UNDERSTANDING HUMAN FACTORS ISSUES IN IMMERSIVE VIRTUAL AND AUGMENTED REALITY APPLICATIONS FOR CONSTRUCTION

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PhD

The Hong Kong Polytechnic University

2021

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Understanding Human Factors Issues in Immersive Virtual and Augmented Reality Applications for Construction

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A thesis submitted in partial fulfillment of the requirement for the degree of Doctor of Philosophy

August 2020

CERTIFICATE OF ORIGINALITY

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ABBAS Ali (Name of Student)

This thesis is dedicated to my mother.

ABSTRACT

The complex nature of the architectural engineering and construction (AEC) industry demands a large exchange of data and complex information among the project's stakeholders on a regular basis and increases the industry's need for recent information technologies such as immersive virtual reality (IVR) and augmented reality (AR). Currently, the AEC industry is moving to embrace IVR/AR technologies for visualization purposes. However, the use of IVR/AR is not just limited to design review. These technologies can be used for different applications such as communication among stakeholders, information access/evaluation, inspection/safety, progress monitoring, and education/training. However, the best utilization of these tools demanded a sound knowledge of human IVR/AR-interaction.

Past research indicated that research into human factors issues related to the use of IVR/AR technology is very limited. In addition, our knowledge of IVR/AR in terms of human factors is almost non-existent, and many researchers have emphasized the need to comprehend the fundamental human factors issues of immersive IVR/AR. Therefore, investigation of human factors issues for IVR/AR system interaction is needed to optimal understand the interactions with this technology and to improve the human cognitive process, performance, and safety for the construction industry. This research aims to provide a better understanding of immersive IVR/AR applications in construction and to examines human IVR/AR interaction issues, particularly to examines three applications of IVR/AR specifically, communication, cognitive task effectiveness, and training.

First, to understand the human IVR/AR interaction, we compared the communication effectiveness of face-to-face communication in a real-world environment and immersive

virtual reality-based communication in a virtual environment for construction. The results of experiments revealed that three factors – the quality of discussion, appropriateness, and openness had higher scores in the FtF condition because it offers the group members to open-minded share the ideas with enjoyment and makes it easy to discern their reactions or identify appropriate moments to speak. And, only one factor, richness, had a higher score in the IVR condition and considered more suitable to its members to communicate because IVR environment provided more detailed and vivid visual information to the participants. Whereas accuracy had found better in the FtF condition, which is believed due to weak human-human interaction in IVR.

Secondly, to examine the cognitive task performance of AR systems we selected the mobile AR (MAR) systems because they are increasingly prominent and allow AR to be moved from the laboratory onto actual construction sites. This study conducted laboratory simulations of rebar-inspection tasks and compared the cognitive load, task performance, and situational awareness of users of two types of MAR system – i.e., head-mounted and handheld compared with traditional paper-based drawing. Participants' CL was measured with the National Aeronautics and Space Administration's Task Load Index (NASA-TLX); their TP, by completion time and the number of rebars correctly detected; and their SA, with Taylor's Situation Awareness Rating Technique (SART). The results revealed that rebar-framework design information provided via a superimposed virtual rebar model in MAR-assisted inspection decreased the inspectors' CL associated with the information-seeking (e.g., the number of rebars required; proper spacing) and processing (e.g., identifying missing or superfluous rebars in the actual rebar framework), however, it negatively impacted their situation awareness in dangerous surroundings. The head-mounted MAR device we used, in particular, decreased its users' understanding of the surrounding environment and increased their inspection-task completion times, as compared not only to paper-based inspection but also to its tablet-based counterpart.

Thirdly, to explore the impact of immersive virtual based training on construction participants behavior and to understand the underlying mechanisms of behavior change with IVR-based training, we used the structural equation modeling approach. This study created IVR based training environment for forklift operator and examined how IVR system features could affect the behavior change outcomes. This identified how IVR system features could influence psychological factors such as presence, motivation, enjoyment, and self-efficacy and their relationships with behavior change outcomes through a structural equation modeling (SEM) approach. Using SmartPLS, the results supported the casual path from IVR system features to presence, motivation, perceived enjoyment, self-efficacy, and from the presence, motivation, perceived enjoyment, self-efficacy to behavior change outcomes. The findings of this study provide a comprehensive framework for understanding the constructs involved in behavior change with IVR training environment and highlight how IVR system features, presence, motivation, perceived enjoyment, and self-efficacy could impact on behavior change outcomes. Overall, the research outcomes from this thesis would contribute to the body of knowledge for human IVR/AR system interaction, and thus, we could better design the IVR/AR system for the construction industry.

LIST OF RESEARCH PUBLICATIONS

Refereed Journal Papers: Published

[1] **Abbas, A.**, Seo, J., and Minkoo, K. (2020). "Impact of Mobile Augmented Reality System on Cognitive Behavior and Performance During Rebar Inspection Tasks." *Journal of Computing in Civil Engineering (ASCE)*, 34 (6). https://doi.org/10.1061/(ASCE)CP.1943-5487.0000931.

[2] Lee, J. G., Seo, J., **Abbas, A.**, and Choi, M. (2020). "End-Users' Augmented Reality Utilization for Architectural Design Review." *Applied Sciences*, 10(15), 5363. https://doi.org/10.3390/app10155363.

[3] **Abbas, A.**, Choi, M., Seo, J., Cha, S. H., and Li, H. (2019). "Effectiveness of Immersive Virtual Reality-based Communication for Construction Projects." *KSCE Journal of Civil Engineering*, 23(12), 4972-4983. https://doi.org/10.1007/s12205-019-0898-0.

Refereed Journal Papers: Under Submission Process

[1] **Abbas, A.**, Seo, J., Ahn, J., Luo, Y., Lee, G., and Wyllie, M. (2020). "How Immersive Virtual Reality Training System Features Impact Behavior Change for Safety? A Structural Equation Modeling Approach." Accident Analysis & Prevention (Elsevier).

Refereed Conference Papers: Published

[1] **Abbas, A.**, Seo, J., and Minkoo, K. (2020). An Augmented Reality System for the Construction Industry and Its Impact on Workers' Situational Awareness, *8th International Conference on Construction Engineering and Project Management (ICCEPM)*, Hong Kong SAR, December 7-8, 2020.

[2] Luo, Y., Seo, J., **Abbas, A.**, and Ahn, J. (2020). Impact of the Fidelity of Interactive Devices on the Sense of Presence During IVR-based Construction Safety Training, *8th International Conference on Construction Engineering and Project Management (ICCEPM)*, Hong Kong SAR, December 7-8, 2020.

[3] **Abbas, A.**, Seo, J., and Minkoo, K. (2020). Exploring the Construction Task Performance and Cognitive Workload of Augmented Reality-Assisted Rebar Inspection Tasks, *ASCE Construction Research Congress 2020*, Tempe, Arizona, USA. March 8-10, 2020.

[4] **Abbas, A.**, Choi, M., Seo, J., Cha, S., and Li, H. (2019). Communication Effectiveness in Face-to-Face and Immersive Virtual Environment: An Initial Evaluation for Construction, *CIB World Building Congress 2019*, Hong Kong SAR, China, June 17-21, 2019.

ACKNOWLEDGEMENT

Verily all praise belongs to Almighty Allah, and salutations to Fourteen Infallible Masoomen (a.s), for granting me the courage and strength to complete my doctoral study.

I would like to express my profound gratitude and heartfelt respect to my Chief Supervisor Dr. JoonOh Seo, for his enormous support, time, and patience. I would also like to thank my co-supervisor, Professor Heng Li for helping and motivating me throughout my Ph.D. research journey.

The guidance and support received from Professor Meng Ni was also extremely vital for the completion of this research. I would also like to take this opportunity to thank Dr. Sun Yi for his instructive suggestions, kindly support, and encouragement during the past study period.

I would also like to express my gratitude for Dr. Irfan Zafar, Dr. Khawaja Mateen, Dr. Jin Xue, for their extended support and motivation throughout my research studies. Finally, I owe my deepest gratitude to my parents, siblings, and other relatives' family members for their enormous support, unconditional love, guidance, and prayers.

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LIST OF ABBREVIATIONS

AEC = Architecture, engineering, and construction

VR = Virtual reality

AR = Augmented reality

IVR = Immersive virtual reality

BIM = Building information modelling

HMD = Head-mounted display

CAVE = Cave automatic virtual environment

FtF = Face-to-face

MAR = Mobile augmented reality

NASA-TLX = National aeronautics and space administration's task load index

SART = Situation awareness rating technique

CL = Cognitive load

TP = Task performance

SA = Situation Awareness

SEM = Structural equation modeling

IVR SF = IVR system features

Pr = Presence

Moti = Motivation

Enj = Enjoyment

Effic = Self-efficacy

BCO = Behaviour change outcomes

AVE = Average variance extracted

CHAPTER 1

INTRODUCTION

1.1 RESEARCH BACKGROUND

The construction industry is considered one of the most information-intensive industry, as the construction process demands a large exchange of data and complex information through paper-based or electronic documents (e.g., drawings, specifications, construction plans, rules, etc.) among the project's stakeholders throughout multi processes with a long-span timeline (Hua, 2013; Zhou et al., 2016). Previous research studies (Golyani and Hon, 2010; Min and Bjornsson, 2008; Zhang et al., 2017; Zhou et al., 2016) indicate existing information presentation or visualization methods involve cognitively demanding information processing because it require searching, understanding, and handling a large amount of data so, it may lead to misunderstanding and generate further critical issues such as conflict among stakeholders, design review, and finally, time and cost overrun. The mental model, as shown in Figure 1.1, describes the three main reasons why this type of information is cognitively demanding. First, this mental model identifies that human have different perceptions and work memory capacity. Second, human has different long term memory capacity. And, lastly, the amount of attentional resource capacity of human is limited because of this the user could not effectively handle a large amount of data and its processing in the brain. These limitations of traditional paper-based or electronic documents are demanding to find out the other effective visualization/presentation methods.

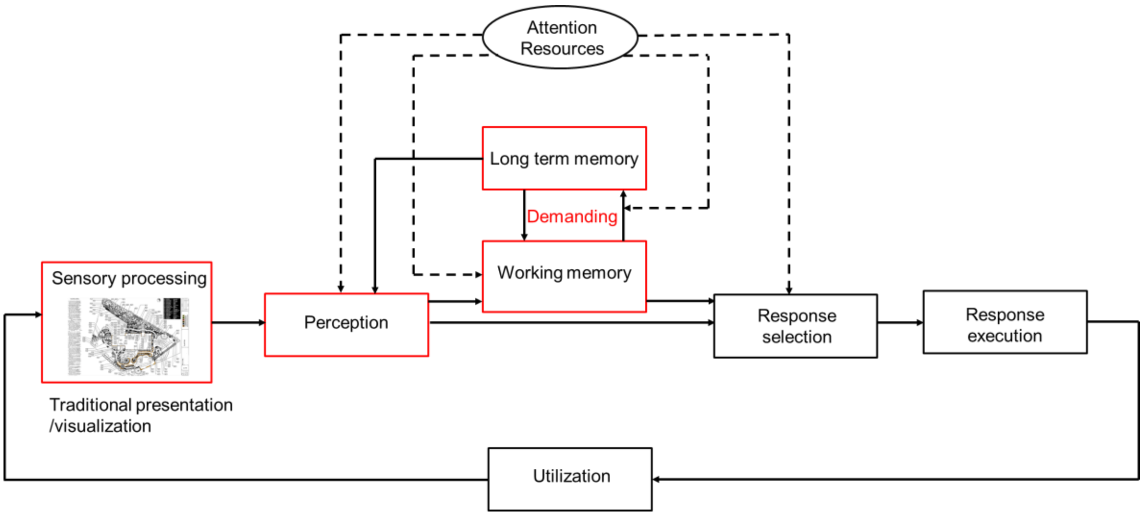

Figure 1.1 Mental Model to Show Cognitive Process (Berlin and Adams, 2017; Helldén and Karlsson, 2020; Wickens et al., 2015)

Recently, to establish clarity among participants and to reduce the uncertainties connected with the project details among stakeholders, assistive technologies such as immersive virtual reality (IVR) and augmented reality (AR) have shown to be effective because it provides context-based information visualization in 3D format (Li et al., 2018). Past research studies (Hou and Wang, 2013; Martínez-Rojas et al., 2016; Rankohi and Waugh, 2013) have also claimed that IVR/AR-based visualization may help to reduce mental efforts, mental load and may increase short-term and long-term memory capacity for encoding, processing, storage, retrieval and utilization of information. IVR allows to experience the information in the completely immersive virtual environment (Radianti et al., 2020) while AR superimposes the additional virtual information in the real environment, and a user can simultaneously interact with the virtual and real environment (Rankohi and Waugh, 2013).

Efforts to use IVR/AR technology to visualize and experience the complex information and to advance the sector of architecture engineering and constriction (AEC) is currently underway. The AEC profession has expressed its desire to use IVR/AR systems for visualization and experience of complex information during the design review phase (Fukuda et al., 2015). However, the use of IVR/AR is not limited to the design review phase; these technologies can be used during the construction phase to improve site preparation and logistics (Heydarian et al., 2015), safety (Li et al., 2018), inspection (Yabuki and Li, 2007), training of construction workers (Carozza et al., 2013), and collaboration and coordination among team members (Heydarian et al., 2015; Messner, 2006).

IVR and AR can also be incorporated with Building Information Modeling (BIM). Especially, the use of IVR/AR with BIM allows virtual 3-dimensional building simulation, information visualization, and as well as coordination and communication among teams. The use of VR/AR with BIM allows participants to walk through BIM models in the high-quality immersive environment and identified critical issues during various project stages (Fukuda et al., 2015; Wang and Love, 2012).

IVR/AR has been widely proposed for many applications in construction. However, the best utilization of these tools demand a sound knowledge of human IVR/AR-interaction first (Malkawi and Srinivasan, 2005). Understanding the human IVR/AR-interaction is also essential as it is different from the traditional human-computer system interaction that comprises three parts: the user, the computer, and the ways they work together. In the IVR/AR interaction, the user continuously experiences the updated information in the immersive environment and interaction methods based on user gestures, motion, and eye movement. In such an immersive environment, there is an always possibility of the ambiguity of how the IVR/AR technical system accurately interprets the intent of the user from the action and how the user perceives and handles the human factor issues related to this state-of-the-art technology (Tory and Moller, 2004).

IVR/AR has human factor issues; for example, in the immersive virtual reality (IVR) environment, participants are needed to perform according to the perception of the immersive digital environment. While AR offers the user with virtual objects in addition to the parts of the real environment in real-time, it also arises new human factors issues such as perceptual, attention, and human information process (Wang and Dunston, 2006). Although, human factors issues are believed the main source of project success and could increase efficiency and performance in the construction industry (Orando, 2013). However, these issues have been a dominant problem which is neglecting from considerable time. Research into human factors issues related to the use of IVR/AR technology is very limited (Livingston, 2013; Livingston et al., 2006). In addition, our knowledge of IVR/AR in terms of human factors is almost non-existent, and many researchers have emphasized the need to comprehend the fundamental human factors issues of IVR/ AR (Kalawsky et al., 2000; Stanney et al., 1998). Therefore, the investigation of human factors issues in the IVR/AR environment is needed to understand the interactions with this technology and to improve human performance and safety for the construction industry.

