Effects of Virtual Reality System Fidelity on Presence using the Fidelity-based Presence Scale

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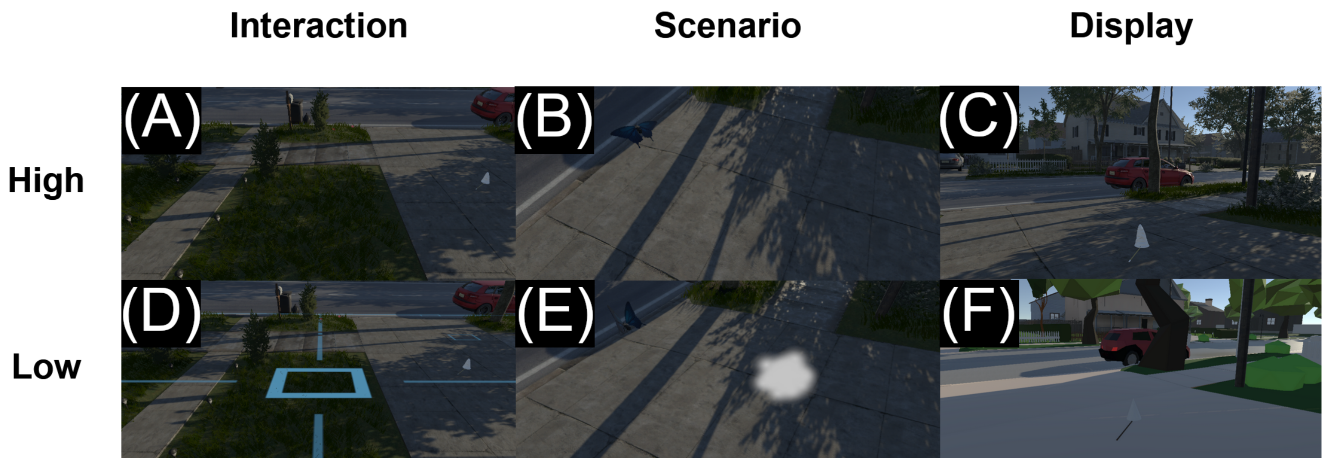

Figure 1: The system fidelity variations we implemented in our user study. The top row (A-C) shows the high fidelity versions of the interaction (i.e. Physically Walking), scenario (i.e. Butterfly flying consistently), and display (i.e. High-poly models and textures.) components of our study. Subsequently, the bottom row (D-F) shows the low fidelity variants of the system fidelity components.

Abstract

Numerous studies have investigated the effects of system fidelity as a whole on one's total sense of presence in virtual reality (VR). The Fidelity-based Presence Scale (FPS), a recently introduced presence questionnaire, provides a method for investigating the effects of different system fidelities (interaction, scenario, and display) on different aspects of one's sense of presence. In this paper, we present one of the first studies to investigate those effects for a locomotion task by conducting a $2 \times 2 \times 2$ within-subjects experiment that reveals insight on how the components of system fidelity affect sense of presence. Like recent research, our results indicate that interaction fidelity and display fidelity significantly affect one's interaction presence and display presence, respectively. However, unlike prior work, we did not find that changes in scenario fidelity significantly affected one's scenario presence. We discuss other results and the possible implications of this research.

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CCS Concepts

• **Human-centered computing** → **Virtual reality**.

Keywords

Virtual reality, presence, fidelity

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1 Introduction

In the past few years, virtual reality (VR) technology has become more ubiquitous and accessible to a broad range of users. With recent advances in VR technologies, such as the Meta Quest 3[1] and the Apple Vision Pro[2] that boast high fidelity virtual experiences, it is clear that there is a push towards building user experiences that make users feel like they have been transported to a new world. However, along with this push, there has not been a lot of research that investigates how the design features of a given virtual environment (VE) influence the sense of being in a VE [61]. This

[1] https://www.meta.com/quest/
[2] https://www.apple.com/apple-vision-pro/

sensation of "being there" in a VE is commonly defined as *presence* [32, 48, 51, 53, 59, 68, 77]. In the past, we have predominantly measured presence through questionnaires, however one critique of previous questionnaires is that there has not been a tool developed that measures presence on the basis of perceived realism and fidelity [4, 59]. Therefore, in our work, we leverage a recently created tool, the Fidelity-based Presence Scale (FPS) [4], to better understand how design decisions across the system fidelity components affect sense of presence.

Compared to previously created questionnaires, the FPS aims to measure presence across three core components: Interaction Presence, Scenario Presence, and Display Presence [4]. These metrics correspond directly to McMahan et al.'s [37, 40] system fidelity framework, which breaks down VR experiences into interaction fidelity, scenario fidelity, and display fidelity. Interaction fidelity refers to any input the user can leverage to effect change within the VE (e.g., object manipulation, locomotion). Scenario fidelity refers to the rules and behaviors the VE abides by (e.g., behavior of agents/objects. Display fidelity encompasses any component of the VR experience that conveys feedback to any of the five senses (e.g. polygon count, audio quality).

Crucially, grounding the FPS in system fidelity represents a fundamental departure from the theoretical structuring used by most established presence questionnaires. Traditional presence measurement tools conceptualize presence primarily as a psychological state inferred from users' subjective impressions of the VE [34, 54, 59, 70]. These factors describe how users feel in the VE, but they provide limited insight into why those feelings emerged from a VR system's design. In contrast, the FPS treats presence as an outcome that can be systematically linked to identifiable components of the VR system itself [4]. Rather than aggregating general user experiences, the FPS isolates which features of the system's interaction mechanics, scenario logic, or display qualities contributed to one's sense of presence.

To better understand the effects of system fidelity on one's sense of presence and to investigate the robustness of the recent FPS questionnaire, we present one of the few studies to control for all three components of system fidelity while administering the FPS. In this paper, we present a $2 \times 2 \times 2$ within-subjects study that controlled interaction, scenario, and display fidelity at low and high levels (see Figure 1). Our study is comprised of collected data across 50 participants, and we learned of the effects of modifying each system fidelity component in a locomotion oriented task where participants attempt to catch a butterfly in VR. Utilizing the FPS, we present the results across Total Presence, Interaction Presence, Scenario Presence and Display Presence. Our results indicate the following in our locomotion task:

(1) High fidelity variations of interaction, scenario and display increases sense of Total Presence
(2) Physically walking lead to higher sense of interaction presence compared to locomotion via teleportation.
(3) The environment with higher audiovisual fidelity lead to higher sense of display presence compared to the environment with lower audiovisual fidelity.
(4) The butterfly flying continuously compared to the butterfly intermittently teleporting were not significantly different with regard to scenario presence.

