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Impact of the Fidelity of Interactive Devices on the Sense of Presence During IVR-based Construction Safety Training

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Abstract: Providing safety training to construction workers is essential to reduce safety accidents at the construction site. With the prosperity of visualization technologies, Immersive Virtual Reality (IVR) has been adopted for construction safety training by providing interactive learning experiences in a virtual environment. Previous research efforts on IVR-based training have found that the level of fidelity of interaction between real and virtual worlds is one of the important factors contributing to the sense of presence that would affect training performance. Various interactive devices that link activities between real and virtual worlds have been applied in IVR-based training, ranging from existing computer input devices (e.g., keyboard, mouse, joystick, etc.) to specially designed devices such as high-end VR simulators. However, the need for high-fidelity interactive devices may hinder the applicability of IVR-based training as they would be more expensive than IVR headsets. In this regard, this study aims to understand the impact of the level of fidelity of interactive devices in the sense of presence in a virtual environment and the training performance during IVR-based forklift safety training. We conducted a comparative study by recruiting sixty participants, splitting them into two groups, and then providing different interactive devices such as a keyboard for a low fidelity group and a steering wheel and pedals for a high-fidelity group. The results showed that there was no significant difference between the two groups in terms of the sense of presence and task performance. These results indicate that the use of low-fidelity interactive devices would be acceptable for IVR-based safety training as safety training focuses on delivering safety knowledge, and thus would be different from skill transferring training that may need more realistic interaction between real and virtual worlds.

Keywords: Immersive Virtual Reality (IVR); Interactive device; Presence; Task performance; Safety training

1. INTRODUCTION

The construction industry has suffered from a high rate of safety accidents at sites [1]. Accidents could occur when workers fail to recognize existing unsafe conditions, and thus safety training could provide safety-related knowledge to workers by improving their safety awareness [2]. Currently, traditional construction safety training methods such as paper-based teaching, videoes, on-site training, and regular safety meetings such as safety orientations or toolbox meetings are commonly used [3]. Even though conventional safety training is now being commonly used to equip workers with safety knowledge, it has been considered passive due to the low level of engagement, limited acquisition and retention of knowledge [4]. In this regard, past studies have questioned the effectiveness of conventional safety training and pointed out that it was not an effective training method for construction workers [5, 6]. Recently, the use of virtual reality (VR) technology has gained its attention as an alternative way to provide safety training [7, 8]. VR-based safety training not only provides various simulated real working conditions without associated construction risks but also improves user's motivation and learning effectiveness [9, 10].

VR is an emerging technology that creates a computer-generated three-dimensional virtual environment with a high degree of realism and interactivity. Generally, a taxonomy of VR is based on three main components: autonomy (e.g., computational models and ability of processes to act and react to simulated events), interaction (e.g., a software architecture of the human-machine interface in the virtual environment system), and presence (e.g., the fidelity of available sensory input and output channels.) [11]. In particular, presence is one of the major contributing factors that could affect performance in VR environment [12, 13]. It refers to a mental state in which a user feels physically present within the computer-mediated environment [14]. It is related to the subjective experience of being in one place or environment, even when one is physically situated in another [15], or in other words: the sense of “being there” [2]. Research [13] indicates a higher sense of presence is linked with higher scores of performance metrics such as completing speed, errors, and quality in VR-based training [13]. This is consistent with the results from Salzman et al. and Lee et al. [16, 17] that indicated a better sense of presence in a virtual environment could enhance user’s learning.

The hardware of VR systems consists of display devices such as Head-Mounted Display (HMD) and other interactive devices for user-VR system interaction. Previous research efforts have found that the fidelity of VR interactive devices has a significant impact on the level of presence by creating more natural control [18, 19] and easier operation [20]. VR-based interactive devices ranging from a simple hand-held controller to a real-like simulator, such as a steering wheel [21] and omnidirectional treadmills [22]. Although several authors have pointed out the importance of sense of presence in the virtual environment, the impact of different levels of fidelity of interactive devices has not been fully studied. Furthermore, even though some devices such as real-like simulators can provide high fidelity of interaction between users and the VR environment, their high price would obstruct the applicability of VR systems in practice. In this regard, cost-effective control systems may need to be developed by understanding how the fidelity of interactive devices would affect the sense of presence and training performance.