1.2 LITERATURE REVIEW

On the reality-virtuality continuum by Milgram, and Kishino (1994), virtual reality (VR) and AR is one part of the general area of mixed reality. In this reality-virtuality continuum, VR can be classified as non-immersive VR and immersive VR. Non-immersive VR is a technology that exhibits virtual content through a computer screen without supplement equipment to develop the immersive experience. Screen-based VR or desktop VR, are examples of non-immersive VR (El Araby, 2002). In contrast, immersive VR allows the users to interact with the technology through more complex tracking methods, such as head-mounted displays (HMD) that trace movement and deliver greater immersion because displays adjust in accordance with small movements. HMD prevents visual cues from the users' physical environments to establish a more restricted environment than that of non-immersive VR. IVR technology is considered distinct from other technologies because of its prominent technical aspects. First, it encloses its user, delivers a three-dimensional illustration; monitor the user's place and orientation, and revise the virtual view to balance the user's movement; concealing cues from the real physical environment and rising the feel of existence within IVE (Bailenson et al., 2008; Sacks et al., 2013). Although many of the research studies have defined IVR still many of the construction stakeholders are lacking to understand IVR. A research study (Setareh et al., 2005) defines IVR offers the ways for a person to reach a virtual 3-D multi-physical environment and embody it in such a method as to strongly inhabit, collaborate, and make the next outcome. Whereas Bailenson et al. (2008) state that an immersive virtual environment (IVE) is one that perceptually surrounds the user, increasing his or her sense of presence or actually being within it. The cave automatic virtual environment (CAVE) is an example of immersive VR (Suh and Prophet, 2018).

In contrast, AR is the technology of merging digital and real information on a virtual device screen, such as a tablet or mobile phone, to deliver a user real-virtual view. AR actually exposed the user with virtual objects in addition to the elements of the real physical environment in real-time. Azuma et al. (2001) define AR as *"A system that supplements the real world with virtual (computer-generated) objects that appear to coexist in the same space as the real world."* AR system is separated from VR because of the following properties (Van Krevelen and Poelman, 2010).

- Mixes real and virtual objects in a real environment.

- Registers (aligns) real and virtual objects with each other.
- Proceed interactively, in the three dimensions (3D) and in real-time.

Mainly three display is commonly used in the AR system such as a head-mounted display (HMD), handheld display, and smart glasses. Hoff, and Vincent (2000) explain the AR system incorporates an HMD, camera, and LED targets all on a helmet. Wagner, and Schmalstieg (2006) describe a handheld display provides flat-panel LCD displays with an attached camera such as Tablet. Whereas smart glasses in general, are head-mounted displays that are worn like regular glasses (Rauschnabel et al., 2015). Google Glass and Microsoft HoloLens are examples of smart glasses.

1.2.1 Immersive virtual reality (IVR) applications

Immersive virtual reality (IVR) has been proposed worldwide in various industries, and there are also many advantages of using IVR in the construction industry. Messner et al. (2005) highlighted those construction participants engaged by working in the IVR could quickly comprehend complex design and construction processes due to the rich visual environment. Sacks et al. (2013) identified as compared to the traditional training method IVR based construction workers' training are more effective regarding workers' learning, recall in identifying and assessing construction safety risks.

IVR has been introduced in the construction because of its rich visualization experience. Messner et al. (2005) highlight that participants engaged by working in the IVR are quickly comprehended complex design and construction processes due to the rich visual environment. Bullinger et al. (2010) observe that planning quality and reliability could be positively enhanced despite the extreme complexity of the project by using virtual reality as a visualization tool during construction meetings.

The findings of these research studies are coherent with the research study (Setareh et al., 2005) that was conducted at Virginia Polytechnic Institute and State University (USA). Results of this study indicated that participants had a very encouraging response to the use of IVR, and almost 74% of the participants have agreed that the use of IVR was useful and along with this response high level of engagement was also noticed while using IVR. A similar research study (Shiratuddin and Sulbaran, 2006) was conducted at the University of Southern Mississippi (USA) and supported the previous research studies findings that IVR environment can provide undeniable features such as visual interface, immersion, interaction, and presence that differentiated it from simple 2D and 3D environment. Du et al. (2017) has also explained that IVR allows an extreme close-up examination of an object and can change the way a participant interacts with the other participants as compared to a simple 3D display.

Along with the visualization experience, several researchers have identified the IVR has great potential for communication among distantly located project participants. A recent study (Ceenu George and Hussmann, 2017) claims that that IVR has the potential to provide such a space environment where communication not only equals the real-world environment but offers improved communication tools for distant collaboration by avatars that are otherwise not conceivable for humans to go beyond real-world experience. However, very limited research has been done that empirically measures the communication effectiveness in immersive virtual and face-to-face (FtF) environment. Despite the aforementioned applications of adopting IVR in the construction, challenges with its implementation are still various and very complex, and mainly related to human factors.

1.2.2 Augmented reality (AR) applications

So far, various industries are using AR applications including medical (Hamza-Lup et al., 2018), smart shopping (Bonetti et al., 2018), education (Wang et al., 2018), entertainment (Angrisani et al., 2018), navigation (Rehman and Cao, 2017), manufacturing (Doshi et al., 2017), assembly (Gavish et al., 2015) and museum and libraries (Oyelude, 2018). In construction, this can be used in a wide range of areas in the AEC. For instance, AR provides advantages in reducing uncertain risk and increasing the safety of a construction worksite (Li et al., 2018). Along with this AR can be used for construction progress monitoring (Lee and Peña-Mora, 2006).

Tang et al. (2003) investigate the effectiveness of AR for an assembly task with a printed manual and computer-assisted instruction. The study concluded that AR helps a user to reduce error by 82%. In the area of facility management, AR could improve the situation awareness of facility managers (Irizarry et al., 2013). In addition, AR could be used for inspection purposes. Inspectors with AR can visualize the reinforcing bar arrangement and can arrange them correctly in accordance with drawings and specifications without using tape measures (Yabuki and Li, 2007). AR can also be used for maintenance and renovation purposes (Webster et al., 1996). AR system may facilitate maintenance workers to prevent hidden, buried features such as electrical wiring, telephone lines, etc. This assures to speed up maintenance and reconstruction tasks as well as decrease the amount of accidental destruction (Karji et al., 2017). AR could also be utilized for construction operator training as it decreases potential error through efficient data and information access (Wang and Dunston, 2007).

Moreover, AR has been shown to be a potential tool in the construction education sector since it can change the traditional way of theoretical teaching to a novel approach. Behzadan, and Kamat (2013) proposed a real-time collaborative visual information structure to strengthen the worksite visual information for students via AR.

1.2.3 Human IVR/AR system interaction

Human-computer interaction is based on analysis, design, and assessment of the work system for human use (Holden et al., 2016). The essential goal for human-computer interaction is to enhance the interaction between the users and computer so that it can make the system more operational based on the user's desires and covers the five aspects of the system such as safety, utility, effectiveness, efficiency, and usability (Thuseethan and Kuhanesan, 2015).

IVR/AR is a novel human-computer interaction tool that provides computer-generated information on the immersive artificial/real-world environment (Bekele and Champion, 2019; Nee et al., 2012). Study of this relatively new human-computer interaction tool could significantly help to understand the cognitive process of human interaction with the IVR/AR system and thus could match the users' attributes based on the capabilities of the IVR/AR system (Abbas et al., 2020; Makransky et al., 2019). Livingston et al. (2006)' research study explain that human IVR/AR system interaction could demonstrate that how a well-designed IVR/AR interface with its features could affect the human perceptual and cognitive process which could make the IVR/AR system safer, more efficient, and reliable. Along with this, it can provide the essential knowledge of whether IVR/AR methods are better than traditional methods of information visualization for different construction task. In addition, this IVR/AR interaction could determine the most important user interface needs with its features for yielding better user performance.

Previous studies in the other domain have tried to focus on human IVR/AR interaction. For example, for human AR interaction, (Trevisan et al., 2002)' study was concerned about the design aspect of human-computer interaction in the AR system and proposed a methodology to examine the interaction in the AR-based system. Livingston (2005)' research guides the design of well design AR system user' interface and leads the two questions: (1) how do we ascertain the most significant perceptual requirements of the AR user and the best possible approach to meet these requirements with AR system interface and (2) for which cognitive tasks are AR-based approaches suitable than the traditional approach. Bonnet (2014)' research discusses the human-computer interaction with AR applications in the laboratory context and highlights their advantages and drawbacks. Doucher (2014) explains the different techniques to interact with the AR-based system. This research explains that the interaction part in the AR system would make more information interactive environment with the users therefore it should be considered first before designing the AR-based system On the other hand, for human and IVR system interaction, (Bednarz et al., 2010)' research highlighted the use of IVR applications for underground coal mining and develop the prototype system for providing training purposes. Antoniou et al. (2018) highlight the research efforts of the virtual reality lab of the University of Peloponnese for the development of various virtual reality applications and for providing the visitors' experience about cultural heritage through a virtual reality environment. Guerra (2019) research focuses on human-computer interaction and the organization of information in the IVR environment. This research emphasizes that information in the IVR environment is perceived by sight, sound, and touch. Therefore, synchronization and the amount of information in the IVR system need to be considered first in relation to the cognitive process of the users. And, lastly, (Ladendorf et al., 2019)' research highlighted that the IVR system environment can provide a high sense of presence and a more authentic experience in the immersive environment. However, the information intensive IVR system may require more attentions and higher level of metal efforts thus could ultimately increase the cognitive process of the users. In conclusion, most of the above-mentioned studies indicate that no matter weather it’s a IVR system or a AR system, the amount of information overload is an extremely important for designing human IVR/AR system interaction and too much information in the IVR/AR system would not effectively process the human brain and therefore could effect the user’s performance.

Considering that the construction industry is the most information-intensive industry and utilization of IVR/AR system could significantly help by providing new visualization method in the complex and dynamic construction environment, failure to address the IVR/AR system interaction issues could affect the users perceptual and cognitive process and thus could undermine the optimal effectiveness of IVR/AR applications at construction sites. However, previous studies for IVR/AR system interaction for use in AEC have not fully considered this aspect. Therefore, an in-depth understanding of how human IVR/AR system interaction could affect the human perceptual and cognitive process would be helpful to design a safer and more effective IVR/AR system for AEC use.

1.3 RESEARCH OBJECTIVES

This research aims to provide a better understanding of human IVR/AR system interaction and to check the impact of these technologies on the user’s perceptual and cognitive process. As depicted in Figure 1.1, the study begins with the identification of IVR/AR system features. Based on these unique IVR/AR system features, previous research studies have reported that we need to understand the human IVR/AR interaction first (Bombari et al., 2015; Miller et al., 2019) before its utilization for practical purposes. As construction site is considered a complex dynamic environment and failure to address fully human IVR/AR interaction before its utilization at the construction site can undermine the potential effectiveness of IVR/AR applications and thus could serious negative effects on construction worksite safety. Therefore, this study further aims to better design the IVR/AR system aiming to enhance their applications' effectiveness. and to examine the issues of information processing in IVR/AR system and its cognitive interaction with user. Mainly, this research focused on the three IVR/AR applications, particularly to examine information acquisition (communication), information processing (cognitive task performance), and information perception (safety training). These three applications are selected among many other applications of IVR/AR because these are the recent prominent applications of IVR/AR (Li et al., 2018; Rankohi and Waugh, 2013), and many of the researchers in the other domains are trying to utilize these applications for their industry (Baumeister et al., 2017; Ceenu George and Hussmann, 2017; Pedram et al., 2020). However, very litter efforts have been done to utilize these applications for the AEC industry perspective. The detailed objectives of this research are presented as follows.

1) To compare the communication effectiveness of face-to-face communication in the real-world environment and immersive virtual reality-based communication in a virtual environment for construction.
2) To examine how a lack of understanding of human cognitive issues (e.g., cognitive load and situation awareness) could constraints the potential effectiveness of the mobile AR system?
3) To explore the impact of immersive virtual based training on construction participants behavior and to understand the underlying mechanisms of behavior change with IVR-based training through structural equation modeling.

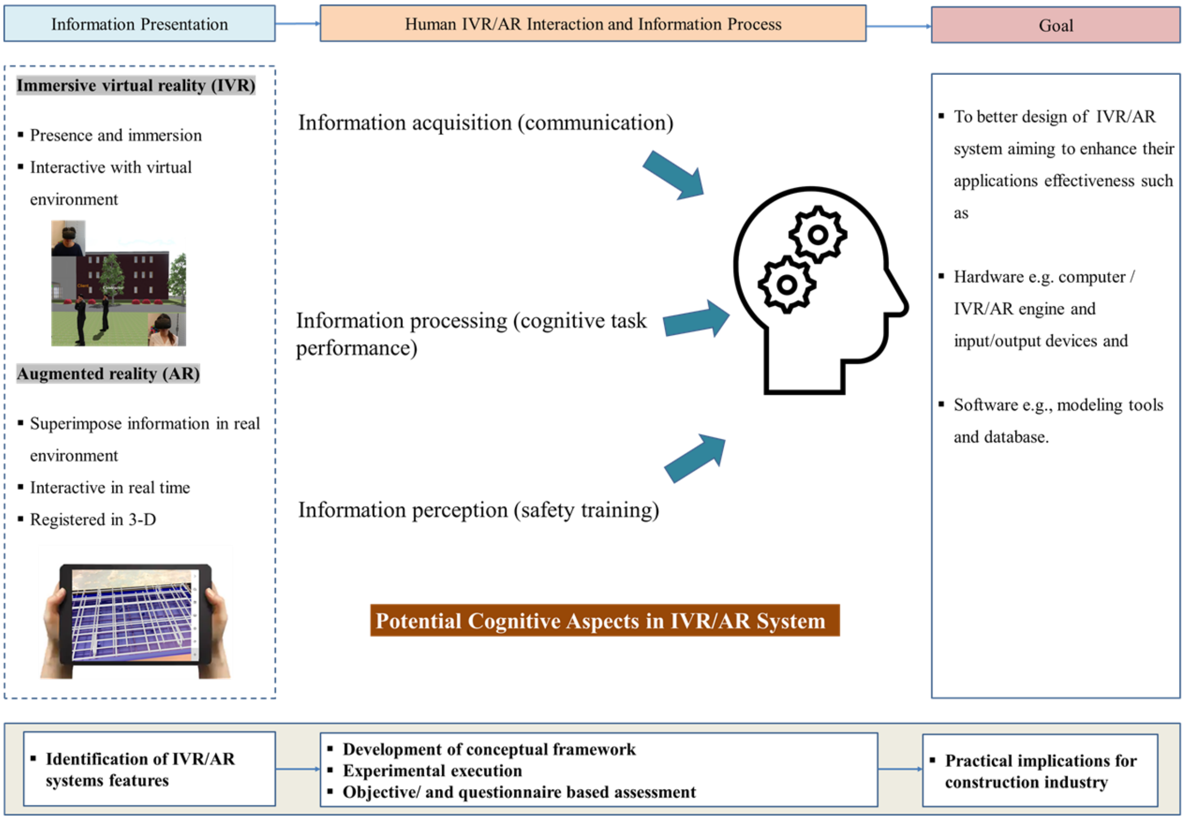

Figure 2.2 The Framework of This Research

1.4 SIGNIFICANCE OF RESEARCH

The research examines the IVR/AR-interaction issues particularly three IVR/AR applications such as communication, cognitive task effectiveness, and construction safety training. This research provides a better understanding of human cognitive aspects in IVR/ AR environment and highlights that how IVR/AR-based information visualization would help to reduce mental efforts. In addition, this research provides a comprehensive framework that highlights the potential factors that could affect the information processing capability of a user in IVR/AR system.