In addition to the aforementioned results, the main contributions of our work include an assessment of how we can better interpret effect sizes with regard to presence, furthering the robustness of the FPS measurement tool by applying it to a locomotion task, and an thorough within-subjects investigation examining each system fidelity component and how each component impacts sense of presence.

2 Related Work

Our work is at the intersection of two adjacent constructs: perceived realism/fidelity and sense of presence. With regard to perceived realism, we focus on previous work that has examined different components of a VE at different fidelity levels (e.g., high visual realism versus low visual realism). We also review how presence questionnaires have been used in the past and consider which presence questionnaire aids in bridging the relationship between perceived realism/fidelity and sense of presence. In our study, participants engage in an environment that systematically evaluates interaction, scenario, and display fidelities at varying levels. By taking inspiration from previous work, we designed a study that allowed our participants to evaluate different variations of the same environment. Therefore, in this section, we provide an overview of relevant literature at the aforementioned intersection.

2.1 Investigation of Realism and Fidelity

In previous work, there are numerous instances in which alterations to fidelity have been investigated to learn more about sense of presence. For example, McMahan et al. [39] evaluated changes in both display fidelity and interaction fidelity with the outcome that high fidelity variants of both components led to significantly higher perceived presence from their participants. Adkins et al. [1] compared object manipulation with a tracked glove and a standard VR controller with the outcome that grasping objects with a tracked glove led users to feel significantly more present within the environment. Dufresne et al. [17] conducted a study in which they evaluated changes in interaction fidelity and display fidelity in a user study contextualized in an Apollo-inspired moon task. In their study, they controlled for the type of input interface, custom gloves with controllers versus standard controllers, and the presence of passive haptics for their object proxy. One key finding from their study was that the custom gloves that simulated astronaut gloves led to a significant, positive impact on sense of general presence. Skarbez et al. [62] conducted a study investigating changes in display fidelity and scenario fidelity. Two key findings in their work was that the higher fidelity variations of being able to see their virtual body in the mirror and the scenario coherence (the appearance of the bar environment) positively impacted their participants' perceived realism. In Newman et al.'s work [42], they constructed four environment spaces, 2 high visual fidelity spaces and 2 low visual fidelity spaces. A key finding was that regardless of the environment, higher levels of perceived realism led to participants reporting significantly higher presence scores.

Table 1: List of previous user studies that measured presence within virtual environments. We highlight which component(s) of system fidelity each study modified as, whether they measured presence based on Total Presence, Interaction Presence and Scenario Presence, and their highest reported effect sizes with regard to presence. Given that some studies reported effect sizes differently, we calculated the Cohen's f value based on their reported effect size [12]

Citation	Interaction Fidelity	Scenario Fidelity	Display Fidelity	Total Presence	Max Effect Size	Interaction Presence	Scenario Presence	Display Presence
[30]		✓		✓	N.R.			
[72]			✓	✓	N.R.			
[63]			✓	✓	N.R.			
[76]			✓	✓	N.R.			
[3]			✓	✓	N.R.			
[22]			✓	✓	N.R.			
[60]			✓	✓	N.R.			
[61]			✓	✓	N.R.			
[42]			✓	✓	N.R.			
[33]			✓	✓	N.R.			
[50]			✓	✓	N.R.			
[23]			✓	✓	N.R.			
[73]	✓		✓	✓	N.R.			
[39]	✓		✓	✓	N.R.			
[62]		✓	✓	✓	N.R.			
[71]	✓			✓	N.R.			
[36]	✓			✓	N.R.			
[5]	✓			✓	N.R.			
[1]	✓			✓	N.R.			
[25]	✓			✓	N.R.			
[56]	✓			✓	f = 0.00			
[57]	✓			✓	f = 0.333			
[66]	✓			✓	f = 0.285			
[58]	✓			✓	f = 0.208			
[20]			✓	✓	f = 0.436			
[41]			✓	✓	f = 0.75			
[7]			✓	✓	f = 0.403			
[9]	✓		✓	✓	f = 0.420			
[13]	✓		✓	✓	f = 0.424			
[17]	✓		✓	✓	f = 0.585			
[4]	✓	✓	✓	✓	f = 1.830	✓	✓	✓
Our Study	✓	✓	✓	✓	f = 1.243	✓	✓	✓

Across the previously mentioned studies, there is a strong implication that environments designed with high fidelity interactions, behaviors, and feedback in mind lead to users experiencing higher levels of presence. However, in review of the literature (see Table 1) there are very few studies that examine changes across the three core components of system fidelity. Furthermore, there are even fewer studies that report presence based on Interaction Presence, Scenario Presence, and Display Presence. Therefore, a key goal with our work is to 1) leverage the FPS to learn how the design decisions we incorporated in our user study affect sense of presence and 2) expand on the work investigating changes across the components of system fidelity. With these goals in mind, our work also aims to investigate the broader implications of reporting results with respect to factors of the FPS.

2.2 Presence Measurement Tools

Given our focus on system fidelity in relation to presence, we examine established presence measurement tools and their underlying factor structures. In our review of the literature, the Witmer-Singer Presence Questionnaire (WSPQ) [74], Slater-Usoh-Steed Presence Questionnaire (SUS) [72], Igroup Presence Questionnaire (IPQ) [54], and ITC-Sense of Presence Inventory (ITC-SOPI) [31] are some of the most widely used presence measurement instruments. We also consider the more recently developed FPS, which was explicitly designed to address presence in the context of VR system fidelity.