This study conducted the experiment with sixty participants to compare the fidelity of two different interactive devices by evaluating the sense of presence and training performance during the VR-based forklift operation. This research would identify whether low fidelity devices such as keyboard would significantly affect IVR-training experience, compared with high fidelity devices (steering wheel and pedals).The Presence Questionnaire [15] was used to find out whether the level of presence would create a significant difference between low-fidelity and high-fidelity groups during VR forklift training sessions. Based on the results, we discussed a method to improve the sense of presence in a cost-effective way.

2. LITERATURE REVIEW

2.1. IVR-based Training

Since the early 21st century, the latest visualization techniques are continuously adopting in various fields, and virtual reality (VR) has been proved to be an effective tool for furnishing people with a better learning environment and experience [9]. In general, VR platforms can be categorized into three paradigms based on the level of immersion: 1) non-immerse system, e.g., hand-held based VR and desktop-based VR; 2) semi-immersive system, e.g., stereoscopic 3D glasses and CAVE; 3) fully immersive system, e.g.,VR HMD. Notably, the first prototype of a fully IVR system (Oculus Rift) was proposed by the Kickstarter project [22], which is currently one of the most prevalent and affordable high-quality VR headsets in the market.

IVR, with its fully immersive technology, can easily build up a space isolated from the outside world, contributing to maintain trainees’ attention and concentration and may help trainees to acquire three-dimension knowledge. Research studies [23, 24] showed evidence that IVR-based training model for enhancing fire evacuee safety has been proved to be effective [23, 24]. Also, Ceenu et al [25] illustrated that instructor representation had a counterproductive relationship with the performance in a memory task and an object finding task in IVR. In construction, IVR-based training has been applied for hazard identification, skill learning and workforce training by benefiting from HMD gears with an affordable price and technological advancement in visual rendering [26, 27]. Diego-Mas et al. and Barkokebas et al. tested HMD-based VR training to investigate its application in avoiding ergonomic risks and acquisition of maintenance skills [28, 29]. Their studies highlighted the effectiveness of such training approach on increasing perception of the ergonomics risks among workers and exploring the complexity of the task in IVR.

2.2. Factors Affecting the Sense of Presence in VR

Even though IVR-based training has been widely proposed in various fields, few studies have done that investigates how IVR systems would affect users' training experiences. However, there have been many studies for non-immervive VR such as Desktop-VR systems, providing a theoretical background on IVR-based studies. In general, factors that affect the sense of presence in VR systems can be categorized into hardware, VR contents, and user characteristics [30, 31]. According to Anthes et al. [22], VR hardware includes both input and output devices. Output devices refer to head-mounted devices, haptic devices and multi-sensory devices while input devices are interactive devices between real and VR environments such as driving wheels, controllers, navigation devices, body tracking, gesture tracking etc. The sense of presence in a VR environment can be measured by several hardware related parameters such as field of view, image quality, refresh rate, sound quality, tracking level, sensory isolation, haptic fidelity and force feedback [32].

Previous studies were conducted with different interactive devices for measuring the sense of presence. Hoffman et al. [33] found output devices such as HMD of 60-degree field-of-view can provide a higher level of presence by attacting attention as a result of reducing pain as well as having greater fun during the pain stimulus compared to the 35-degree VR group. Balakrishnan & Sundar [34] found that an interactive joystick with greater degrees of steering motion could enhance the sense of presence while navigating and searching for clues in a virtual office environment. In addition, it has been found that takeover quality only improved when user practices with steering wheel and pedals comparing to the game controller in IVR environment in a highly automatic car-driving task [21]. However, existing studies focus more on how internal parameters of output devices affect the sense of presence, especially spotlighting on HMD. Input devices are one part of the VR systems, understanding how they make contributions to the sense of presence and performance in VR environment is relatively important. Therefore, our study investigates how different fidelity level of input interactive devices influence the sense of presence and task performance in IVR-based training.

3. METHOD

To achieve this research study's objective, participants were recruited and randomly divided into two groups with low-fidelity (keybord) and high fidelity (a steering wheel and pedals) interactive devices for performing the forklift operation tasks. To provide a fully immersive environment, all the participants were equipped with a head-mounted display VR device. All of them were required to complete four forklift-operation tasks (basic introduction about forklift, steering a forklift, operating a fork, picking up a pallet) in the IVR environment. After completing the experiment, they filled out the Presence Questionnaire [15] for mensuring the level of presence. The finishing time of all four tasks was also recorded for comparing the task performance between two groups. Based on the previous literature review, we brought up the following assumptions:

H0:

Different VR interactive devices have different sense of presence;

High-fidelity devices have higher sense of presence;

The high-fidelity device group has a better performance (shorter task completion time).