This research study would significantly help the construction professionals to improve the construction industry performance and safety through a better understanding of human IVR/AR-interaction which would enable the construction professionals to successfully utilize IVR/AR applications at construction sites and would provide better solutions to handle a large amount of information compared with traditional methods such as paper-based or electronic documents. In addition, the outcomes of this study can be used to guide the practitioners and trainers to develop and use IVR/AR systems for practical purposes (e.g., communication, cognitive task performance, and training). This would open a new door to provide IVR/AR-based training for construction participants and would provide a strong foundation to digitalize the construction sector based on the 21st-century requirements.

1.5 STRUCTURE OF THE THESIS

This thesis contains five following Chapters.

Chapter 1: Introduction. This chapter is about the background of IVR and AR, human IVR/AR system interaction, research problem, aim and research objective, research framework, and significance of this research work.

Chapter 2: Effectiveness of Immersive Virtual Reality-based Communication for Construction Projects. This chapter discusses the communication effectiveness of face-to-face communication in IVR based communication in a virtual environment for construction.

Chapter 3: Impact of Mobile Augmented Reality System on Cognitive Behavior and Performance During Rebar Inspection Tasks. This chapter highlights how a lack of understanding of human cognitive issues (e.g., cognitive load and situation awareness) could constraints the potential effectiveness of the mobile AR system.

Chapter 4: How Immersive Virtual Reality System Features Impact Behavior Change for Safety? A Structural Equation Modeling Approach. This chapter discusses the impact of immersive virtual based training on behavior change outcomes through structural equation modeling.

Chapter 5: Conclusions and Recommendations. This chapter covers conclusions and recommendations that can be drawn from this research for future research studies.

1.6 CHAPTER SUMMARY

This chapter presents a general introduction of the research background including traditional information handling process in construction, IVR and AR applications in construction, human IVR/AR system interaction, and research problems. It also highlights the research aims and objective, research framework, and significance of the research. Finally, the structure of the thesis was shown.

CHAPTER 2

EFFECTIVENESS OF IMMERSIVE VIRTUAL REALITY-BASED COMMUNICATION FOR CONSTRUCTION PROJECTS

2.1 INTRODUCTION

The success of any construction projects depends heavily on effective means of sharing a variety of information among different stakeholders (den Otter and Emmitt, 2008). However, effective communication during such projects is often challenging because of their interdisciplinary work environments that require continuous cooperation by members of multiple organizations (Dainty et al., 2007; Günhan et al., 2012). Moreover, international construction projects are increasingly common, and by their nature, create obstacles to their participants visiting construction sites and attending in-person meetings. As such, construction projects frequently suffer from poor and inefficient communication, which can lead to critical issues such as design errors, conflicts among participants, or failures of risk management, resulting in cost and/or time overruns (Gamil and Rahman, 2017).

To overcome these challenges, construction stakeholders increasingly use BIM for information sharing. BIM not only offers the opportunity for multiple organizations to work together on a single building model, but also allows its users to identify critical

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This chapter is based on published study.

Abbas, A., Choi, M., Seo, J., Cha, S. H., & Li, H. (2019). "Effectiveness of Immersive Virtual Reality-based Communication for Construction Projects." *KSCE Journal of Civil Engineering*, 23(12), 4972-4983. https://doi.org/10.1007/s12205-019-0898-0.

issues during various project stages (Svalestuen et al., 2017). These days, BIM serves as a platform for virtual communication by integrating it with VR and online communication technologies (Zaker and Coloma, 2018). In particular, the use of IVR adds a new dimension of experiencing BIM and can further improve virtual communication between remotely located stakeholders (Wang et al., 2018). Additionally, IVR-based virtual communication in the 3D virtual environment can benefit from the use of an avatar that can make IVR communication similar to face-to-face (FtF) interaction (Greenwald et al., 2017). An avatar is the digital representation of a user in the virtual environment (Nowak and Fox, 2018), and today avatar-mediated communication is most common within entertainment applications such as games. For example, a multiplayer online role-playing game provides a platform to the player to interact with the virtual environment and have social interaction with the other players via an avatar (Johansson, 2015). These applications imply its great potential of IVR-based communication in construction projects.

Despite the usefulness of IVR-based communication as a remote communication channel, however, whether it is as effective as FtF communication for exchanging project-related information and decision making is still questionable. This issue could be more critical when considering the specific characteristics of communication in the construction environment where construction participants are from different organizations and lack of collaboration among them may lead to significant conflicts. Also, as important decisions are generally made through communication among participants, misunderstanding of other’s intention could lead to significant consequences to the project. So, the communication effectiveness through IVR should be explicitly validated to prove its reliability and to understand communication behaviors for further improvement.

Therefore, this study compared IVR-based communication in a virtual environment featuring avatars against FtF communication in terms of their communicative effectiveness for a construction project. Specifically, we conducted comparative experiments where two groups of students role-played different construction professionals and discussed each other for decision making during a design phase through FtF and IVR-based communication, respectively. In order to compare the various aspects of communication behaviors and effectiveness, five criteria suggested by (Lowry et al., 2006) (i.e., discussion quality, appropriateness, richness, openness, and accuracy) were assessed by subjects after a discussion. In particular, discussion quality denotes the participants' issue understanding, knowledge sharing, and feelings of satisfaction during the discussion. Appropriateness refers to behavioral acts such as politeness and social manner. Richness indicates the overall quantity and comprehensiveness of information-sharing within a group. Openness is the inclination of group members to be open-minded to others' opinion, and accuracy is whether the information is communicated to the right people and accurately understood by them. Based on the evaluation results, the ways to maximize the benefits of IVR-based communication for construction stakeholders are discussed.

2.2 LITERATURE REVIEW

2.2.1 Virtual communication in construction

In construction projects where many professionals from different organizations must work together, effective inter-organizational communication is a vital factor in project success (Adriaanse and Voordijk, 2005). For decades, FtF communication has been preferred for inter-organizational communication in the construction industry, especially for important decision-making during projects, as it allows individuals to share their thoughts directly and obtain instant feedback (Senaratne and Ruwanpura, 2016). However, inter-organizational FtF communication is not always efficient, notably because of the time constraint and financial costs of gathering project stakeholders at a specific physical location (Heller, 2010). As a result, the construction industry has tried to use electronic communication tools (e.g., e-mail, video and audio conference, web-conference, chatting, etc.) to connect with remotely located participants. In particular, the use of cloud computing and online video conferencing methods enable us to share more complicating information between multiple participants without being present at a same physical space (Bond-Barnard et al., 2016; Fathi et al., 2012).

These days, a great deal of attention exists on the use of IVR driven by BIM and online conferencing technologies for enhancing project communication in construction by taking advantages of both FtF and electronic communication (Du et al., 2017). IVR technology offers the ways for a user to reach a virtual 3-dimensional multi-physical environment (Setareh et al., 2005), and perceptually encloses the user in such a way that continuously provides a feeling of presence or in fact exist within this virtual environment (Bailenson et al., 2008). Nowadays, IVR with a head-mounted display (HMD) has promised a 360º immersive experience by using a laser tracking system and delivering the high level of immersion to the users in the virtual environment (Calogiuri et al., 2018). This immersion force derives the high sense of presence in the virtual environment (Zhang, 2017). High Tech Computer (HTC) Vive, Oculus, and Samsung devices are the most popular models of HMDs for this purpose (Martín-Gutiérrez et al., 2017). Also, as shown in Figure 2.1, inserting an avatar (i.e., a virtual human model) in the virtual environment can make virtual communication in the IVR environment more realistic like FtF communication (Greenwald et al., 2017)

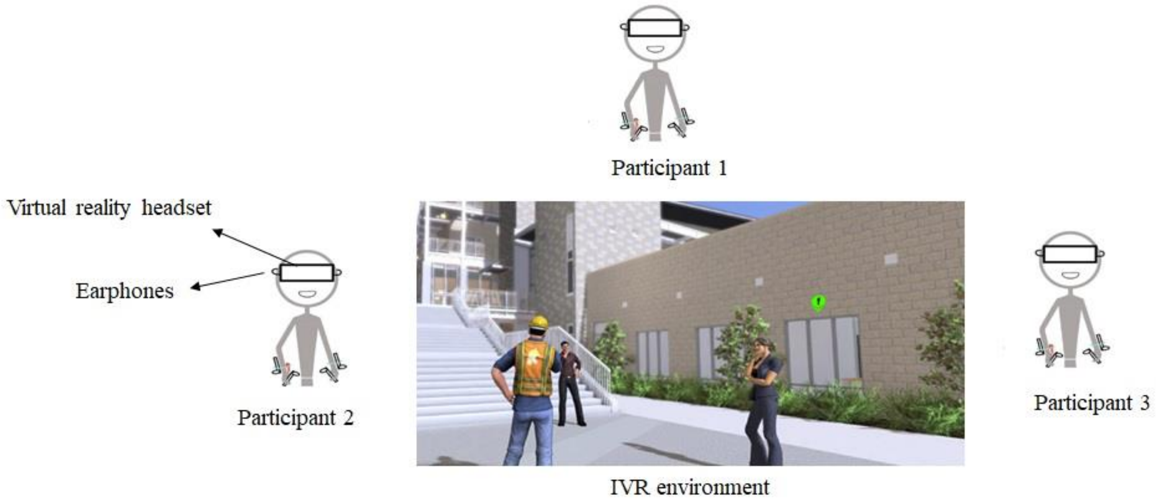

Figure 2.1 Example of Virtual Communication in the IVR Environment with Avatars (Fuzor^{TM}, 2019)

One of the advantages of using IVR-based communication in construction is that BIM models themselves can serve as a virtual space for communication, and thus additional time and efforts to create a virtual environment are not necessary. By simply adding an online conferencing function, IVR-based communication is enabled. Recently, some commercial solutions that provide an IVR-based communication platform are available in the market, such as Fuzor (https://www.kalloctech.com/).

In construction, IVR-based communication has great potential to apply in construction practices (Anderson, 2015). For example, walking around a model in an immersive virtual environment, along with other participants' avatars, represents a unique new mode of visualization. In addition, with the visualization experience, an IVR-based communication can enhance global collaboration between international AEC stakeholders as it provides a feeling of being there without limiting the distance barriers. In this virtual environment, they can feel that they truly are a team working in the same environment to communicate on the same project (Wu et al., 2017). Another recent study by (Nowak and Fox, 2018) has claimed that avatar-mediated communication in an immersive virtual environment not only maximizes the advantages of virtual communication, but also provides a realistic approximation of FtF interaction, and offers greater flexibility than its FtF counterpart when it comes to modifying one's self-presentation during communication. The other prominent benefit of the expansion of BIM-based IVR in the design and construction industries is due to the opportunities that are increasing the involvement, and interaction with various stakeholders from the design process to the completion of the project (Tutt et al., 2013). In addition, IVR has a potential to provide such a space environment where communication not only equals the real-world environment but offers improved communication tools for distant collaboration by avatars that are otherwise not conceivable for humans to go beyond real-world experience (Ceenu George and Hussmann, 2017). Research studies by (Greenwald et al., 2017; Greiner et al., 2014) have found that avatar-to-avatar communication can significantly impact on reducing the amount of communication required to achieve optimal solutions.

Although, research has also shown that avatars, if designed properly, can provide a realistic sense of communication among parties (Roth et al., 2017), however, avatar-mediated communication reduces important non-verbal communicative cues such as facial expressions, bodily postures, and hand gestures, thus rendering meeting participants more reliant upon spoken words than they would be in FtF settings (Dodds et al., 2011). Also, the lack of interactions in IVR such as human-to-human interaction, data interaction, and human-building interaction in IVR is impeding the adoption in the construction industry (Du et al., 2017). This effect can be even more marked in construction projects, where managers are habituated to working in real physical environments and spend large amounts of time engaged in FtF interaction (Laufer et al., 2008). Despite these limitations, IVR has great potential as a new communication channel in construction, enabling ubiquitous access to project information (e.g., BIM) and removing limits of space and time for collaboration and coordination in construction projects. Considering that IVR is still an emerging technology, a clear understanding on the impact of technical limitations of current IVR technologies on communication effectiveness is necessary for better use of IVR communication and further improvement on IVR-based communication technologies.

2.2.2 Evaluation of communication effectiveness

While a number of rival definitions of *effective communication* exist, this study considers it to be the exchange of information, knowledge, and instructions between members of separate organizations to achieve a shared understanding (Olanrewaju et al., 2017). There are several types of communication effectiveness in the construction industry such as interpersonal communication, group and team communication, organizational communication, and corporate communication (Dainty et al., 2007). The measurement of communication effectiveness is not at all same at the organizational, group and individual level because the communication goals of a user may differ enormously from context to context (Littlemore, 2003).

Previous studies in construction have tried to measure the effectiveness of communication channels considering diverse aspects of communication not only for understanding communication behaviors of certain channels but also for improving their communication performance (Andres, 2002; Tanaka et al., 2014). Guevara, and Boyer (1981) highlighted the cause of poor communication in construction organizations, which was based on four key factors, including information overload, information underload, gatekeeping, and distortion. To examine more, the Construction Industry Institute examined 72 construction projects and measured the communication effectiveness through six critical variables including accuracy, timeliness, procedures, understanding, barriers, and completeness were identified (Thomas et al., 1998). This research study has established a quantifiable relationship between project success and effective communication through these six critical variables and suggested these variables to measure communication effectiveness during execution stage of engineering, procurement, and construction (EPC) projects. Due to the importance of project communication in construction and to examine more, (Xie et al., 2010)'s research measured the communication through eleven variables including, communication accuracy, procedure, barriers, understanding, timeliness, completeness, information flow, overload, underload, distortion, and gatekeeping. Although these studies have conducted research studied on measuring communication effectiveness, however, they only focused on communication effectiveness at the organizational level in construction.

Whereas, in the other domain, Lowry et al. (2006) and Roberts et al. (2006) measured communication effectiveness with FtF and computer-mediated communication channels at the small group level through five key factors of communication effectiveness: discussion quality, appropriateness, richness, openness, and accuracy. *Group discussion quality* refers to the participant' assessment in terms of the level of discussion effectiveness, understanding and sharing the information and satisfaction felt during the discussion. *Communication appropriateness* refers to behavioral acts such as politeness and social manner during communication. *Communication richness* implies an exchange that is clear, topically focused, and yields comprehensive answers. *Communication Openness* reflected how much the team members enjoyed and open-minded during the session. And *communication accuracy* reflects that the information transferred between meeting participants is communicated accurately and comprehended adequately. These measures have been widely adopted in various studies that investigated small-group communication effectiveness in different conditions such as video conferencing (Guo et al., 2009), training by using various communication channels (Lam, 2016) and students' group project communication (Lam, 2015).

2.3 RESEARCH METHODOLOGY

This study aims to understand the impact of technical limitations of IVR-based communication on communication effectiveness, compared with traditional FtF communication during construction projects. Among different types of communication in the construction industry (e.g., organizational, group and individual level), communication in a small-group level is one of the most typical types of communication at the project level where a group of professionals with different skills, knowledge, and abilities formed small groups from various organizations to interact and monitor the project throughout the project lifecycle (Dainty et al., 2007). Also, considering the context of the construction environment, a small group of professionals who are physically located in different organizations needs to frequently interact with participants throughout the project lifecycle. So, this study limited the research scope on communication effectiveness at the small-group level.