For the WSPQ, each item can load onto four primary factors: control factors (CF), sensory factors (SF), distraction factors (DF), and realism factors (RF) [74]. The SUS questionnaire, one of the most widely utilized presence measurement tools [59], does not leverage a factor or subscale metric [72]. The IPQ draws from both the WSPQ and SUS questionnaires and utilizes the factors: Presence, Spatial Presence, involvement, and Realness [54]. The ITC-SOPI presence questionnaire leverages four factors: Physical Space, Engagement, Ecological Validity, and Negative Effects [31]. Lastly, the FPS, as mentioned earlier, utilizes the Interaction Presence, Scenario Presence, and Display Presence and its factors [4].

When reviewing established presence questionnaires, such as the WSPQ and the IPQ, certain factors suggest a relationship between fidelity and the sense of presence (e.g., realness in the IPQ and involvement/control in the WSPQ). Our work, however, specifically examines how presence is influenced by variations in interaction fidelity, scenario fidelity, and display fidelity. In this context, the FPS offers a valuable opportunity to investigate presence with respect to system fidelity. Although the FPS is a relatively recent measure, its explicit grounding in VR system fidelity and design make it a suitable presence measurement tool for our study [4]. Being able to report presence based on fidelity-oriented metrics allows us to further understand the potential components of a virtual environment that affect sense of presence. Therefore, in our work, we utilize the FPS for the ability to report Total Presence, Interaction Presence, Scenario Presence, and Display Presence.

2.3 Previously Reported Effect Sizes

In our review of the literature, we compiled a list of 31 user studies that reported presence measurements. In addition to highlighting which components of system fidelity were altered in each study, we report each study's largest reported effect sizes as seen in Table 1. Of the 31 studies we reviewed, 19 of the studies did not report an effect size when measuring presence. With presence often being a subjective measure reported in VR user studies, reporting effect sizes helps provide additional insight into how impactful certain conditions are. Furthermore, with much previous work utilizing a wide variety of presence scales, reporting the effect size can provide readers and future researchers an idea of the magnitude of the effect a given VE had on sense of presence.

Conversely, 12 of our reviewed studies did report the effect sizes of their results for presence. For additional context, we follow the effect size criteria by Cohen et al. [12] in which $0.10 \leq f < 0.25$ for small effect sizes, $0.25 \leq f < 0.4$ for medium effect sizes, and $f \geq 0.40$ for large effect sizes. Across these studies, we note that some studies reported effect sizes in different ways than others. For example, one study reported effect size through a Wilcoxon signed rank test, which outputs an r-value [20]. Another study, reports general presence through an ANOVA, which outputs a partial eta squared value [17]. Despite reporting effect sizes, the differences in presence measurement tool and effect sizes reporting make it unclear on how we can potentially compare the effects of virtual experiences on sense of presence across studies. Within Table 1, we individually calculated the Cohen's f based on each study's reported effect size as the different effect size families (e.g., Cohen's d, Cohen's f, partial eta squared, and r), can be calculated from one another [12, 69]. To further hone on leveraging effect sizes to provide an idea of the magnitude of participants' perception of a given design decision, having a consistent effect size reporting can aid in being able to compare impact between user studies more effectively.

There exists a gap in which there are subset of studies that report effect sizes for presence measurement results. In our work, we aim to continue the trend of reporting our effect sizes. Furthermore, our results in particular have one of the largest effect sizes for total presence when compared to previous work. Through our comparison of previous work and calculating the effect sizes across different statistical analyses, we also provide guidelines for reporting effect sizes to facilitate broader comparisons between user studies. By combining the usage of the FPS and reporting our effect sizes, our work represents a crucial step forward in how we evaluate presence with respect to design decisions for VR experiences. Through the FPS, not only can we report effect sizes for Total Presence, but we can also report effect sizes for Interaction Presence, Scenario Presence, and Display Presence. These additional metrics can aid in understanding both whether there are significant differences in design changes as well as the magnitude of participant perceptions of these fidelity changes.

3 Study Methods

In our study, we adopted a similar study design to Belga et al. [4]. Our study is a $2 \times 2 \times 2$ ($InteractionFidelity \times ScenarioFidelity \times DisplayFidelity$) within-subjects VR user study. We ensured to counterbalance our conditions through applying a Latin square design. For all eight conditions, participants were immersed into a neighborhood environment with the task of trying to catch a butterfly with a butterfly net. In our study, we aimed to better understand the effects of fidelity in a locomotion task. We choose to focus on locomotion as it has and continues to be a challenge in VR research [35]. Limited physical spaces paired with expansive VEs often necessitate a form of virtual locomotion. This conflict between physical space and virtual space has led to locomotion being a prominent category of VR interaction [29]. This area of research has yielded numerous techniques such as Point-and-Teleport [28] and Redirected Walking [67]. Furthermore, researchers have compiled systematic reviews and taxonomies in order to better understand locomotion techniques [11, 45]. Therefore, in our work, we believe locomotion is an important interaction feature and we are motivated to learn of how different locomotion techniques impact sense of presence in VR contexts. This expands on previous work (e.g. object manipulation), as instead of transforming objects within the VE, the user is transforming themselves within the VE.

3.1 Independent Variables

The three independent variables we investigate in our study are: interaction fidelity, scenario fidelity, and display fidelity. For each independent variable, we implemented a low and high fidelity variant for each system fidelity component. Given our task focuses on locomotion, we chose certain implementations to represent each of the system fidelity components. We note the techniques we employed in our study are not comprehensive representations of each system fidelity component.

3.1.1 Interaction Fidelity. In our locomotion task in VR, we implemented two locomotion techniques for both the high and low interaction fidelity conditions. In our high interaction fidelity conditions, our participants moved in the VR environment through real walking. Conversely, for low interaction fidelity conditions, our participants traversed the VR environment through the point & teleport technique [8, 52]. Real walking provided our participants with a higher level of biomechanical symmetry (i.e. degree with which real-world body movements are reproduced by an interaction [40, 47]).