3.1. Participants

A pilot study with two participants was conducted to provide a formative evaluation of the procedures and instruments. A total of 60 graduate students (57% of male, 43% of female) were recruited from the Faculty of Construction and Environment at the Hong Kong Polytechnic University and were randomly divided into two equal groups. Participants ranged in age from 20 to 40. All of the participants had heard about virtual reality, while 25% of total respondents had used VR-based applications or devices before.

3.2. VR System

Technical features. The forklift training scenario used in the study was developed using Unity 3D (version 2018.3.12f1), and all the participants wore a Samsung HMD Odyssey Plus (shown in Figure

1). The display resolution of this HMD was 1440 × 1600 per eye covered approximately 110° field of vision, refresh rate was 90 Hz and it also comes with a dual array MICs built-in headphone with AKG brand. These apparatuses provide users with an isolated, immersive and wide-field virtual environment.

In the low-fidelity IVR group, participants were provided a keyboard for forklift driving and a joystick for manipulating the fork. While in the high-fidelity VR group, the keyboard was replaced by a steering wheel and pedals that are similar with real forklift operating gears, as shown in Figure 1. Both groups performed the same training tasks in the same IVR environment.

Figure 1. Devices Used in The Experiment

Training contents. Firstly, all participants were taking basic knowledge about forklift operations to familiarize themselves with forklift operations in a virtual environment. Then, they were performing the different forklift operation tasks (e.g., steering a forklift, operating a fork, picking up a pallet, etc.)that were designed to provide task-based safety knowledge during forklift operations through interactive feedback. For example, while they performed a specific task such as moving forward, safety instructions were shown on the screen, and if they didn’t follow the instructions, the system gave an alarm to users in the virtual environment. The training sessions include representative forklift-related tasks such as driving forward and backward, loading and unloading a pallet using a fork, etc.

3.3. Measurement

Subjective questionnaires are the most commonly used method to measure the sense of presence [35]. There are a few prevailing questionnaires in measuring presence, according to the number of citations in the Google Scholars database, the top five questionnaires are: Witmer & Singer 1998 [15](no of citations, 5088) , Schubert et al. 2001[36] (no of citations, 1232), Lessiter et al.2001[37] (no of citations,1085) , Usoh et al. 2000 [38] (no of citations, 704) and Slater [39](no of citations 628). To check the sense of presence with different VR interactive devices used in this study, the Presence Questionnaire (PQ) [15](as shown in Table 1) of Witmer & Singer 1998 (WS) was adopted in this experiment. Witmer & Singer used factors based on the premier issue of Presence: Teleoperators and Virtual Environments and integrated them into the presence questionnaire (PQ). PQ includes four major factors: (1) control factors, (2) sensory factors, (3) distraction factors and (4) realism factors [15] and consists of 32 items using a five-point Likert-type scale. The degrees are “Very low” “low” “Medium” “High” and “Very high” corresponding to 1 through 5, respectively.

Table 1. Presence Questionnaire (PQ) [15]

Group Factors	Item Stems
CF	How much were you able to control events?
	How responsive was the environment to actions that you initiated (or performed)?
	How natural did your interactions with the environment scene?
	How well could you actively survey or search the virtual environment using the device (e.g: wheel, joystick)?
	How proficient in moving and interacting with the virtual environment did you feel in the experiment?
	How much did the control devices interfere with the performance of assigned tasks or with other activities?
	How easy was it to identify objects through physical interaction, like touching an object?
	How easily did you adjust to the control devices used to interact with the virtual environment?
	How natural was the mechanism which controlled movement through the environment?

SF	How much did the visual aspects of the environment involve you? How much did the auditory aspects of the environment involve you? How compelling was your sense of objects moving through space? How completely were you able to actively survey or search the environment using vision? How compelling was your sense of moving around inside the virtual environment? How involved were you in the virtual environment experience? How much delay did you experience between your actions and expected outcomes? How quickly did you adjust to the virtual environment experience? How completely were your senses engaged in this experience? How much did your experiences in the virtual environment seem consistent with your real-world experiences? Was the information provided through different senses in the virtual environment (e.g., vision, hearing, touch) consistent?
DF	Were you able to anticipate what would happen next in response to the actions that you performed? How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities? To what extent did events occurring outside the virtual environment distract from your experience in the virtual environment? Were you involved in the experimental task to the extent that you lost track of time? How much did you focus on using the display and control devices instead of the virtual experience and experimental tasks? Were there moments during the virtual environment experience when you felt completely focused on the task or environment?
RF	How well could you identify sounds? How well could you localize sounds? How closely were you able to examine objects? How well could you examine objects from multiple viewpoints? How well could you move or manipulate objects in the virtual environment? How much did the visual display quality interfere or distract you from performing assigned tasks or required activities?