This study designed controlled experiments to simulate real-like FtF and IVR-based communication for important decision making during a design phase by recruiting student participants, and compared communication effectiveness through survey questionnaires based on five key factors proposed by Lowry et al. (2006) and Roberts et al. (2006). Details on the experimental sessions are as follows.

2.3.1 Participants

A total of 24 fourth-year undergraduate students seventeen males and seven females, who were majoring in building engineering and management, surveying, and property management at the Hong Kong Polytechnic University were randomly recruited for role-playing of the construction industry stakeholders. All the respondents had completed several subjects related to construction project management and gained basic construction industry experience through internships at construction companies. The participant pool was divided into eight groups, each of three people, who were randomly assigned the roles of client, architect, and contractor. Before the experimental sessions commenced, they were briefed on the study's purpose, and process and their background information were collected through a survey. The results of this survey indicate that all participants had a theoretical knowledge about BIM and virtual reality.

2.3.2 Task overview

All eight groups were asked to engage in both FtF and IVR-based communication sessions. They were given different communication tasks for each FtF and IVR-based communication session. Two different building types, i.e., office and residential were used for each experiment to minimize the learning effects of a given group's previous discussion. For example, four of these groups first engaged in FtF communication for an office building project, and then in IVR-based communication for a residential building. The remaining four teams experienced first IVR-based communication for a residential building and then performed FtF communication for an office building project. Also, the participants within each group did swap roles between their two sessions, and between two sessions, one week was given to minimize possible learning effects from the previous session.

In each experimental session, the participant team was role-playing of construction professionals and was involved in the decision-making task early for selecting construction-project design options. The main task was to select the best alternatives for external-wall material (i.e., concrete, brick, or curtain wall), structural material (i.e., concrete or steel), and floor height (i.e., low or high) based on the aesthetics, cost, and construction duration of a three-story building. The specific design options for each category and their expected influence on the project's cost and duration were provided to the participants during the experiment, together with relevant BIM models (Tables 2.1 and 2.2).

Table 2.1 Poject Information

Design Options		Cost	Duration
External wall materials	Concrete	Low	Medium
	Brick	Medium	Long
	Curtain wall	High	Short
Structural materials	Concrete	HK$20,000/m^2	48 weeks
	Steel	HK$18,000/m^2	45 weeks
Floor height	Low	Slight increase with higher floor height	No significant difference
	High		

Table 2.2 BIM Images of Floor-height Design Options

External Wall Material	Category: Floor Height	
	Low	High
Concrete 		
Brick 		
Curtain Wall 		

In addition, different goals were provided to each participant based on his or her assigned role. The client's main goals were that the project be completed at the lowest cost and in the shortest time period possible; and secondarily, that the design of the building be attractive to potential tenants. For the architect, the main focus was the aesthetic aspect of the building, and students who took on this role were instructed to de-emphasize project cost and duration in their own decision-making. Nevertheless, they were told it was essential that they accommodate the client's needs. Lastly, the contractor's chief goal was to complete the project as fast as possible, and his/her secondary goal, to keep both the client and the architect satisfied. Project costs and types of materials were not among the contractor's key concerns.

2.3.3 Procedure

As mentioned above, the subjects had been assigned to their different roles, and relevant project information was given according to their roles in both FtF and IVR-based sessions. After fully understanding their roles and project information, they were instructed to share opinions in a project meeting to find solutions for the assigned task. The length of each experimental session was approximately 60 minutes including the researchers' instructions, the group discussion, and each participants' completion of the survey questionnaires.

In the FtF session, three participants in a group were seated together in the same room and communicating with each other through BIM-based project visualization as shown in Figure 2.2. The project information details and Autodesk Revit BIM models were used to show the various design alternatives, as shown above in Table 2.1 and Table 2.2 respectively. Autodesk Revit BIM models were provided on a monitor screen as aids to FtF communication. One BIM professional was also seated in the FtF session, showing the BIM-based information on the monitor screen. In addition, participants had this opportunity to walkthrough the BIM model through the assistance of a BIM professional.

Figure 2.2 Experimental Settings of FtF Communication

Then, after a one-week break, the same groups engaged in an IVR-based communication session with different building types. In the IVR session, the relevant BIM models were incorporated into Fuzor Virtual Design Construction software so that the design alternatives could be experienced in the immersive virtual environment. Each group member in the IVR-based communication session was seated at a different location and was instructed to communicate with other two group members through IVR. All participants in the session were equipped with HTC Vive, a head-mounted display device equipped with a microphone and earphones. This enabled each participant to verbally communicate with other group members through voice chat and to observe their individual avatars while exploring specific parts of the BIM model in the virtual environment Figure 2.3. Participants in the IVR sessions also have this opportunity to walk through the building in the immersive virtual environment and can see each other individual avatars, but their avatars were not making certain gestures such as facial expression, head, eye, or other non-verbal expressions.

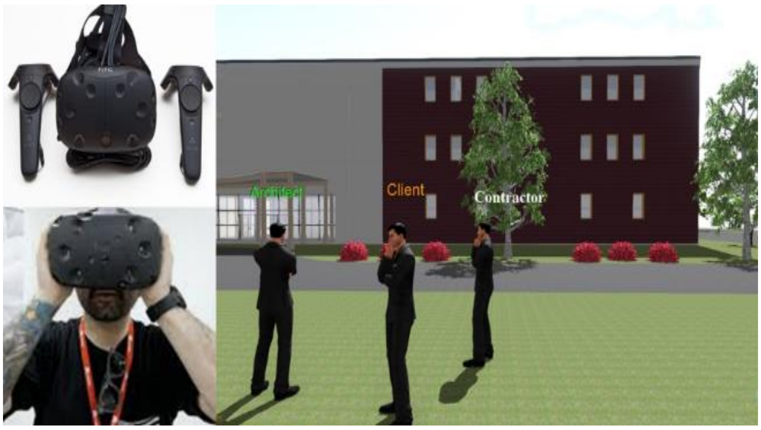

Figure 2.3 Experimental Settings of IVR-based Communication

Three types of questionnaires were designed for the experiment including 1) immersive tendencies, 2) presence and 3) communication effectiveness questionnaires. First, the immersive-tendencies questionnaire – which was designed to measure individuals' susceptibility to feelings of immersion in virtual environments – was completed immediately prior to their commencing the IVR experiment (Witmer and Singer, 1998). The presence questionnaires, completed upon their completion of the IVR session, focused on their subjective experiences of being in a particular environment and were intended to confirm that an appropriate level of presence was maintained during the experiment (Witmer and Singer, 1998). The specific questions included in each item of immersive tendency and presence questionnaire are summarized in Table 2.3 and Table 2.4. Responses to each item were measured on a seven-point Likert scale ranging from 1 to 7.

Table 2.3 Immersive-tendencies Questionnaire

Items
1. I extremely physically fit today.
2. I mentally alert at the present time.

3. I blocked out external distractions very effectively when I am involved in something.
4. When I involved in a television program or book, then people faced problems to get my attention.
5. I am extremely involved in projects that are assigned to me by my instructor.
6. Often, I become so involved in doing something that I lose all track of time.
7. I can well examine objects from multiple viewpoints.

Table 2.4 Presence Questionnaire

Items
1. I was able to concentrate on the assigned tasks or required activities.
2. I was involved with the visual aspects of the environment.
3. I was quickly adjusted to the virtual-environment experience.
4. I was getting consistent experience in the virtual environment like real-world experience.
5. I was involved in the virtual-environment experience.
6. I was felt confused at the beginning or at the end of the experimental session

Finally, the communication-effectiveness questionnaire (as shown in Table 2.5) was used to measure the participants' perceptions of the effectiveness of the experimental sessions' FtF and IVR-based communication methods. It was administered to the participants at the end of each session, immediately after their discussion ended, and designed to capture in detail the perceived levels of Lowry et al.'s (2006) five criteria for effective group communication (i.e., discussion quality, appropriateness, richness, openness, and accuracy), as more fully explained below.

Table 2.5 Communication Effectiveness Questionnaire

Discussion Quality
(Issue understanding) I correctly understood the issue that I had to discuss.
(Knowledge sharing) The group members effectively shared information about the project.
(Satisfactory solution) The solution produced by the group discussion was satisfactory.
(Discussion effectiveness) The overall group discussion was an effective means of finding a solution.
Communication Appropriateness
(Concentration on others) I focused on other members when they were speaking.
(Concentration from others) Other members focused on me when I was speaking.
(Politeness to others) I treated other members politely during communication.
(Politeness from others) Other members treated me politely during communication.
Communication Richness
(Overall information quantity) A rich amount of information was shared during the discussion.
(Information quantity from others) Others provided me with enough information when they spoke.
(Information quality to others) I could provide vivid information on the subject when needed.
(Information quantity to others) I could provide detailed information on the subject when needed.
Communication Openness
(Open-mindedness) It was easy to communicate openly with all group members.
(Enjoyableness) I found it enjoyable to talk to other group members.
Communication Accuracy
(Communication accuracy) I often had to go back and check the information I received.
(Misunderstanding others) I often did not understand what others were saying.
(Misunderstood by others) I often had to re-explain statements I had previously made.

First, Group discussion quality was assessed in terms of how effectively information was shared and how well it was understood, the discussant's level of satisfaction with the discussion's outcome/decision, and his/her feelings about whether the discussion had been effective. Communication appropriateness was broken down into the respondent's self-reported level of concentration and politeness, and his/her perceptions of the other team members' concentration and politeness. Communication richness included both qualitative and quantitative aspects of the information that was shared, and communication openness reflected both how much the team members enjoyed and open-minded during the session. Finally, communication accuracy comprised the respondent's assessment of how the information passed among the team members. All responses were provided on a five-point Likert scale ranging from 1 = strongly disagree to 5 = strongly agree.

2.4 RESULTS

The internal consistency of all completed questionnaires was examined using Cronbach's coefficient alpha. Internal consistency defines the extent to which all the items in a questionnaire measure the same concept or construct (Tavakol and Dennick, 2011). As shown in Table 2.6, the Cronbach's alpha values of the questionnaires from both the FtF and IVR conditions were greater than the minimum acceptable value of 0.7 (Zahoor et al., 2016), indicating that the data had excellent internal consistency.

Table 2.6 Cronbach's Alpha Values, Communication Effectiveness Questionnaires

Effective Communication Factors	FtF Condition	IVR-based Condition
Group Discussion Quality	0.85	0.88
Communication Appropriateness	0.81	0.74
Communication Richness	0.90	0.88
Communication Openness	0.70	0.72
Communication Accuracy	0.71	0.76

2.4.1 Immersive tendency and presence

All items on both the immersive-tendencies and presence questionnaires received mean scores higher than 4.0 (as shown in Table 2.7 and Table 2.8 respectively), with the exception of the item on the presence questionnaire that asked about the level of confusion the respondent felt at the beginning or end of the experimental session, which received a mean score of 3.1 (Table 2.8). Taken as a whole, these results indicate that the participants did not experience any major issues affecting their involvement in, or ability to maintain focus on, the experimental activities. In addition, the presence questionnaire results suggested that the participants were able to concentrate and focus on the session environment, as shown in Table 2.8.

Table 2.7 Immersive-tendencies Questionnaire Results

Items	Mean (SD)
1. I extremely physically fit today.	5.25 (0.96)*
2. I mentally alert at the present time.	4.5 (1.31)
3. I blocked out external distractions very effectively when I am involved in something.	5.25 (0.96)

4. When I involved in a television program or book, then people faced problems to get my attention.	4.7 (1.42)
5. I am extremely involved in projects that are assigned to me by my instructor.	5.08 (1.24)
6. Often, I become so involved in doing something that I lose all track of time.	4.33 (1.43)
7. I can well examine objects from multiple viewpoints.	5.08 (0.99)

*Mean (Standard deviation)

Table 2.8 Presence Questionnaire Results

Items	Mean (SD)
1. I was able to concentrate on the assigned tasks or required activities.	5.66 (0.78)*
2. I was involved with the visual aspects of the environment.	5.91 (0.99)
3. I was quickly adjusted to the virtual-environment experience.	5.41 (1.31)
4. I was getting consistent experience in the virtual environment like real-world experience.	5 (1.12)
5. I was involved in the virtual-environment experience.	6.08 (0.67)
6. I was felt confused at the beginning or at the end of the experimental session.	3.1 (1.12)

*Mean (Standard deviation)

2.4.2 Communication effectiveness

The *paired samples Wilcoxon test* was conducted on FtF and IVR-based communication channels, as shown in Table 2.9. The two factors, communication appropriateness, and accuracy indicate that there were statistically significant differences between FtF and IVR-based group communication means as determined by *paired samples Wilcoxon test*. In addition, the mean values of these factors indicate that FtF communication is considered more suitable to its members to communicate and correctly comprehend the information appropriately. However, no statistically significant mean differences have found in the other three factors (discussion quality, communication richness, communication openness). This implies that these three factors in both FtF and IVR-based communication enable the members to successfully understand and define the problem with richer information.

Table 2.9 Paired Samples Wilcoxon Test Results, Communication-effectiveness Questionnaire

	Communication-effectiveness Criteria				
	Quality of Discussion	Appropriateness	Richness	Openness	Accuracy
FtF Communication	4.06 (0.6) *	4.48 (0.56)	3.74 (0.64)	4.25 (0.56)	3.27 (0.86)
IVR-based Communication	4 (0.6)	4.03 (0.42)	3.81 (0.7)	3.93 (0.58)	3.79 (0.63)
P value	0.64	0.04	0.71	0.15	0.03

*Mean (Standard deviation)

2.4.2.1 Quality of discussion

The *paired samples Wilcoxon test* for the quality of discussion (Table 2.9) revealed no statistically significant difference between the FtF and IVR conditions’ respective overall means $p > 0.05$. The four subcomponents of quality of discussion – i.e., issue understanding, knowledge sharing, satisfactory solution, and effective discussion – were also tested using the *paired samples Wilcoxon test* (Table 2.10), but again, there were no statistically significant differences between the FtF and IVR sessions for any of these subcomponents.

Table 2.10 Paired Samples Wilcoxon Test Results, Discussion-quality Subcomponents

	Issue understanding	Knowledge sharing	Satisfactory solution	Discussion effectiveness
FtF Communication	4.25 (0.67)*	4.08 (0.71)	4 (0.78)	3.91 (0.65)
IVR-based Communication	4.37 (0.49)	3.79 (0.77)	4.04 (0.8)	3.79 (0.77)
P value	0.49	0.82	0.17	0.46

*Mean (Standard deviation)

2.4.2.2 Communication appropriateness

As shown in Table 2.9, above, *paired samples Wilcoxon test* on the mean scores the participants assigned to communication appropriateness revealed a statistically significant difference between the FtF and IVR conditions $p < 0.05$. However, the detailed results for this construct's subcomponents (Table 2.11) show that three of them (i.e., concentration on others, politeness to others, and politeness from others) were not significantly different across the two conditions, meaning that the overall difference was heavily dependent on just one subfactor: concentration from others $p < 0.05$.

Table 2.11 Paired Samples Wilcoxon Test Results, Communication Appropriateness Subcomponents

	Concentration on others	Concentration from others	Politeness to others	Politeness from others
FtF Communication	4.37 (0.82)*	4.5 (0.65)	4.37 (0.71)	4.33 (0.70)
IVR-based Communication	4.04 (0.80)	4.04 (0.69)	4.25 (0.6)	4.29 (0.55)
P value	0.55	0.01	0.81	0.59

*Mean (Standard deviation)

2.4.2.3 Communication richness

The paired samples Wilcoxon test identified no statistically significant difference between the overall richness means for the FtF and IVR conditions $p > 0.05$ (Table 2.9). As shown in Table 2.12, detailed analysis via *paired samples Wilcoxon test* of each of its four subcomponents also found no statistically significant differences between the FtF and IVR sessions' means.