3.1.2 Scenario Fidelity. For our scenario fidelity conditions, we implemented two variants of our butterfly that our participants attempted to catch. In high scenario fidelity conditions, the butterfly would continuously fly and respond to the participant when approached, similarly to how a butterfly would in real life. In the low scenario fidelity conditions, there was a 60% chance that the butterfly would teleport away from the participant instead of flying away. This teleport action was followed by a small cloud to indicate to participants that the butterfly had teleported away. With these approaches, our study varies the attribute coherence (i.e. how consistent attributes of the virtual objects are to their real world counterpart [38]) of the experience. We were not able to investigate behavioral coherence as our environment design did not include virtual agent interactions and thus we cannot evaluate the quality or consistency of virtual agent behaviors [38]. In previous work, results indicated that when observing other avatars teleporting as opposed to continuously moving, participants experienced reduced levels of presence [18, 19]. Due to these previous results, we believed applying the teleporting mechanic for our low fidelity condition would yield similar effects with regard to presence. We further detail our implementation of the butterfly in Section 3.4.1.

3.1.3 Display Fidelity. Our study was contextualized in a suburban neighborhood environment. We varied the visual fidelity (i.e. the degree to which realistic visuals are reproduced [38, 47]) and auditory fidelity (i.e. the degree to which realistic audio stimuli are reproduced [38, 47]). In the low display fidelity neighborhood environment, the textures resembled a very 'cartoon'-like world and there was no sound present in the environment. Conversely, the high display fidelity environment was comprised of very detailed textures, lighting, and the inclusion of ambient noises that simulated road noise and insect noises from the surrounding trees. Figure 2 showcases the high display fidelity and low display fidelity environments we used in our study.

3.2 Hypotheses

Given our reviewed literature, we investigated four main hypotheses:

- H_1 High fidelity variations of interaction, scenario and display increases sense of Total Presence [4]
- H_2 For interaction fidelity, physically walking will lead to higher sense of interaction presence compared to locomotion via teleportation. [52, 65]
- H_3 For scenario fidelity, the butterfly flying continuously will lead to higher sense of scenario presence compared to the butterfly intermittently teleporting. [18, 19]
- H_4 For display fidelity, the environment with higher audiovisual fidelity will lead to higher sense of display presence compared to the environment with lower audiovisual fidelity. [4, 26]

3.3 User Study Procedure

Participants recruited were asked to review and complete a pre-screening survey through Qualtrics. In this survey, participants were asked to review an informed consent document, eligibility document, and provide demographic information such as age, gender, video game experience, first-person shooter experience, and VR experience. Once they completed the survey, participants were prompted to schedule a day and time in which they would be able to participate in the in-person portion of the VR study.

On the scheduled day of their study session, participants were greeted and introduced to the Meta Quest 3, the VR system utilized to administer our user study. This introduction was comprised of instructions on how to adjust the headset's straps such that it comfortably rested on the participant's head. We also provided a thorough explanation of the controls and actions needed to perform the tasks during the study. After familiarizing themselves with the headset and controllers, we then informed participants on the task they would be engaging in. We explained to participants that the study is comprised of eight trials of exploring a neighborhood environment, designed by Hmaiti et al. [21], to catch a butterfly with a butterfly net they held onto in VR. We also explained that between each trial, aspects of the virtual world may change (interaction fidelity, scenario fidelity, and display fidelity). Participants would know when a trial is completed once the in-VR FPS questionnaire was presented for them to respond to. The physical space needed to administer the study was an empty 15 feet by 15 feet area.

After explaining the procedure, we verified that the participant understood how to use the controls and then they were immersed into the eight trials. In each trial, participants were allotted 1 minute to try to catch the butterfly. This was done to reduce the potential of simulator sickness given the physical nature of the task. At the end of each trial, the participants responded to each item of the FPS on a 7-point Likert scale. After four trials, participants were offered an opportunity to take a break from the study. In addition to the constant half-way point break, participants were informed that they were allowed to ask for a break at any time if needed. After the half-way point break, participants would complete the remaining four trials of the study.

Following the completion of all eight trials, participants were asked what aspects of the neighborhood environment did they feel affect their sense of being in the environment. In addition, participants were asked if they had any comments, questions, concerns regarding their experience. The overall time required to complete the pre-screening survey, the in-person VR study, and post-VR study commentary was 60 minutes. Participants who completed the aforementioned steps were compensated $20 USD via an Amazon e-gift card.

3.4 Apparatus

In addition to outlining our independent variables in Section 3.1, we further detail the design decisions for our Scenario Fidelity and Display Fidelity conditions. Additionally, we also provide details on the format of the FPS we applied to our study and the calculations utilized for our results.

3.4.1 Study Environment Design Details. Our study environment was designed using Unity 2020.3.18f1. For our VR interaction toolkit,

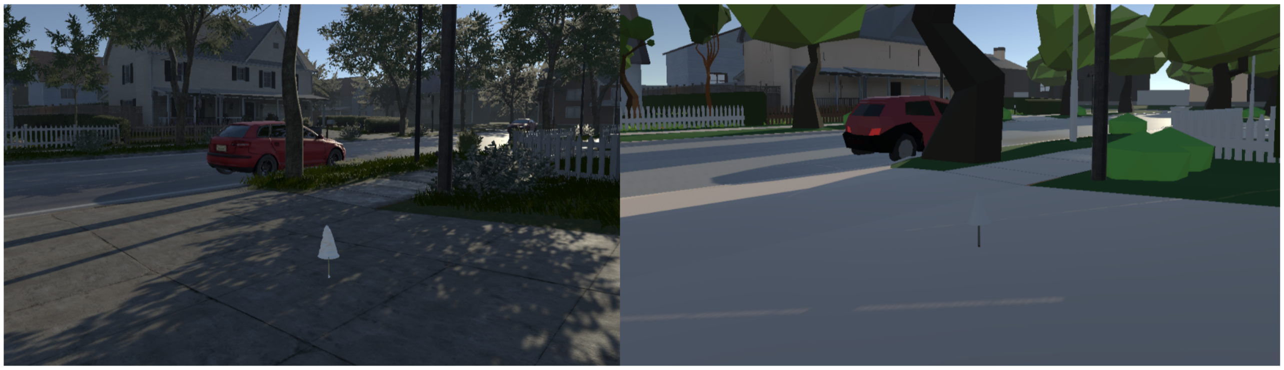

Figure 2: The high display fidelity (left) and low display fidelity (right) variations we utilized in our user study. These environments were designed by Hmaiti et al. [21] wherein each element within the environment is replicated between one another at a high poly/textured level and a low poly/textured level.

we utilized the SteamVR SDK [3] paired with the Meta Quest 3 to administer the user study.

