game (Ghost Giant). The participants were randomly assigned to play games with either a low resolution of 512 ppi or a high resolution of 2048 ppi. Data indicated that the rendering resolution did not affect user immersion, but the game type did affect immersion and the situational game type was determined to be significantly more immersive than the other game types.

B. Specific Research Question Conclusions

RQ1: Main effects: Does the resolution affect users' immersion?

The results from the T-Test comparing the immersion between the low- and high-resolution groups indicates that resolution does not influence user's sense of immersion in VR, relative to the experiment's parameters. This finding is inconsistent with the results from Bracken's study [39], which found that participants with the higher quality display television resolution treatment of 1080 ppi felt a stronger sense of presence than the lower quality resolution of 480 ppi. This could be due to differences in display quality between the earlier and current study; differences in the technology for image delivery, i.e., that VR technology's ability to immerse participants in a virtual world peaks at or below the study's lower resolution; or to participants not being aware of the difference in quality, due to their being exposed to only one level of resolution. This latter concern is similar to a failure to appreciate a deficiency in sensory acuity—e.g., vision, hearing—until that deficiency is corrected. A future study could have participants play the same VR game in succession with the lower and higher resolution to see if the ability to compare the resolutions would affect users' sense of immersion.

RQ2: Interaction effects: Does the treatment effect vary with game type?

The finding that situational game types influenced sense of immersion indicates that the nature of a virtual situation can influence a user's sense of immersion in a VR application. This finding could be due to Richie's Plank Experience's total focus on realism, as opposed to the other games' fantastical elements. This result proves that VR research needs to account for and clearly describe the virtual situation in use. This result also implies that therapeutic VR applications should use more realistic scenarios to optimize user immersion.

VIII. FUTURE WORK

Much of the literature on game quality focuses on the impact of frame rate on UX. This study focused on rendering resolution rather than frame rate because of my inability to manipulate RFR and refresh rate. It also uses a smaller sample size than I would have preferred, due to a lack of volunteers. These considerations should be addressed in future studies.

Due to technical difficulties outside of the research staff's control, the Oculus Quest 2 would at times recalibrate the games' environments and some participants saw or ran into the guardian boundary grid. Future work should investigate how to guarantee the user staying in the play area so the guardian boundary is never seen.

Other difficulties were created by the requirements for screening prospective participants. The multi-step nature of the process, together with the processes needed to maintain participants' confidentiality, made it difficult to map demographic data to participants in the study. This problem could be addressed by surveying participants immediately before conducting the treatments, thereby ensuring that each participant's results can be matched to one demographic survey.

Future work should use live measurements because of the difficulty of recalling an experience even immediately after an activity [49], in this case playing the games. Furthermore, once a person understands an action, it becomes an automatic or unconscious motion in execution, which makes it hard to thoroughly describe the activity afterwards. A live brain activity feed, e.g., electroencephalogram (EEG), functional magnetic resonance imaging (fMRI), eye tracking, heart monitor, and/or breathing monitor, can give a more accurate characterization of a user's response to the current activity.

Future work could further investigate if resolution affects users' sense of immersion in virtual reality. This can be accomplished by having each participant play a given game at various levels of resolution. The consecutive comparison and change in resolution would allow participants to evaluate the difference in image quality and indicate whether the change in resolution affected their sense of immersion.

The studies reviewed here also failed to determine long-term ecological validity of VR therapy sessions. Long-term ecologically valid therapies help patients improve their lives outside of therapy. Parsons [5] proposes VR has potential to be a long-term ecologically valid therapy, but the ecological validity of VR is uncertain.

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APPENDIX A. DEFINITIONS

Embodiment: The degree to which users feel their bodies are inhabiting a virtual avatar.

Frame rate: The rate at which a graphical processing unit (GPU) generates frames; measured in frames per second (FPS).

Immersion: The degree to which a user regards a virtual environment as a satisfactory simulacrum for reality. This includes the degree to which virtual stimuli, objects, and interactions with the simulation seem real, natural, and intuitive. Indications to this effect include natural, engaging reactions like flinching, dodging, reaching out to grab something, and verbal reactions to stimuli.

Narrative game: A game with a story arc involving conflict and resolution and interactive character(s) with a narrative or personality.

Objective game: A game with a clear goal(s) without a necessary narrative or reason behind said goal(s).

Presence: The degree to which users feel they are experiencing a real and reactive environment.

Refresh rate: The rate at which an image is updated; measured in hertz (Hz).

Rendering frame rate (RFR): See Frame Rate.

Situational game: A game with no clear objective or purpose; it places a user in a situation and enables the user to choose actions in response to said situation.

APPENDIX B. QUESTIONNAIRE

Immersion Tendency Questionnaire

1. Did you easily become entirely involved in the virtual environment?

|________|________|________|________|________|________|________|

NEVER OCCASIONALLY OFTEN

2. Did you ever become so absorbed in the virtual environment or visuals that people have problems getting your attention?

|________|________|________|________|________|________|________|

NEVER OCCASIONALLY OFTEN

3. How mentally alert did you feel at the present time?

|________|________|________|________|________|________|________|

NEVER OCCASIONALLY OFTEN

4. Did you ever become so involved in the virtual environment that you are not aware of things happening around you?

|________|________|________|________|________|________|________|

NEVER OCCASIONALLY OFTEN

5. How often do you find yourself closely identifying with the characters in the storyline?

|________|________|________|________|________|________|________|

NEVER OCCASIONALLY OFTEN

6. Did you ever become so immersed in the video game that it is as if you are inside the game rather than moving a joystick and watching the screen?

|________|________|________|________|________|________|________|

NEVER OCCASIONALLY OFTEN

7. Do you normally enjoy the virtual environment experience?

|________|________|________|________|________|________|________|

NEVER OCCASIONALLY OFTEN

8. When you experienced the virtual game, how completely are all of your senses engaged?

|________|________|________|________|________|________|________|

NEVER OCCASIONALLY OFTEN

9. How much of the visual aspects of the virtual environment involve you?

|________|________|________|________|________|________|________|

NEVER OCCASIONALLY OFTEN

10. How much of the auditory aspects of the virtual environment involve you?

|________|________|________|________|________|________|________|

NEVER OCCASIONALLY OFTEN