Table 2.12 Paired Samples Wilcoxon Test Results, Communication Richness Subcomponents

	Overall information quality	Expressing detailed information	Expressing vivid information	Information quantity provided to others
FtF Communication	3.66 (0.81)*	3.79 (0.65)	3.75 (0.73)	3.75 (0.73)
IVR-based Communication	3.58 (0.97)	4 (0.69)	3.7 (0.77)	3.95 (0.75)
P value	0.33	0.82	0.58	0.85

*Mean (Standard deviation)

2.4.2.4 Communication openness

As shown in Table 2.9, above, there was no statistically significant difference between the FtF and IVR conditions' overall means for openness, $p > 0.05$. The detailed *paired samples Wilcoxon test* results for each subcomponent of openness are presented in Table 2.13. Neither of them exhibited a statistically significant difference between the FtF and IVR conditions: open-mindedness, $p > 0.05$; enjoyableness, $p > 0.05$.

Table 2.13 Paired Samples Wilcoxon Test Results, Communication Openness Subcomponents

	Open-mindedness	Enjoyableness
FtF Communication	4.41 (0.58)*	4.08 (0.65)
IVR-based Communication	3.92 (0.88)	4.04 (0.69)
P value	0.06	0.83

*Mean (Standard deviation)

2.4.2.5 Communication accuracy

As noted in Table 2.9, above, the *paired samples Wilcoxon test* for accuracy revealed a statistically significant difference between the overall mean scores for the accuracy of the FtF and IVR conditions, $p < 0.05$. Because this communication-effectiveness factor consisted of negative items, the IVR condition's higher mean implies that the participants perceived FtF communication as allowing them to share their opinions more clearly and correctly than IVR-based communication did. The *Paired samples Wilcoxon test* of each accuracy subfactor (Table 2.14) revealed that the first two – communication accuracy and misunderstanding others – were not the source of this statistically significant difference, which instead depended on the third subfactor, misunderstood by others, $p < 0.05$.

Table 2.14 Paired Samples Wilcoxon Test Results, Communication Accuracy Subcomponents

	Communication accuracy		Misunderstood by others
FtF Communication	3 (1.06)*	3.53 (1.01)	3.25 (1.07)
IVR-based Communication	3.45 (0.93)	3.83 (1.01)	4.08 (0.58)
P value	0.14	0.73	0.00

*Mean (Standard deviation)

2.5 DISCUSSION

The results of our experiments designed to test the relative effectiveness of FtF and IVR-based communication during simulated construction-project meetings indicated that discussion quality, communication richness, and communication openness were found no large statistical difference across these two communication methods. However, the participants perceived higher levels of communication appropriateness and accuracy during FtF communications. These results have important implications for those designing IVR-based communication methods or considering adopting them in the construction industry.

The higher level of group discussion quality and communication richness can be considered as particularly critical factors during communications in construction projects. High-quality group discussion enables the members to successfully understand the scope of the problem and define the problems (Lowry et al., 2006). Given that stakeholders in construction projects deal with countless complex issues, an overall agreement on the problem space and the precise nature of each problem can save them considerable time and effort when seeking appropriate solutions. IVR-based communication is likely to be particularly helpful in such situations, insofar as it can allow stakeholders to closely examine a target issue in real-time, despite being in different physical locations. Being able to share the same visual information in the same environment at the same time can reduce the chances of miscommunication among participants in different locations. In this regard, IVR-based communication has enormous potential to surpass other communication channels such as email and teleconferencing in terms of discussion quality. And perhaps most importantly, conducting a real-time meeting in front and around a virtual building model can dramatically reduce the time and cost that would otherwise be involved in gathering a large number of participants from different places on a construction site.

Like discussion quality, communication richness is essential in construction projects, because it enables the members to exchange detailed responses and vivid messages (Lowry et al., 2006). The experiment result on the communication richness is in accordance with previous research stating that IVR can provide undeniable features such as visual interface, immersion, interaction, and presence that is different from simple 2D and 3D environment (Shiratuddin and Sulbaran, 2006). The BIM information provided in both of our communication conditions is known to facilitate rich visual communication, which in turn has a greater influence upon information-sharing than verbally provided information does (Lee and Kim, 2018); however, our results imply that the IVR environment provided more detailed and vivid visual information to the participants, as well as a greater sense of immersion and presence than FtF communication did. As such, it is reasonable to conclude that rich communication can assist effective communication among construction-project stakeholders by facilitating the exchange of detailed and realistic building information, and thus help them to better understand complex issues that are beyond their immediate spheres of expertise.

Also, communication openness is vital for construction projects, because it offers the group members to open-minded share the ideas with enjoyment (Lowry et al., 2006). Considering that in the construction projects, stakeholders deal with countless complex issues on a daily basis. Open-minded handling critical problems can save them considerable time and efforts when seeking appropriate solutions. IVR-based communication is expected to be particularly helpful in such conditions, insofar as it can allow remotely located stakeholders to open-minded examine the target issues in real-time with enjoyment, despite being in different physical locations.

However, there are still some challenges that IVR-based communication needs to overcome to be widely used for construction projects. First, the experiment result demonstrated that the communication appropriateness should be improved during IVR-based communication compared to FtF method. Appropriate communication refers to suitable, applicable, and satisfying communication to its members (Lowry et al. 2006). On the other hand, inappropriate communication can create process losses, including listening issues and resolving the conflict. During our IVR-based experimental sessions, consistent concentration and politeness to others sometimes appeared challenging for the participants, who had to depend only on others' voices while exchanging opinions. Without real images of other members, it was difficult to discern their reactions or identify appropriate moments to speak. This problem frequently caused the participants' speech to overlap and/or be ignored, leading to inefficiency (i.e., communication that seemed to take longer than FtF exchange of the same verbal content would have taken).

Our experimental results also confirmed that the studied IVR method's communicative appropriateness and communicative accuracy should both be improved. With regard to the former, misunderstandings of others and being misunderstood by them were both more frequently observed during the IVR-based communication sessions than during the FtF ones. This may have been interrelated with the weakness of interaction among team members during IVR, which could have been caused by a lack of non-verbal conversational cues such as eye contact, facial expressions, and gestures, as previously discussed. However, IVR voice chats' lower sound quality (as compared to FtF conversation) could also have contributed to IVR's lower scores for communicative accuracy.

In summary, the strengths of the IVR-based communication are associated with visual communication by utilizing building information model in the immersive virtual environment. However, the virtual setting hinders users' interpretation of others' non-verbal cues, as well as their active engagement in interaction that would tend to produce clear, accurate, and enjoyable communication. Due to these weaknesses, some interventions aimed at increasing the effectiveness of IVR-based communication for construction projects should be considered. First, because interaction during FtF communication typically comprises only 7% words and 38% vocal tone, as against 55% body language (Günhan et al., 2012), changes to IVR-based communication systems should enable their users to perceive and understand each other's communicative cues visually and not just aurally. An accurate reading of body language, along with eye contact and facial expressions, helps people to easily and quickly understand one another's intentions, levels of attention, and probable reactions, and so these aspects' inclusion alongside speech and BIM information would help increase the accuracy of IVR-based construction-project communications. Another promising means of increasing the effectiveness of IVR-based communication would be to organize in-person meetings of team members prior to their first encounter in the virtual environment, as virtual meetings have been found to feature enhanced interpersonal relations, trust, socialization, and comprehension of the project when FtF communication was established first (Powell et al., 2004).

2.6 CONCLUSIONS

This research investigated the strengths and weaknesses of IVR-based communications in comparison to in-person FtF communications for construction projects. The authors compared the communication effectiveness of traditional FtF communication in a real-world environment and IVR-based communication in a virtual environment. The experiment results showed that FtF and IVR-based communication enables effective communication in regard to the quality of discussion, communication richness, and communication openness. The finding suggests that IVR-based communication can be an alternate communication channel for connecting remotely located inter-organizations while providing rich information. However, communication appropriateness and accuracy of IVR-based communications need to be enhanced to assist a more effective communication among construction project members. Specifically, we recommend that IVR systems be upgraded to allow the exchange of non-verbal communication cues and that where possible, in-person meetings of project teams should be convened prior to those teams' use of IVR-based communication.

Despite the useful findings and understanding on communication behaviors and effectiveness in FtF and IVR-based communication, there are some limitations in this study, suggesting the future research direction. This research examined IVR-based communication effectiveness with a relatively small sample size and simplified discussion topics. This can be further addressed with a larger sample size and by simulating more complex communication for decision making during different project stages.

The findings from our study emphasize that enhancing human-human interaction in the IVR environment is one of the important factors to improve communication effectiveness. In particular, designing IVR-based communication tools that allow the exchange of non-verbal communication cues (i.e., facial expressions, body posture, gestures, and eye contact) would be of importance. This could not only increase the feeling of being present together in the IVR environment for distantly located project stakeholders but also minimize any misunderstandings between them, contributing to better communication appropriateness and accuracy. Even though IVR-based communication may need further technical improvements, it has great potential as an alternative communication means by supplementing or replacing the traditional communication channels. Specifically, it is expected that the IVR-based communication could help to better manage large-scale global projects by linking far-distant participants in real-time.

2.7 CHAPTER SUMMARY

This chapter discussed the strengths and weaknesses of IVR-based communications in comparison to FtF communications. The findings of this research indicate that the quality of discussion, appropriateness, openness, and accuracy of IVR-based communication need to be enhanced. However, in terms of richness, IVR-based communication would provide more visual information to the participants with a greater sense of immersion and presence in the IVR environment compared with the FtF condition.

CHAPTER 3

IMPACT OF MOBILE AUGMENTED REALITY SYSTEM ON COGNITIVE BEHAVIOR AND PERFORMANCE DURING REBAR INSPECTION TASKS

3.1 INTRODUCTION

Augmented reality (AR) is a technology for enhancing the real world by superimposing computer-generated information such as computer graphics, text, or sound onto real-world scenes (Kalawsky et al., 2000). AEC industry stakeholders are embracing its potential applications at various project stages, including visualization during the design stage (Alsafouri and Ayer, 2019); safety management/inspection during construction (Heinzel et al., 2017; Olsen et al., 2019); and information access (Irizarry et al., 2013) and evaluation for maintenance (Ammari and Hammad, 2014) during the facility-management stage (Rankohi and Waugh, 2013). One prominent benefit of using AR at construction sites is that it enables construction stakeholders to review construction drawings at full, i.e., 1:1 scale, and thus identify errors that might not otherwise be spotted (Agarwal, 2016). For example, installation of a structural steel column requires not only the placement of its base in a specific location, but also a critical 3D assessment of its vertical alignment. Thus, AR can help prevent steel-column installation errors and save inspection time, since each object in its superimposed model is uniquely referenced to a

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This chapter is based on published study.

Abbas, A., Seo, J., & Minkoo, K. (2020). "Impact of Mobile Augmented Reality System on Cognitive Behavior and Performance During Rebar Inspection Tasks." *Journal of Computing in Civil Engineering (ASCE)*, 34 (6). https://doi.org/10.1061/(ASCE)CP.1943-5487.0000931.

unified system of coordinates, eliminating the possibility of errors accumulating across different sets of reference materials drawn at multiple scales (Shin and Dunston, 2009). Also, by marrying spatial data to real-world physical objects and locations, AR supports construction tasks such as a layout task, the process whereby relevant points in a construction space are earmarked for future work, by strongly leveraging its users' spatial cognition and memory (Chalhoub et al., 2019). As such, AR assistance for cognitive-based construction tasks such as assembly work (Lei et al., 2013), point layout (Chalhoub et al., 2019) and inspection (Zhou et al., 2017) could reasonably be expected to reduce both mental workload and task-completion time.

While various types of AR devices and systems have been developed, mobile AR (MAR) systems are increasingly prominent, as they allow AR to be moved from the laboratory onto actual construction sites (Izkara et al., 2007). MAR can be divided into two main categories – handheld devices such as tablets, and wearable devices like smart glasses and head-mounted displays (HMDs) – both of which afford their users high mobility and anytime/anywhere management of spatially registered information. Some previous AEC-focused research on AR has looked at how to apply it to and through mobile devices, such as for registration of virtual objects, real-time tracking, and calibration (Bae et al., 2013; Kopsida and Brilakis, 2016; Kwon et al., 2014). Unsurprisingly perhaps, the usefulness and technical advancement of MAR have taken center stage in such research, which in most cases has ignored that the AR environment could create perceptual issues, including but not limited to field-of-view, registration, and depth-perception errors (Dey et al., 2018). These issues, in turn, could severely affect users' cognition, performance, and comprehension of augmented content (Kruijff et al., 2010). In addition, the reference frame of AR information is critical to the cognitive functioning needed to understand one's surroundings when using MAR (Li and Duh, 2013). Nevertheless, previous studies' proposed MAR designs have not given due consideration to these issues, and no specific MAR design guidelines exist (Li and Duh, 2013). These absences necessitated the current investigation of how cognitive factors and corresponding task and safety performance could be affected by MAR environments. In this regard, we aim to understand the effects of two distinct types of MAR (i.e., handheld and head-mounted systems) on construction professionals' cognitive load (CL), task performance (TP), and situational awareness (SA), relative both to each other and to paper-based techniques. To achieve this research objective, we conducted experimental studies of a rebar-inspection task that is not only information-intensive, but also cognitively demanding, at construction sites. Specifically, our three participant groups were given the task of inspecting rebar for a concrete slab using MAR on a tablet, MAR on Microsoft HoloLens, and traditional drawings. TP was measured using task-completion time and error-identification rate; CL was measured using the National Aeronautics and Space Administration's Task Load Index (NASA-TLX); (Hart, 2006) in a laboratory setting; and SA was measured using the Situation Awareness Rating Technique (SART); (Taylor, 1990) and by simulating a construction site-like environment in a laboratory.Based on the result, we discussed participants' TP , CL, and SA of the surrounding environment in traditional drawings and MAR -assisted rebar inspection.

3.2 LITERATURE REVIEW

3.2.1 Application of mobile augmented reality in construction

MAR's known and potential capabilities are attracting AEC industry stakeholders to embrace its use during various stages of their projects. Wang (2007) used ARTag tracking markers and ARToolKit software to plan construction worksites through AR, and highlighted that traditional 2D paper media were less effective than MAR when it came to understanding both spatial constraints and resource-allocation strategies. Woodward, and Hakkarainen (2011) proposed a MAR for construction-site visualization and interaction with complex 4D building-information models, and Kim et al. (2013), construction job-site defects monitoring using MAR and computer vision-based algorithms. Kwon et al. (2014) used a MAR with ARToolkit to automatically detect dimensional errors and omissions on the worksite and found it easier to use for this purpose than the manual-based defect management process. Kopsida, and Brilakis (2016) used a markerless BIM registration method for MAR-based inspection and reported that it reduced inspection time by providing the inspector with instantaneous access to the information stored in the BIM. Zaher et al. (2018) developed two MAR applications that allow their users to update the progress of construction-site activities, which can be used through implementing a 4D ‘as-planned’ phased model integrated with an augmented video showing real or planned progress. Alsafouri, and Ayer (2019) investigated the feasibility of wearable and handheld MAR systems for industry practitioners in design and constructability-review sessions, and found that both allowed their users to ‘walk through’ and interact with virtual environments, facilitating their decision-making, problem-solving, and creation of design alternatives. Olsen et al. (2019) used MAR through wearable Microsoft HoloLens device for inspecting missing or misaligned embeds, sleeves and penetrations in concrete and masonry construction, and found that HoloLens speeded up the locating of the embeds, which are hard to represent in 2D drawings. Lastly, Lamsal, and Kunichika (2019) developed an AR system specifically for adaption to MAR via iPads and other tablet computers using Vuforia and AR markers, and tested it on the rebar construction phase of a 13-story steel building in Japan, reporting its strong potential to increase productivity.