With our participants tasked with catching a butterfly, we needed to design a butterfly that would fly around and also be able to fly around a certain space. Therefore, our implemented technique was to utilize virtual waypoints for the butterfly to fly towards. Figure 3 showcases the eight waypoints the butterfly could fly to during the experience. There was not a pre-determined pattern the butterfly would fly, the decision to fly to each waypoint was based on the participant and their proximity to the butterfly. For each waypoint, if the butterfly decided to stay at a given waypoint, we simulated it flying around in place by utilizing a unit sphere to periodically randomize the location of the waypoint the butterfly would fly towards.

In the case that the player's position was within 2.0m of the butterfly, the butterfly would fly towards a different waypoint. The determined waypoint was the waypoint that was 4th farthest away from the user at the point of decision. The 4th farthest away waypoint was chosen to ensure a balance between the butterfly evading the user but also reducing the potential head rotation a participant would need to perform to find the butterfly. This logic was still consistent for the low scenario fidelity condition with the caveat that 60% of the time, the butterfly would teleport to a different waypoint followed by a white cloud that denoted it teleported away as showcased in Figure 1e. This implemented mechanic of choosing waypoints also allowed us to ensure that participants would not approach the physical bounds of the allotted space we provided for our user study.

In addition to the butterfly development, we incorporated two locomotion techniques for our study. First being physically walking, which did not require any implementation and participants were able to pick up the butterfly net and begin walking as they would in real life. For teleporting, we leveraged the built-in teleporting prefabs provided by the SteamVR SDK for Unity. In Figure 1b, we highlight the teleport area that we implemented in our neighborhood environment.

[3]https://store.steampowered.com/app/250820/SteamVR/

3.4.2 The Fidelity-based Presence Scale. In our work, we utilize the FPS. We made no modifications to the questionnaire and each item was presented on a 7-point Likert Scale. Each item was anchored with 1 being "Fully disagree" and 7 being "Fully agree". The inventory our participants responded to is as follows:

(1) My sense of being in the virtual world was like being in a real place.
(2) During the experience, I felt the virtual world was reality for me.
(3) I felt like I was actually there in the virtual world.
(4) I felt present in the virtual world.
(5) I felt I could control my actions within the virtual world.
(6) I felt the virtual world was responsive to my actions.
(7) I felt I could move or manipulate objects easily in the virtual world.
(8) I felt involved in the virtual world experience.
(9) I could concentrate on the virtual activities rather than the controls to perform them.
(10) When something happened to my virtual body, I felt it happened to my real body.

To respond to each item, participants would utilize a raycast selection technique to interact with the questionnaire interface. Once a participant responded to an item, the subsequent item would appear sequentially. Administering the FPS in VR allowed us the ability to attempt to produce results as similar as Belga et al. [4]. Previous work also highlights that the transition from VR to out of VR can cause a significant break-in-presence (BIP) [27, 64]. In Putze et al.'s work, they evaluated participants' questionnaire responses as well as physiological measures. Across their results, they found that in-VR questionnaires are less invasive and provide more reliable self-reports [46]. Similarly, Schwind et al. conducted a similar study and concluded that responding to questionnaires in VR decreases the chance of a BIP occurring [55]. Figure 4 showcases how the FPS items were displayed to our participants in the neighborhood environment.

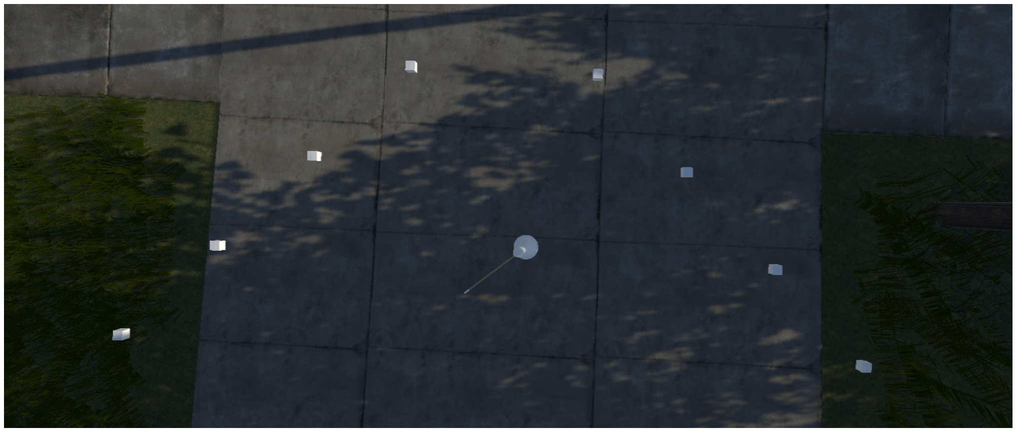

Figure 3: The eight waypoints our butterfly would fly to during each trial of our 8 conditions. This semi-circle configuration would allow participants enough space to move around, especially in the high interaction fidelity condition.

Figure 4: The presentation of the FPS items within our neighborhood environment. The item would be presented at the top of the UI element with the 7-point Likert Scale be presented directly below the item.

3.5 Participants

For our user study, we recruited a total of 50 participants (19 Female, 31 Male) from our local university. Participants were required to be 18 years of age or older, have normal or corrected-to-normal vision, be able to hear, be able to walk and extend both arms, and speak and understand English. Participants with any visual, auditory, neurological, or physical disabilities were excluded. Our participants' ages ranged from 18 to 35 with a mean age of 23.48. Participants also reported the frequency of Video Game, First-person Shooter, and VR usage which is summarized in Table 2. We also conducted an adhoc power analysis using G*power for an F-test ANOVA analysis with a Cohen's $F = 0.232$ [12], $\alpha = 0.05$, and a power of 0.95. Given that our study design is within-subjects and there are eight conditions, our power analysis revealed that an adequate sample size is at least 27 participants, which we exceeded with our 50 participants.

Table 2: Our participants' self-reported frequency of Video Game, First-person Shooter, and VR usage. Participants were able to report as None, Daily, Weekly, Monthly or Yearly for each category.