Note. CF = Control Factors, SF = Sensory Factors, DF = Distraction Factors, RF = Realism Factors.

3.4. Procedure

First, participants were randomly allocated to the Low-fidelity IVR (LF-IVR, n=30) and High-fidelity IVR (HF-IVR, n=30) forklift training . Then each participant was filled a consent form and was briefed about this IVR experimental session. Before entering into the IVR environment, we further explained to participants how to use the joystick to navigate inside it and how they can use the other devices keyboard or steering wheel and pedals to interact with the training tasks. We then adjusted the HMD to the head of each participant and calibrated the pupil distance and volume for the best visual and audio effects. The participants were told that they would be further help on condition that they encountered any problems or they could not perform some movements in experiencing in the virtual environment. In the next step, participants were immersed into virtual world and finished the designated four tasks (basic introduction about forklift, steering a forklift, operating a fork, picking up a pallet) one by one in this sequence. On average time spent by each participant was approximately 26 min. After completing all these training tasks, participants were asked to finish the Presence Questionnaire [15] through an online platform outside the IVR environment. All questions displayed online were presented in a counterbalanced order to prevent any sequence effects.

4. RESULTS

There are two categories of metrics, one is the score in Presence Questionnaire, which will be compared with groups of factors referring to Control Factors (CF), Sensory Factors (SF), Distraction Factors (DF) and Realism Factors (RF) descried by Witmer and Singer [15], another is finishing time in IVR tasks between two experimental conditions as the measurement of participants' performance. Before analyzing the data in detail, the first internal consistency of all questionnaires was checked using

Cronbach's alpha. Cronbach's alpha is a measure to check the internal consistency and reliability of the data. The consistency calculated by SPSS was found excellent in both experimental conditions(LF-IVR group: α = 0.930, HF-IVR group: α = 0.900). These alpha values indicate that the data reliability quality is high and can be used for further analysis. Then, the Shapiro-Wilk test [40] was used to test the data normality. The *p* values of the participants' task completion time produce by this test were greater than 0.05, indicating that such data were normally distributed. Therefore, parametric analysis was applied on this data. The *p* values of the other four factors (CF, SF, DF, RF) produced by the Shapiro-Wilk test were 0.000, indicating that such data were not normally distributed. Therefore, non-parametric analysis was used for four factors's data analyses.

4.1. Presence Measurement

A non-parametric analysis method (Mann-Whitney U test) was conducted for the comparison between HF-IVR and LF-IVR groups.The difference in all the group factors was found non-significant. However, the mean values of each group factor in the HF-IVR group are higher than the LF-IVR group, as shown in Table 2. This may imply that a steering wheel,joystick and pedals can produce a higher sense of presence and can assist to experience high immersive environment.

Table 2. Results of the Presence Questionnaire

Group Factors	HF-IVR (M±SD)	LF-IVR (M±SD)	MannWhitney U	*p*
CF	3.608±0.564	3.470±0.517	382	0.313
SF	3.810±0.390	3.673±0.578	407.5	0.528
DF	3.494±0.400	3.466±0.466	434	0.811
RF	3.605±0.527	3.573±0.531	447.5	0.970

Note: * p<0.05 ** p<0.01

4.2. Participants' Performance

For normal distribution of participants' performance, an independent t-test was conducted to the metric of time. No statistically significant difference was observed in task completion time between two groups, LF-IVR group (Mean ± SD=26.13 ± 7.77) and HF-IVR (26.30 ± 7.69), p = 0.934 > 0.05. Nevertheless, in Linear Regression analysis, the regression coefficient value of CF was -6.541 (t=-2.180, p=0.034<0.05), which means that CF had a significant negative influence on time while the other three group factors were not significant (as shown in Table 3). This may imply partially that less time was required to complete the tasks with more advanced apparatus.

Table 3. The Linear Relationship between Time Performance and Group Factors

Group Factors	Coefficients	t	*p*
CF	-6.541	-2.18	0.034*
SF	3.924	1.126	0.265
DF	-4.510	-1.684	0.098
RF	1.660	0.696	0.490

Note: * p<0.05, ** p<0.01

5. DISCUSSION

This study examines how different types of interactive devices (LF-IVR, HF-IVR) affect the sense of presence and task performance in IVR-based forklift training environment.