As the above discussion suggests, the MAR systems developed to date have been very diverse, with features including touchscreens providing virtual keyboards and onscreen buttons, integrated cameras, wireless connectivity, global positioning system capabilities, and computer-generated data displays (Alsafouri and Ayer, 2019). Yet, while all the studies cited above have endorsed the use of MAR applications for at least one construction task, little research has focused on MAR's impacts on AEC-industry users' perception and/or cognitive behavior, or how such impacts may be linked to AEC task performance. The present study is intended to fill those research gaps.

3.2.2 Potential impact of mobile augmented reality on cognitive behavior and corresponding task and safety performance

Human cognitive-behavioral research focuses on understanding how mind, brain, and body interact, through observation of human cognitive behavior such as CL, SA, perceptual processing, and information processing (Curtin and Ayaz, 2017). While a number of definitions of CL exist, this study adopts Brunken et al.'s (2003) view that it comprises the amount of mental effort one expends during information processing. According to Doswell and Skinner's (2014) CL theory, human working memory can only simultaneously handle an average of seven (plus or minus two) disconnected items; and thus, cognitive overload tends to occur when human working memory is forced to process larger amounts of information quickly. As such, the amount of information that needs to be handled can significantly affect a person's task performance. From a cognitive perspective, all the major tasks in the AEC industry involve information-intensive processes, so under such conditions, MAR interfaces could overload the user with information, such that important cues from their actual environments could be missed. Previous studies on MAR systems to support surgical procedures (Doswell and Skinner, 2014) and procedural tasks (Baumeister et al., 2017) have reported that the use of MAR systems in the complex environment could lead to increase the cognitive burden. In addition, (Li and Duh, 2013)'s study raised the cognitive issues based on the findings of existing literature and explained that an excessive amount of information, its representation, placement, and view combination visualization techniques of MAR assisted system such as zooming and panning to understand the meaning of detailed information could impact the user’s cognitive functioning. Considering that the nature of construction sites is dynamic and complex, it is more expected that an excessive amount of information and its placement in the MAR assisted system could increase the visual-processing and information interpretation issues and have negative impacts on construction workers CL, TP, and SA.

In general terms, SA consists of being aware of what is happening around you. More specifically, Endsley (1988a, p. 97) defined it as “the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future.” MAR has a strong inherent potential to enhance visual perception via superimposition of information and thus has been argued to enhance overall SA (Lukosch et al., 2015). However, in most cases, AR environments have been found to cause perceptual issues during the visual processing and interpretation of information, affecting field of view, registration, depth perception, and so on, which in turn negatively impact the user’s cognition, performance, and comprehension of augmented content (Kruijff et al., 2010). In addition, various studies (Lindblom and Thorvald, 2014; Lyell et al., 2018; Paas et al., 2004) have looked at the general relationship between cognitive issues and performance (see Figure 3.1). Specifically, Paas et al. (2004) and Lindblom, and Thorvald (2014) found that too little CL (underload) as well as too much CL (overload) could lead to performance issues. For example, cognitive underload can occur when a user heavily relies so heavily on a system during tasks that he/she may lose interest in them, leading to more task-related errors. But at the other extreme, the amount of information coming from a system can surpass and overwhelm human processing capacity. These insights led Mendel, and Pak (2009) to argue that user performance could be increased by reducing CL during information-intensive tasks.

In conclusion, prior studies indicate that the amount of information provided to AR system users can influence their performance, and should be carefully considered, with too much and too little information both being problematic. Given that any MAR system can only achieve optimal performance when it provides an appropriate amount of information, it is critically important to gauge users' CL in specific MAR environments, as well as how variations in that CL relate to their performance.

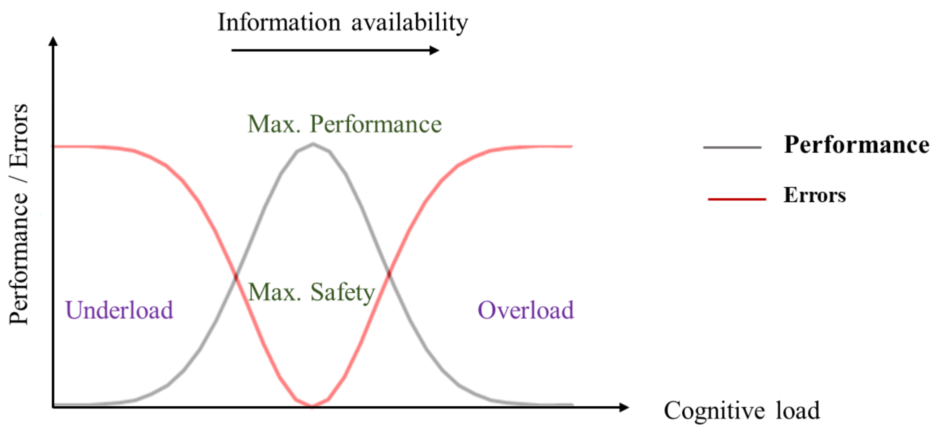


Figure 3.1 Relationship between Cognitive Load and Performance (Lindblom and Thorvald, 2014; Lyell et al., 2018; Paas et al., 2004)

Because a construction site is a complex, dynamic environment, failure to address AR users' visual-processing and information-interpretation issues could have serious negative effects on worksite safety (Bhandari et al., 2018). However, previous proposals for MAR systems for use in AEC have not fully considered these issues, and there are no specific design guidelines that take account of how MAR environments may affect CL, TP, and SA (Li and Duh, 2013). An in-depth understanding of how MAR can affect its users' cognitive behavior and performance would be helpful in the creation of such guidelines, and therefore to the design of safer and more effective MAR systems for AEC use.

3.2.3 Cognitive load, task performance, and situational awareness measures

CL is commonly measured using one or more of four broad sets of techniques: subjective, performance, physiological and behavioral (Khawaja et al., 2014). The subjective techniques primarily include gathering data directly from subjects, who rate their own CL on a Likert-type scale. The most reliable subjective CL results have generally been attained using the NASA-TLX (Hart, 2006). The performance-based CL measurement technique, on the other hand, assesses subjects' performance while a task is being carried out: for example, using task-completion time, critical errors, false starts, speed and/or correctness (Paas et al., 2003). The physiological approach, meanwhile, relies on changes in human cognitive functions being reflected physiologically, e.g., through brain activity, eye movement, or heart rate (Joseph, 2013). And lastly, behavioral measures can provide non-intrusive, objective, and implicit analyses of individuals' CL, as they are based on data collected during task completion without the participants' prior knowledge. Some commonly used behavioral measures of CL include speech features (e.g., pitch, prosody) and linguistic features (e.g., pauses, patterns of language) (Khawaja et al., 2014). Across all CL measurement techniques, however, the NASA-TLX is one of the easiest to use, least expensive, most reliable, and most sensitive to small variations in workload (Bhandary et al., 2016; Dadi et al., 2014; Hou et al., 2013).

Cognitive TP measures are based on the assumption that the mental workload of an individual interacting with a particular system or interface during the performance of a particular task is a good indicator of CL (Lee et al., 2018). Examples of cognitive TP metrics include reaction time to a secondary task, task-completion time, and error rate (Longo, 2018).

In their reviews of SA measurement techniques, (Salmon et al., 2006; Salmon et al., 2009) categorized past approaches into five general types, including (1) physiological methods such as eye-tracking and electroencephalograms (EEGs); (2) performance-based methods for example mission success or failure, hazard detection, etc; (3) self-rating methods, such as SART (Taylor, 1990), the Crew Awareness Rating Scale (McGuinness and Foy, 2000) or the Mission Awareness Rating Technique (Matthews and Beal, 2002) (4) observer-based rating methods like the Situation Awareness Behavioral Rating Scale (Matthews et al., 2005); and (5) freeze-probe methods, such as SA global-assessment techniques (Endsley, 1988b). Although there are both advantages and disadvantages of each technique, among these, SART is widely acknowledged as non-intrusive, inexpensive, easy to perform, and simple to analyze (Endsley and Garland, 2000; Endsley et al., 1998; Stanton et al., 2005). Its three key dimensions – i.e., understanding of the situation, demands on attentional resources, and supply of attentional resources – together provide a comprehensive measurement of individuals' SA (Hasanzadeh et al., 2018; Naderpour et al., 2016; Salmon et al., 2009).

3.3 RESEARCH METHODOLOGY

To achieve this study's research objective, as shown in Figure 3.2, the participants we recruited were assigned to one of three rebar-inspection groups: one using paper-based inspection methods, another using tablet-based MAR, and a third, HoloLens-based MAR. Two experiments were performed. Experiment I assessed the respective impacts of the traditional paper medium and each type of MAR on the participants' TP (as measured by completion time and number of errors) and CL as measured by using NASA-TLX (Hart, 2006) in a laboratory environment. Then, Experiment II added a simulated construction site to the laboratory environment and assessed how each of the three inspection modalities affected individuals' awareness of the surrounding environment during inspection tasks, and their overall impact on CL, TP, and SA. The task again consisted of rebar inspection, albeit with a different slab rebar framework to minimize learning effects; and each participant used the same inspection modality that he/she had used in Experiment I. To assess the impact of construction-safety conditions on Experiment II's results, we performed inter-group comparisons of CL and TP, and also measured each participant's SA using SART (Taylor, 1990). The procedures of both experiments are explained below in greater detail.

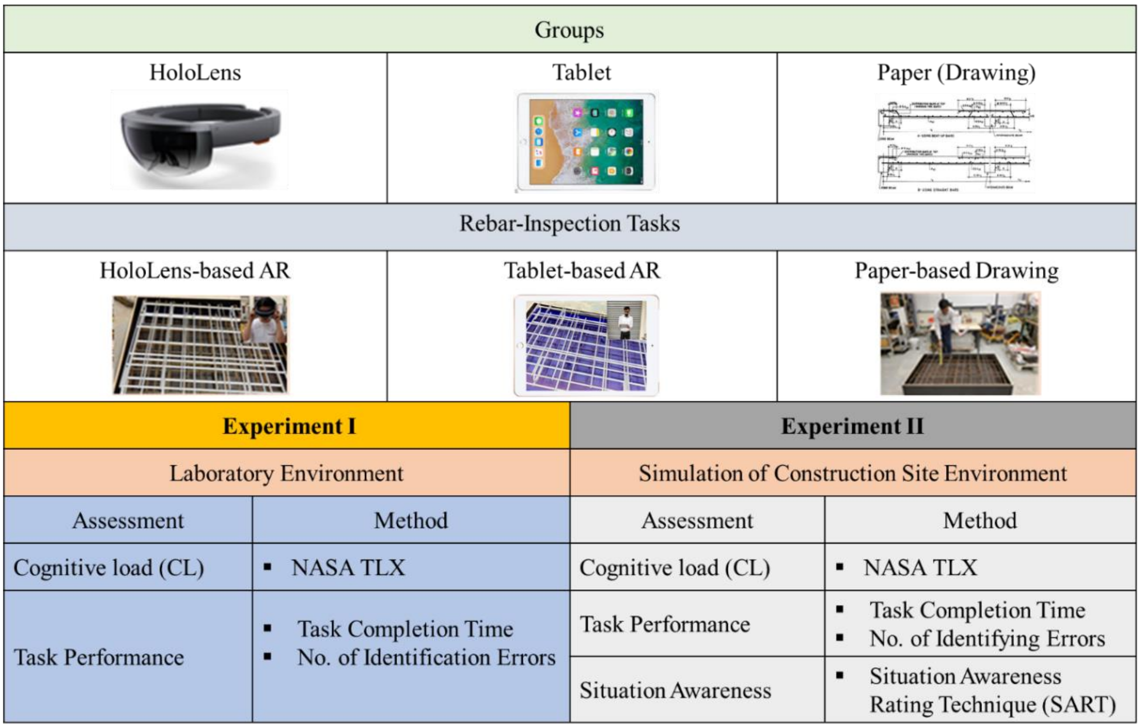


Figure 3.2 Experimental Methodology

3.3.1 Participants

A sample of 45 Ph.D. students from the Department of Building and Real Estate at the Hong Kong Polytechnic University was recruited for the two experiments. All participants had previously taken multiple classes related to construction project management and had some professional construction-industry experience, and thus were familiar with rebar inspection. They were randomly divided into three groups of 15, each of which would perform its rebar inspections using the same modality (i.e., paper, tablet MAR, or HoloLens MAR) across both experiments. Before the experimental sessions, we provided clear and concise instructions to each participant by using organized materials regarding the experimental procedures and provided multiple training sessions on how to use MAR devices for rebar inspection. In addition, to avoid the potential response bias during the post-experiment surveys, we made questions concise and easy to understand and informed participants that survey data would be strictly used for research purposes only on an anonymous basis.

3.3.2 Task overview

In both experiments, all participants played the role of a construction inspector tasked with checking for the following eight types of reinforcement errors: (1) spacing between rebars, (2) missing rebars, (3) extra rebars, (4) insufficient rebar cover at the side face, (5) insufficient rebar cover at the bottom face, (6) incorrect number of anchorage bars, (7) insufficient length of anchorage bars, and (8) bars incorrectly tied and supported. In all, 20 errors were intentionally placed in the rebar framework to be inspected, as shown in Figure 3.3.

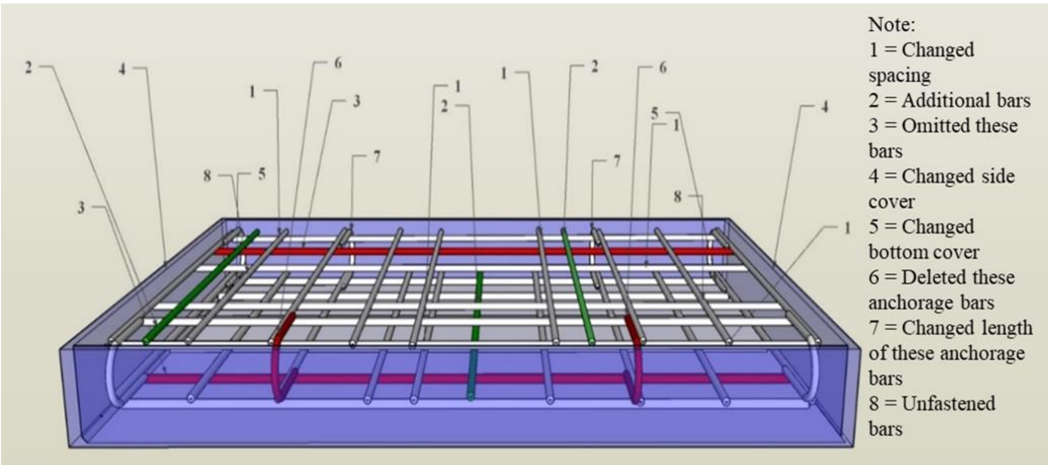


Figure 3.3 Conceptual Diagram of Errors in a Rebar Framework

3.3.3 Experimental procedure

During the paper-based inspection session of each experiment, the participants were asked to find rebar errors of each of the eight types given above by comparing the physical rebar framework against a drawing, as shown in Figure 3.4 (left), using a tape measure if they wished. The second group of participants performed the same task using a tablet that, when pointed at the physical rebar framework, showed a 3D rebar model superimposed on it, as shown in Fig. 4 (middle). This 3D rebar model had first been drawn in SketchUp and then integrated with *SketchUp Viewer*, a tablet AR app (https://www.sketchup.com/products/sketchup-viewer). The third group of participants performed the same task while wearing Microsoft HoloLens headsets that showed a 3D rebar model superimposed on physical rebar framework, as shown in Fig. 4 (right). This second 3D rebar model was also first drawn in SketchUp, but then integrated with Trimble Connect, a HoloLens-specific AR app (https://mixedreality.trimble.com/). Participants in all three groups were instructed to perform the inspection task as fast and accurately as possible, with their respective inspection speeds and numbers of errors both being collected in real-time. NASA-TLX was then used at the end of each experiment to measure their CL.