	Participant Gaming Demographics				
	None	**Daily**	**Weekly**	**Monthly**	**Yearly**
Video Games	14%	20%	22%	32%	12%
First-Person Shooters	20%	4%	18%	46%	12%
VR	24%	8%	14%	20%	34%

4 Results

In our results, we calculated and analyzed Total Presence, Interaction Presence, Scenario Presence, and Display Presence Scores.

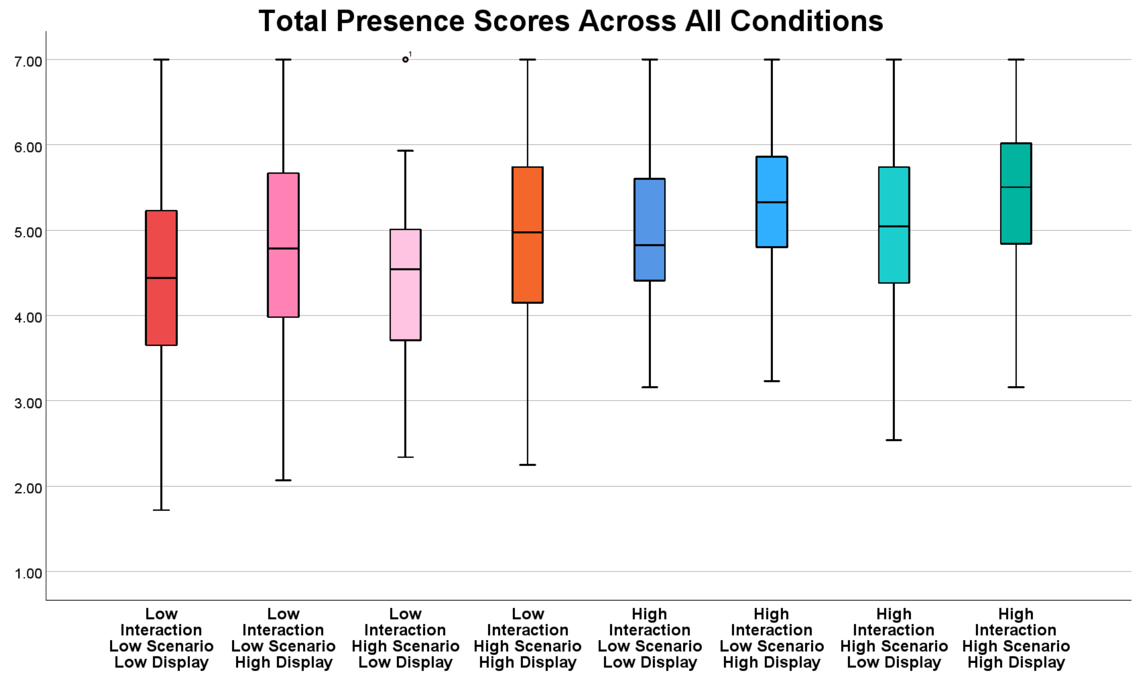

Figure 5: Box plots for the Total Presence Score across all eight conditions from our user study.

In our study, we found our data to be in violation of normality, therefore we performed the Aligned Rank Transform to conduct an ANOVA on non-parametric data [75]. For each of our presence scores, we report their respective analysis of variance (ANOVA). Additionally, we conducted one-way ANOVAs for each of the individual presence scores because the FPS is comprised of three core components, and we wanted to analyze these effects individually across the conditions [4].

To calculate each of the presence scores, we applied the recommended calculations:

- Interaction Presence Score: (FPS-1 + FPS-2 + FPS-4 + FPS-5 + FPS-6 + FPS-7 + FPS-8 + FPS-9) / 8
- Scenario Presence Score: (FPS-3 + FPS-4 + FPS-8) / 3
- Display Presence Score: (FPS-1 + FPS-2 + FPS-3 + FPS-4 + FPS-7 + FPS-8 + FPS-10) / 7
- Total Presence Score: $(\sum_{n=1}^{10} FPS_n)$ / 10

4.1 Total Presence Score

For Total Presence, our ANOVA highlighted significant main effects for interaction fidelity ($F_{1,49} = 62.776, p < 0.001, \eta_p^2 = 0.562$) with physically walking ($M = 5.16, SD = 0.94$) conditions yielding significantly higher Total Presence Scores over teleportation ($M = 4.64, SD = 1.13$) conditions, scenario fidelity ($F_{1,49} = 4.677, p = 0.03, \eta_p^2 = 0.087$) with the continuously flying butterfly ($M = 4.97, SD = 1.07$) yielding significantly higher Total Presence Scores than the teleporting butterfly ($M = 4.86, SD = 1.08$), and display fidelity ($F_{1,49} = 70.549, p < 0.001, \eta_p^2 = 0.59$) with the higher audiovisual environment ($M = 5.18, SD = 1.04$) yielding significantly higher total presence scores than the lower fidelity environment with no audio ($M = 4.65, SD = 1.05$). For interaction fidelity, our Cohen's f is 1.133, scenario fidelity yielded a Cohen's f of 0.309, and display fidelity yielded a Cohen's f of 1.199.

With regard to interaction effects, we found no significance between interaction fidelity and scenario fidelity ($F_{1,49} = 0.43, p = 0.510, \eta_p^2 = 0.009$; Cohen's f = 0.095), interaction fidelity and display fidelity ($F_{1,49} = 0.178, p = 0.674, \eta_p^2 = 0.004$; Cohen's f = 0.063), and scenario fidelity and display fidelity ($F_{1,49} = 0.273, p = 0.602, \eta_p^2 = 0.006$; Cohen's f = 0.078). We also did not find significance for a triple interaction across interaction fidelity, scenario fidelity, and display fidelity ($F_{1,49} = 0.017, p = 0.897, \eta_p^2 = 0.00$; Cohen's f = 0.00).

4.2 Interaction Presence Score

For our Interaction Presence Score, our one-way ANOVA revealed significant main effects for interaction fidelity ($F_{1,49} = 67.94, p < 0.001, \eta_p^2 = 0.581$). Physically walking ($M = 5.28, SD = 0.92$) conditions yielded significantly higher Interaction Presence Scores over teleportation ($M = 4.72, SD = 1.10$) conditions. Figure 6 outlines the median difference between low interaction and high interaction fidelity conditions. Based on our partial eta squared value of 0.581, our resulting Cohen's f is 1.18.