5.1. Impact of Interactive device on the sense of presence

The first hypothesis regarding that different interactive devices have different degrees of presence couldn't find enough supporting materials in this study. 31 PQ items were not significant except for the second question ($p = 0.044 < 0.05$) in PQ, which refers to "How responsive was the environment to actions that you initiated (or performed)?" From this point of view, HF-IVR with steering wheel and pedals provided participants with a better reactive action experience. This seems to be a sign of good interaction with the virtual world. However, that is a small part of the virtual reality interaction; others like control, naturality and richness are not be reflected at all. Of course, it is undeniable that mean scores in HF-IVR are commonly higher than LF-IVR, this might suggest high interactive devices would have a little improvement but not a decisive role in presence.

It is worth noting that the fidelity of the scene or virtual environment in IVR is relatively high and is akin to reality by offering a good field of view(110 degrees) and real auditory of site construction. Thus it could provide a high sense of the presence of real construction worksite. What's more, the contents in IVR training environment mainly focused on gaining forklift operations knowledge rather than real forklift operation tasks, and the tasks were relatively simple compared to some complex operation training, such as aviation training. These may impair the effect of interactive devices on inducing presence in this forklift training. Comparing the different fidelity of the scene with these two interactive devices would be the next step in the future study.

5.2. Effect of Presence on Performance

The results partially support the third hypothesis, showing that there was no remarkable difference of task execution time between the HF-IVR (26.30min) and the LF-IVR (26.13min) group, or even that the mean time is almost identical. However, the linear relationship was found significant between time and CF (Control Factors) with a negative value of -6.541. Other group factors were also correlated with time, but the coefficients were not significant. Fully presence may mean all kind of factors show a significant relationship to the task or the scene. Research study [41] delved into the various components of immersion that benefit VR, noting that full immersion are not indispensable [41]. This is in line with Bailey and Grassini [13, 42], who emphasized that high presence would be detrimental to the cognitive process and memory. It is under proven that full immersion is not necessary indeed. Based on this study, we can make a assumption that different tasks require different levels of presence, or specific presence. For example, we provided interactive equipments in addition to the IVR environment, which corresponded to Control Factors from Witmer and Singer questionnaires. Therefore Control Factors were significantly correlated with task performance. Thus, the function of different factors are based on the scene and we could not add up all the factors diluting the effect of the main ones.

5.3. Limitations and Future Directions

Considering several limiting factors, the results of this study need to be interpreted. A few participants complained that the fourth task (pick up the pallet) did not provide enough sight of view that they had difficulty in putting the fork inside the pallet. Later we found out that it was the problem of sitting-place adjustment. This inevitably gave rise to the problem of external interference. WS presence questionnaire is the method to observe presence in this study, but the individual question within the grouping factors are self-divided. This may cause some measuring error because of the classification. Nevertheless, we made sure that the grouping and order of the online questionnaires were consistent.

Future experiments are expected to fill up the questionnaire inside the VR headset. Completion of questionnaire forms outside the IVR may cause inconsistency and may depend on the individual's memory. Although this study used the most prevailing presence questionnaire, there are many ways to measure presence except the subjective questionnaire method (such as heart rate, eye data, skin conductor, etc.), which can be considered in future research.

6. CONCLUSION

Although past research studies have examined presence in various domains, few studies have been carried out on safety training and the effect of presence on behavior in VR. With the maturity of visual technology, more and more head-mounted displays (HMD) appear and the fully immersive virtual reality (IVR) shows an increasing trend with affordable price. However, IVR has not been widely applied as a low-cost solution in safety training. In this study, we developed an IVR environment of forklift training and explored how two types of interactive devices (low-fidelity IVR, high-fidelity IVR) affected the sense of presence and task performance in the fully immersive virtual environment. Then we compared presence factors and time performance between two groups. Our findings contribute to safety training performance in IVR with a better understanding of the sense of presence in several ways.

First, the high interactive device made little difference in presence compared to low interactive equipment which would help us to choose an inexpensive apparatus. Second, time performance in four tasks between the two groups were found almost no difference. Third, different parts of presence factors contributed to impacting time performance with different input or output devices. Based on these findings, further research may attempt to explore more factors affecting presence to better understand the relationship with immersive virtual reality-based safety training.

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