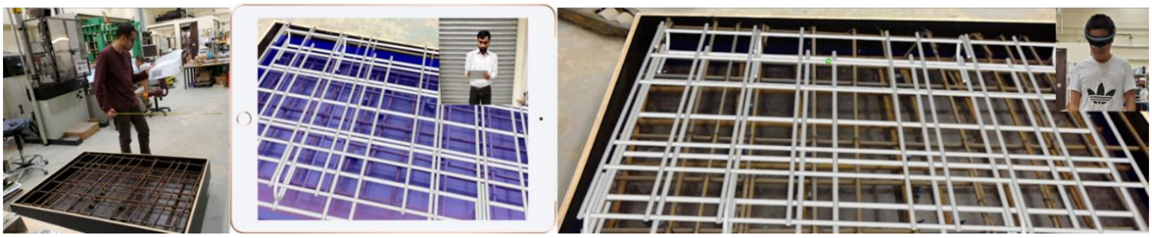


Figure 3.4 Paper-based, Tablet-based and HoloLens-based Inspection (Experiment I)

One week after Experiment I, we conducted a very similar experiment, with the same groups using the same inspection modalities, but a different rebar model, and with a more realistic simulation of a construction environment within the laboratory. Specifically, this environment was designed to expose the participants to realistic construction scenarios as a test of their SA: with recorded sounds of construction equipment played at accurate volumes, and a person employed to drive a laden forklift trolley near each participant during his/her inspection task. During this experiment, the same techniques as in Experiment I were used to measure participants' TP and CL, while SART was used at the end of the experiment to measure their SA.

3.3.4 Measurements

To measure cognitive load, we used NASA- TLX method that has been widely used for measuring cognitive load (Bhandary et al., 2016; Dadi et al., 2014; Hou et al., 2013). The original NASA- TLX contains six items (mental demand, physical demand, performance, temporal demand, effort, and frustration level). However, physical demand – defined as how much physical activity is required during a task – was not deemed relevant to our research, and so was omitted from the version of NASA-TLX that was used. One of the remaining five items, performance, could have been measured directly; however, as used in the NASA-TLX, it incorporates non-objective factors such as level of satisfaction, self-esteem, and motivation, and we retained it for that reason. Therefore, based on mental demand, performance, temporal demand, effort, and frustration level, participants in each experiment were rated on a scale from 1=Low to 5=High, as shown in Table 3.1.

Table 3.1 The Five NASA-TLX Questions Used for Measuring Cognitive Load (Hart, 2006)

Dimension	Question
Mental Demand	How mentally demanding was the task?
Temporal Demand	How temporally demanding was the task?
Performance	How successful were you in accomplishing what you were asked to do?

Effort	How hard did you have to work to achieve your level of performance?
Frustration	How insecure, discouraged, irritated, or stressed were you during the task?

While TP was measured objectively, as a combination of (1) the actual amount of time a participant took to complete his/her assigned inspection task in a given experimental session, and (2) the number of rebar errors that he/she correctly identified during that session.

Finally, to measure SA we used the SART method. It is a well-known post-trial subjective rating technique for the assessment of a participant's SA, further details of which are shown in Table 3.2. SART was completed by our participants at the end of Experiment II using a five-point Likert scale ranging from 1=Low to 5=High. The original SART instrument contains 10 items covering the environment's (1) information quantity, (2) information quality, and (3) the participant's familiarity with it ; (4) the instability (5) the variability of the prevailing situation and (6) complexity.; (7) arousal, (8) concentration, (9) division of attention, and (10) spare mental capacity. However, these 10 items can be grouped into three major dimensions: i.e., understanding of the surrounding situation (U), demand on attentional resources (D), and supply of attentional resources on the surrounding situation (S), where U is the sum of items (1), (2), and (3); D, is the summation of items (4), (5) and (6); and S, is the summation of items (7) through (10). A person's overall SART score can then be calculated as SA=U-[D-S].

Table 3.2 Items for Measuring Situational Awareness (Taylor, 1990)

Domain	Items	Questions
Understanding (U)	Information Quantity (1)	How much information about your surroundings did you take in?
	Information Quality (2)	How well did you understand/comprehend the information about your surroundings that you took in?
	Familiarity (3)	How familiar with your surroundings did you become during the task?
Attentional Demand (D)	Instability (4)	How much was the situation in your surroundings changing during the experimental session?
	Variability (5)	Were a number of different factors in the surrounding environment changing?
	Complexity (6)	How complex was the surrounding situation?
Attentional Supply (S)	Arousal (7)	How alert were you to observing the surrounding situation?
	Concentration (8)	How much were you concentrating on your surroundings?
	Division of Attention (9)	What proportion of your attention was devoted to your surroundings, as opposed to your inspection task?
	Spare Mental Capacity (10)	How much mental capacity did you have to spare for your surroundings?

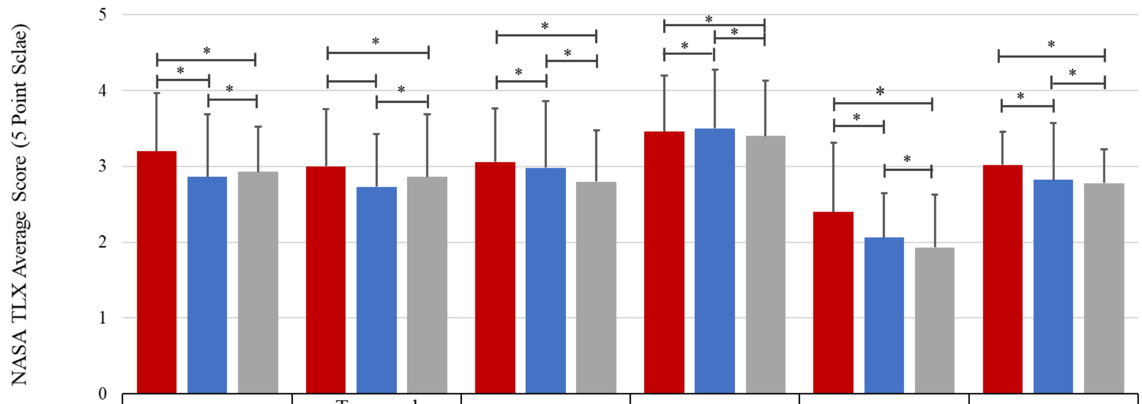
3.4 RESULTS

Before analyzing the data in detail, we first performed a Shapiro-Wilk test, a widely used method of testing data normality in sample sizes smaller than 50 (Ahad et al., 2011;

Mishra et al., 2019). The common alpha value for testing normality (i.e., 0.05) was used in conducting this test, and if the *p*-value produced by the test is lower than the accepted value, then we can conclude that the data are not normally distributed (Darko and Chan, 2018). All the *p* values produced by the Shapiro-Wilk testing of the present study's data were 0.00, indicating that such data were not normally distributed. Therefore, non-parametric tests – which are considered suitable for non-normally distributed data – were used for the remainder of our analyses. Non-parametric Kruskal-Wallis H can be used to assess statistically significant differences among three or more independently sampled groups (McKight and Najab, 2010), and therefore was chosen for use with both the Experiment I and Experiment II data to identify any statistically significant differences among the paper, tablet and HoloLens users.

Experiment I: general comparison among inspection modalities

As the purpose of the Experiment I was to assess how traditional paper-based inspection and the two focal types of MAR would affect the participants' CL, the Kruskal-Wallis H test was conducted first, as shown in Figure 3.5. Its results indicated that paper-based inspection was the most cognitively demanding of the three modalities, and HoloLens the least, though differences among them were not statistically significant. Then, a detailed comparison was made of the three inspection groups' NASA-TLX data. As Figure 3.5, indicates, users of both MAR systems perceived lower CL than the participants using the paper-based inspection method did. Again, however, the mean differences were found to be non-significant (p>0.05).



	Mental Demand	Temporal Demand	Effort	Performance	Frustration	Total Average CL
Paper	3.2	3	3.06	3.46	2.4	3.02
Tablet	2.86	2.73	2.98	3.5	2.06	2.82
HoloLens	2.93	2.86	2.8	3.4	1.93	2.78

Figure 3.5 Cognitive Load Scores, by Item

Note. *=No significant difference (p>0.05); **=Significant difference (p<0.05).

Next, the Kruskal-Wallis H test was applied to the Experiment I data on users' average completion times (Figure 3.6) and error-identification rates (Table 3.3). As shown in Figure 3.6 which presents a comparison of completion times across the three experimental groups, the paper-based group, at 11.85 minutes, took significantly longer than either of the two MAR-assisted groups (p<0.05). However, there was no statistically significant difference between the completion times of the tablet-based and HoloLens-based MAR groups (6.17 and 6.59 minutes, respectively; p>0.05).

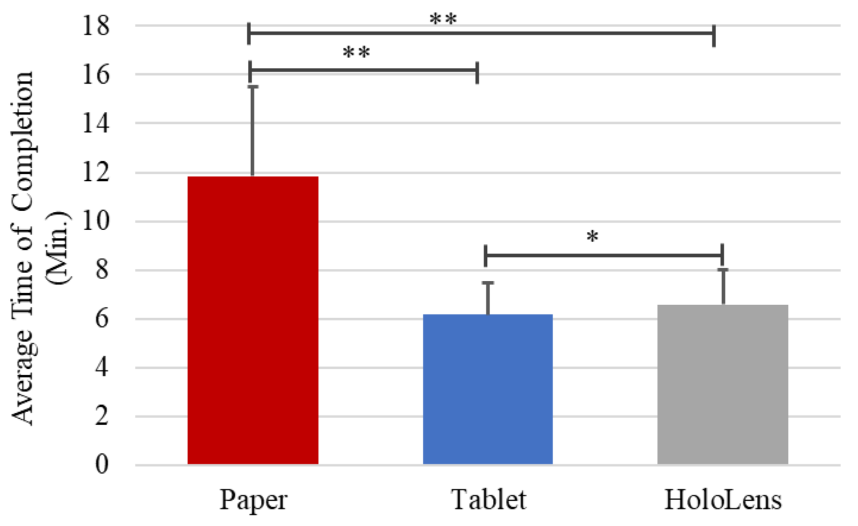


Figure 3.6 Average Time of Completion

Note. *=No significant difference (p>0.05); **=Significant difference (p<0.05).

Each group's error-identification rate was analyzed through the Kruskal-Wallis H test, as shown in Table 3.3. There were no statistically significant differences among the three groups' mean performance at identifying missing-bar and extra-bar errors. However, statistically significant differences did emerge between both MAR groups, on the one hand, and the paper-based group, on the other, when it came to identifying spacing, side-cover, bottom-cover, bar-number, length, and tying/support errors (p<0.05), with the paper-based group performing significantly better in these areas. And overall, out of 20 errors that were intentionally placed in the physical rebar framework, an average of 13.5 were correctly identified by the paper-based group, as against 9.5 by HoloLens users and just 9.1 by tablet users; and this difference was also found to be statistically significant (p<0.05).

Table 3.3 Average Number of Errors Correctly Identified, by Inspection-modality Group

Rebar errors	Mediums	No. of Errors Placed	Experiment I Mean (SD)	Kruskal-Wallis H	*p*
Spacing between bars	Paper		2.73 (1.43)		
	Tablet	5	2.06 (0.88)	6.54	0.03**
	HoloLens		3.00 (0.75)		
Missing rebars	Paper		1.60 (0.63)		
	Tablet	2	1.53 (0.45)	0.52	0.77*
	HoloLens		1.46 (0.63)		
Extra rebars	Paper		1.66 (0.48)		
	Tablet	3	2.13 (0.99)	3.80	0.14*
	HoloLens		2.00 (0.84)		
Incorrect side-cover spacing	Paper		1.66 (0.61)		
	Tablet	2	0.44 (0.83)	18.55	0.00**
	HoloLens		0.40 (0.63)		
Incorrect bottom-cover spacing	Paper		0.60 (0.82)		
	Tablet	2	0.06 (0.25)	7.96	0.01**
	HoloLens		0.06 (0.25)		
Incorrect number of anchorage bars	Paper		2.00 (0.00)		
	Tablet	2	1.66 (0.72)	6.27	0.04**
	HoloLens		2.00 (0.00)		
Incorrect length of anchorage bars	Paper		1.73 (0.73)		
	Tablet	2	1.00 (0.75)	15.61	0.00**
	HoloLens		0.46 (0.74)		
Bars improperly tied and supported	Paper		1.53 (0.74)		
	Tablet	2	0.20 (0.56)	28.82	0.00**
	HoloLens		0.00 (0.00)		
	Paper	20	13.51 (5.44)	19.61	0.00**

Total number of errors	Tablet	20	9.08 (5.43)
	HoloLens	20	9.42 (4.29)

Note. *=No significant difference (p>0.05); **=Significant difference (p<0.05).

Experiment II: relationships between safety conditions and inspection modalities

The Kruskal-Wallis H test was performed on the Experiment II data to see how the addition of realistic construction sounds and potentially dangerous environment affected the participants' CL, TP, and SA. Although no significant mean difference in CL was found across the two experiments (as shown in Figure 3.7), average CL for all three inspection groups was higher in Experiment II than in Experiment I.