4.3 Scenario Presence Score

In the analysis of our Scenario Presence Score (M = 4.91; SD = 1.16), our one-way ANOVA did not reveal significant main effects for Scenario Fidelity ($F_{1,49} = 2.64, p = 0.105, \eta_p^2 = 0.051$). There was no significant differences in the Scenario Presence Score between conditions with the continuously flying butterfly ($M = 5.27, SD = 1.16$) and conditions with the teleporting butterfly ($M = 5.13, SD = 1.19$). Figure 6 highlights the median difference between low scenario and high scenario fidelity conditions. Based on our partial eta squared value of 0.051, our resulting Cohen's f is 0.232.

4.4 Display Presence Score

Finally, with our Display Presence Score (M = 4.14; SD = 1.39), our one-way ANOVA revealed a significant main effect for display fidelity ($F_{1,49} = 75.689, p < 0.001, \eta_p^2 = 0.607$). The higher audio-visual environment ($M = 5.19, SD = 1.12$) yielded significantly higher total presence scores than the lower fidelity environment with no audio ($M = 4.61, SD = 1.13$). Figure 6 shows the median difference between low and high display fidelity variations. Based on our partial eta squared value of 0.607, our resulting Cohen's f is 1.24.

5 Discussion

In this paper, we have applied the FPS to a locomotion task in a similar fashion as the original creators of the FPS did with an object manipulation task [4]. Our results align with much of the previous literature indicating that high-fidelity variations of environments lead to higher levels of perceived presence, reinforcing the importance and impact of fidelity on sense of presence. However, a key differentiator is that our results did not reveal significance for Scenario Presence, which suggests certain design decisions under the scenario fidelity category may not be as influential on sense of presence as initially thought. We discuss the implications of why this may be and also what our results indicate with respect to how to use the FPS in future user studies. Additionally, we detail the limitations of our approach and discuss potential avenues for future work that could further our understanding of the relationship between system fidelity and sense of presence.

5.1 Effect Size Differences Indicative of Individual Perceptions of Fidelity Differences

In our results, we report the effect sizes of each of our metrics through partial eta squares. For total presence, we witness large effect sizes for both interaction and display fidelity main effects. On the other hand, scenario fidelity is shown to have a medium effect size for total presence. For our individual presence scores, Interaction Presence has a large effect size for interaction fidelity, Scenario Presence has a small effect size for scenario fidelity, and Display Presence has a large effect size for display fidelity. Our large effect sizes support our $H_1, H_2, and H_4$. We found significance for the main effects for Total Presence, and we found significance for both Interaction Presence and Display presence when analyzing each respective fidelity. However, given both our small effect size and non-significance for Scenario Presence, H_3 was not supported by our results.

Previous work already indicates the relationship of higher fidelity experiences leading to higher perceived level of presence (e.g.,[4, 39, 60]). However, as highlighted in Table 1, not many studies often report the effect sizes of their subjective measures. In contrast, our work provides the effect sizes through partial eta squares and calculating our Cohen's f value. Between the effect sizes and significant results from our study, we believe that the effect sizes of subjective presence measures, like the FPS, can indicate participant perceptions of fidelity differences. Specifically with the FPS, we are able to evaluate the effect sizes for presence that is associated with different components of the System Fidelity. This in turn allows us to better understand how much of an effect a specific design feature had on a participant.

Given that previous work does not often discuss the effect sizes with regard to presence, our work provides an avenue of future work that re-evaluates how we measure and report presence. Furthermore, with a tool like the FPS, we consider the idea of iterative development in which future researchers or developers assess the FPS' presence scores and effect sizes to improve their VR experiences. This would expand on the FPS' original foundation of evaluating presence based on System Fidelity to now incorporating an assessment of how effective each of these system changes are to participants and users.

5.2 Acceptability of Scenario Fidelity

Across our results, the outcome of no significance for Scenario Fidelity was particularly interesting for Scenario Presence. When compared to our Interaction Presence Score and Display Presence Score, our results aligned with previous work, which indicated that higher fidelity levels should yield higher perceived sense of presence. We believe that we can attribute this result to our participants' previous experience with video games.

In Table 2, over 40% of our participants reported playing video games on either a daily or weekly basis. Furthermore, 46% of our participants reported playing first-person shooter style video games on a monthly basis. While we cannot report on the type of non-first-person shooter video games our participants played, there are plenty of examples within the video game industry of games that are not inherently "realistic" (e.g. Minecraft). Additionally, there were instances where participants mentioned that when they saw the butterfly teleport, they treated the experience as if it were a game. For example, P33 mentioned "When the butterfly would teleport, I started to think of the experience as a game." Another example, P50 mentioned that "when the butterfly teleported, it did not really impact how I felt about the environment as much as the level detail and being able to walk did".

This result is interesting as it indicates that there is a bound of acceptability that participants are able to entertain when engaged in a VR experience. Previous work notes that if an individual's experience in a VE is "good enough" users will remember and report a high level of presence [60]. In contrast, if an experience is riddled with failures and/or glitches, participants are more likely to recall those instances [60]. Given these conclusions, we believe a potential reason Scenario Presence was not significant may be due in part to our participants perceiving the teleporting butterfly as an "acceptable/good enough" implementation for the locomotion task. However, this potential reason does present an avenue of future work investigating these unrealistic implementations and how they affect one's sense of presence.

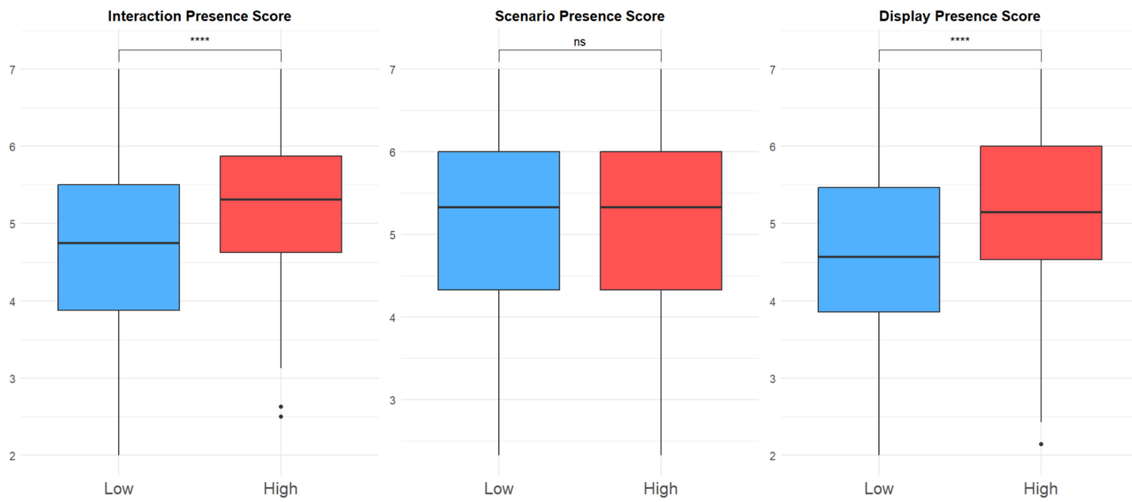

Figure 6: Box plots for Interaction Presence, Scenario Presence, and Display Presence Scores. Each box plot highlights the significance between the low and high conditions for each fidelity alongside the median for each condition

5.3 Participant Phantom Tactile Sensations

In our study, there were also instances where participants reported receiving sensory feedback despite our VE not being implemented with the reported sensations. P43 noted that during the experience, they "thought it was cool that the authors implemented haptic feedback in the controllers to inform where the butterfly was". P25 also noted that the behavior of the butterfly impacted their sense of presence the most and indicated that "when the butterfly flew towards me, I thought it was going to hit me and I could hear it flutter in my ear". P30 also highlighted that "[they] could hear the butterfly flapping as it flew by". However, in our design, we did not implement any haptic or auditory feedback associated with the butterfly.

These unexpected sensations are very much akin to the popular "rubber hand illusion" in which an individual feels a rubber hand is an extension of themselves when interacted with [6, 49]. There have also been instances where this sensation has been investigated within VR contexts, such as Pilacinski et al.'s work on the Phantom touch Illusion [44]. However, a key difference between our study and these examples is that these sensations arose naturally as opposed to being the sole focus of investigation. In 2024, Chen et al. [10] conducted a review of what they identified as "Phantom Tactile Sensation" (PTS). In their review, they collected and reported numerous individuals who either unintentionally or intentionally developed the ability to feel sensations while engaged in VR experiences. Given that we are attempting to measure presence, we consider the possibility that these self-developed sensations can also influence how present one feels within a virtual environment. We believe this area of research is relatively new given the recent accessibility to consumer VR headsets, which is further supported by the fact that there are very few studies that investigate PTS [2, 43, 78].

Therefore, in our study, it is very much possible that this unexpected experience of sensory illusion across our participants could affect how one responds to the FPS. Despite the butterfly's behavior being implemented with scenario fidelity in mind, the reporting of the butterfly's behavior causing participants to feel sensations lends itself more to Display Presence than Scenario Presence. We believe that this presents an additional path for future investigations to better understand how these phantom tactile sensations develop and impact one's experience and sense of presence.

5.4 Limitations and Future Work

One of the limitations of our work is the investigation of other subconstructs within the components of system fidelity. With display fidelity, we have primarily focused on visual and auditory feedback. Future work would investigate how other sensory feedback technologies affect sense of presence, such as olfactory and gustatory techniques. For scenario fidelity, we were not able to investigate behavioral coherence as this is typically attributed to the behavior and ability to interact with virtual agents [38, 40]. With technologies such as large-language models (LLMs), we believe future work could incorporate the interaction with LLM-backed virtual agents to better understand how that affects sense of presence. With regard to interaction fidelity, the FPS has been applied to an object manipulation task [4] and now a locomotion task within our work. Future work would encompass more techniques than the ones we have presented in our work and those presented in the FPS' orginal work [4].

As highlighted in Section 5.3, there seems to be instances in our user study and previous work in which users report feeling sensations during a VR experience. This opens up a potential avenue of research investigating how these phantom sensations impact the sense of presence. Contrary to early works investigating the phantom sensation through intentional studies evoking the phantom tactile sensation, it is apparent that with the rise of popularity of VR technologies there is an organic ability for users to begin experiencing sensations during VR experiences. We also acknowledge our assertion of our participants' acceptance of the environment is supported by observed behavior, however we believe this phenomenon can be investigated in future work. Future research would encompass user studies that aim to learn more of the causes of these phantom sensations and how users are potentially able to control these phantom sensations.

Another limitation of our work is the exclusion of avatars to embody our participants. With our participant population ranging a broad range of ethnic and cultural backgrounds, we wanted to prevent the possibility of an avatar affecting our participants' experience. This falls in line with previous work on embodiment that highlight the nuanced effects of incorporating avatars within virtual experiences [14–16, 24]. Additionally, given recent work highlighting PTS within VR experiences, an avenue of research that would be interesting is if the presence of avatars supplements this sensation, considering FPS question 10 explicitly asks "When something happened to my virtual body, I felt it happened to my real body." Interestingly, with the significance of Display Presence on our participants and our broader discussion on sensory illusion in Section 5.3, it is possible that an avatar would increase this sensation.

6 Conclusion

In this paper, we presented a multi-factor, within-subjects study investigating how systematic changes in VR system fidelity impact the sense of presence during a locomotion task. Our study design aimed to provide a context that is both familiar and engaging to participants. Furthermore, we extended the application of the Fidelity-based Presence Scale (FPS) to a novel study context and found results that were consistent with previous work. In our user study (n=50), we evaluated interaction, scenario, and display fidelity at both high and low levels. This approach allowed us to identify which components of system fidelity significantly impacted overall presence as well as specific forms of presence through Interaction Presence, Scenario Presence, and Display Presence. Through our user study and application of the FPS, we were able to provide further implications on how using the FPS could broaden our understanding of how VR environment design and implementation can affect users' sense of presence.

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