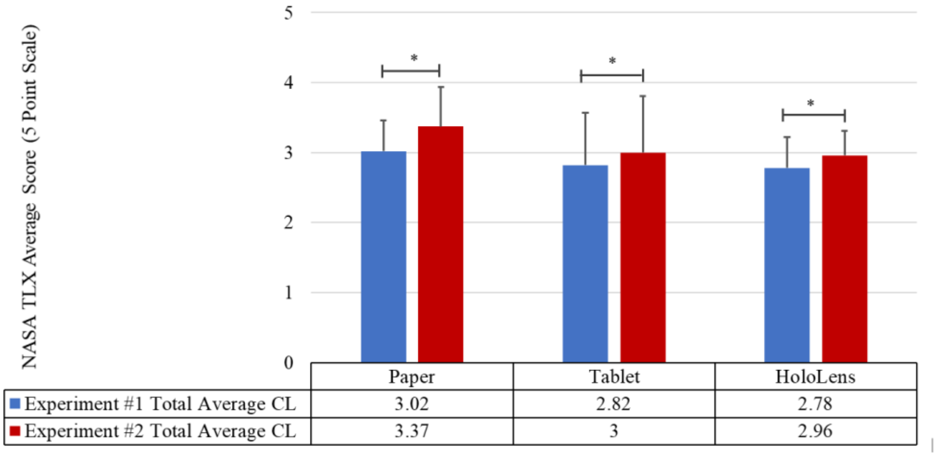
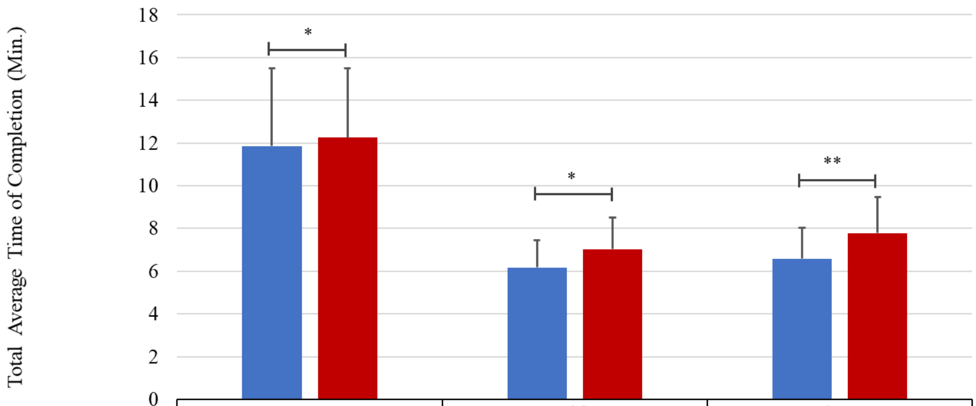


Figure 3.7 Comparison of Total Average Cognitive Load, Experiments I and II

Note. *=No significant difference (p>0.05); **=Significant difference (p<0.05).

As shown in Figure 3.7, we also found that average completion time for each inspection modality was higher in Experiment II than in Experiment I. However, this mean difference was found to be statistically significant only for the HoloLens group. As indicated in Table 3.4, the Experiment II data also showed that fewer errors were identified by the tablet and HoloLens users than by the traditional-inspection group. The latter group was also exceptional in that the increased environmental noise and hazard levels had no marked negative impact on its error-identification performance. However, no statistically significant overall difference in error identification was found between Experiment I and Experiment II.



	Paper	Tablet	HoloLens
Experiment # 1	11.85	6.17	6.59
Experiment # 2	12.26	7.02	7.79

Figure 3.8 Comparison of Average Time of Completion, Experiments I and II

Note. *=No significant difference (p>0.05); **=Significant difference (p<0.05).

Table 3.4 Average Number of Errors Correctly Identified, Experiments I and II

Mediums	Number of Errors Placed	Total Errors Identified in Experiment I, Cumulative Mean (SD)	Total Errors Identified in Experiment II, Cumulative Mean (SD)	Kruskal-Wallis H	*p*
Paper	20	13.51 (5.44)	14.58 (4.70)	2.94	0.08*
Tablet	20	9.08 (5.43)	8.53 (4.12)	0.69	0.40*
HoloLens	20	9.42 (4.29)	8.72 (4.98)	0.25	0.61*

Note. *=No significant difference (p>0.05); **=Significant difference (p<0.05).

Finally, we examined the inspection-group SART scores from Experiment II through the Kruskal-Wallis H test. Table 3.5 presents the cumulative mean SART values, along with their SDs, Kruskal-Wallis H values, and significance levels (p). For this purpose, we first grouped the 10 SART items into the three main dimensions U, D, and S, as described above. There were significant mean differences in two of these three SART dimensions, i.e., D and S (p<0.05). While no such significant difference was found for the third dimension, U, the paper-based inspection modality still had a higher U (9.8) than either its tablet-based (9.53) or HoloLens-based counterpart (8.86). The cumulative average values of D were also found to be highest in the paper-inspection group (10.31, vs. 9.26 for the tablet group and 9.18 for the HoloLens group). Lastly, the cumulative average values of S were highest for the paper-inspection group (13.39). Total SART score, calculated using the formula Situational Awareness=Understanding-[Demand-Supply], was higher on average in the paper-based inspection modality (12.88) than in either the tablet (11.53) or HoloLens modality (10.93); however, these differences were not statistically significant (p>0.05).

Table 3.5 Situation Awareness Rating Technique Scores

SART Item	Modality			Kruskal-Wallis H	*p*
	Paper Mean (SD)	Tablet Mean (SD)	HoloLens Mean (SD)		
Information Quantity (1)	3.40 (0.91)	3.33 (1.29)	2.93 (0.79)	2.10	0.34*
Information Quality (2)	3.0 (0.84)	3.13 (1.35)	3.00 (0.75)	0.00	0.99*
Familiarity (3)	3.40 (0.98)	3.07 (1.38)	2.93 (0.35)	2.06	0.35*
Instability (4)	3.46 (0.92)	3.26 (0.79)	3.24 (0.70)	0.68	0.70*
Variability (5)	3.40 (0.73)	2.86 (0.91)	2.85 (0.83)	4.18	0.12*
Complexity (6)	3.46 (0.64)	3.20 (0.67)	3.06 (0.79)	2.13	0.31*
Arousal (7)	3.33 (0.74)	2.66 (1.23)	2.86 (0.91)	4.75	0.09**
Concentration (8)	3.20 (0.94)	2.73 (1.16)	3.00 (0.84)	1.30	0.52*
Division of attention (9)	3.40 (1.05)	2.80 (1.08)	2.66 (0.61)	4.16	0.12*
Spare mental capacity (10)	3.46 (0.91)	3.06 (0.79)	2.73 (0.79)	2.10	0.34*
Understanding (U)	9.8 (2.73)	9.53 (4.02)	8.86 (1.89)	2.33	0.31*
Attentional Demand (D)	10.31 (2.29)	9.26 (2.37)	9.18 (2.32)	7.02	0.03**
Attentional supply (S)	13.39 (3.64)	11.26 (4.26)	11.25 (3.15)	12.70	0.00**
SART=U-[D-S]	12.88 (4.08)	11.53 (5.91)	10.93 (2.72)	1.23	0.53*

Note. *=No significant difference (p>0.05); **=Significant difference (p<0.05).

3.5 DISCUSSION

This study compared the impact of two popular types of MAR (i.e., handheld and head-mounted systems) on CL, TP, and SA. Through Experiment I, we revealed that the rebar-drawing information provided by superimposed computer imagery in both MAR systems helped to decrease their users' CL, as compared with the traditional paper-based inspection. Also, we found that the paper-based group took more time to complete their inspection task than either of the MAR-assisted groups. However, because of perception issues associated with both MAR systems, notably involving depth and registration, the paper-based group identified more errors than either of its MAR-assisted counterparts. Then, Experiment II established that a more realistic construction-site environment increased the cognitive demand on the subjects and lowered their TP; and that the same environment also negatively impacted SA across all three dimensions of the SART.

In terms of CL, the fact that both MAR systems tended to reduce participants' mental demand during Experiment I may have been because the 3D information they superimposed on the real environment (as shown in Figure 3.9) facilitated their users' cognitive processes: enabling inspectors to simultaneously perform several cognitive activities, such as looking, comprehending, searching, remembering, and deciding, unlike with paper-based inspection. Also, temporal stress in Experiment I was probably less for the members of the two MAR groups than for the traditional-inspection group, because the former two sets of participants did not need to perform time-consuming gaze shifts between paper drawings and the real environment (Polvi et al., 2018). Thus, MAR's 3D superimpositions on the real environment could be said to have lowered inspector effort physically as well as mentally. And unsurprisingly, our Experiment II results confirmed that performing the same tasks in a realistically simulated hazardous construction environment increased the cognitive demands on all three groups.

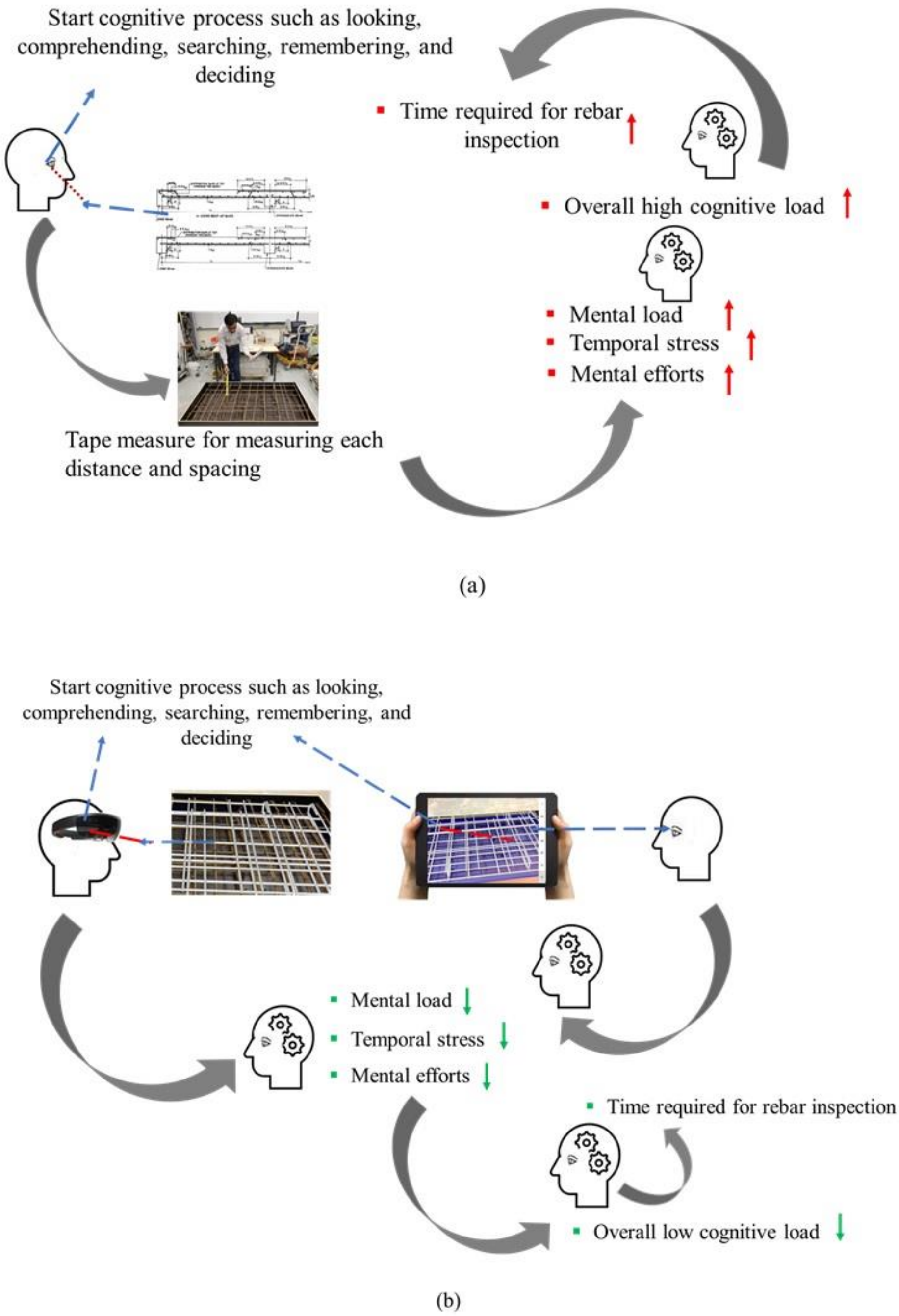


Figure 3.9 Cognitive Process during (a) Paper-based and (b) MAR-assisted Inspection

In terms of performance, Experiment I established that the two MAR systems' superimposed 3D rebar models increased the participants' performance when it came to detecting errors in the numbers of rebars or their spacing. Also, MARS has the potential to allow its user to more focus on the task by reducing the number of necessary gaze shits between the real and augmented environment, and thus user's performance is expected to increase (Polvi et al., 2018). However, the reduction in the number of these shifts can vary according to the AR-assisted display system. However, both MAR systems we tested also appeared to have some negative impacts on inspection performance. For example, neither could provide clear depth information regarding rebar placement, due to perception issues, and this resulted in significantly lower performance by the MAR groups (as compared to the paper-inspection group) when it came to finding side-cover, bottom-cover, and tying/support errors. On the other hand, participants equipped with either version of MAR were able to complete their inspection tasks more quickly than those who were not, with the tablet group finishing quickest, probably thanks to their devices' relatively large field of view, as compared to HoloLens.

Our Experiment II results, meanwhile, confirmed that the MAR-assisted groups' TP decreased slightly more than the traditional-inspection group's did when all three groups were placed in a more realistic construction environment. In particular, task-completion time increased significantly for the HoloLens group, probably implying that HoloLens's relatively small field of view made task performance more time-consuming when the environment was more complex, distracting, and potentially hazardous.

The superimposed 3D rebar models shown in both head-mounted and tablet-based MAR appeared to help their users to understand the inspection task itself. However, both had disadvantages, relative to paper-based inspection, in terms of SA: which was observed to be lower for both groups of MAR users across all three dimensions of the SART. First, both MAR systems, but especially HoloLens, appeared to provide their users with less understanding of their surroundings (U), probably because both restrict the field of view. Generally, human have a horizontal field of view of 104 degrees to 94 degrees for each eye (over 180 degrees approximately) (Knapp and Loomis, 2004), while tablet and HoloLens have a relatively small field of view. HoloLens users, in particular, tend to keep their gaze constantly on the AR environment, making it difficult for them to fully understand their surroundings or to use their cognitive resources (i.e., arousal, concentration, attention, and mental capacity) appropriately, other than on the task at hand. Considering that inspectors on construction worksites must perform several cognitive activities simultaneously – looking, comprehending, searching, remembering, and deciding – they are generally required to achieve full understandings of their surroundings over a very short period. Our experimental results confirm that equipping inspectors with MAR, and especially head-mounted MAR, is likely to be counterproductive, as our participants in the paper-based group were more fully aware of small changes in the background environment than their MAR-assisted counterparts. In short, MAR use by AEC-industry inspectors could reasonably be expected to increase potential worksite-safety issues, in particular, due to the restrictions these devices place on their wearers' fields of view, which tend to focus their attention more narrowly on their tasks than natural human vision would, and thus render them less alert to changes and potential changes in their immediate environment.

Despite these important findings, there may be some limitations of this study. First, even though we obtained statistically significant results from the experimental sessions, the relatively small number of participants may lead to the generalizability issues of the findings due to human variability. For example, the task performance when using new technologies such as MAR devices could be highly affected by the user's technology acceptance or previous experience on using them (Olsson et al., 2012). To minimize the issue, comprehensive pre-training sessions were provided to participants, but the possibility of participants' different learning abilities still may remain. Also, the individual difference in participants' cognitive ability level (i.e., finding errors in rebar placement) was not fully controlled, which may lead to misinterpretation of the results. So, further studies would be needed to provide strong generalizability by considering other human variability issues in the future. Also, the self-assessment survey could suffer from potential bias in response. Participants might obtain different interpretations of questions and respond in a certain way irrespective of the content of the questions, which is known as acquiescence response bias (Kam and Meyer, 2015). More objective measures for cognitive load and situational awareness may need to be investigated. Recently, measurement techniques using sensor data such as eye-tracking or electroencephalogram (EEG) signals have been tested for measuring cognitive workload, showing the potential as objective assessment (Borys et al., 2017). Lastly, while our second laboratory experiment tried to simulate a real construction-site inspection experience as closely as possible, the complexity and uncertainty of an actual construction site are very difficult to replicate. During real inspection tasks at construction sites, the cognitive demands on workers may be even higher than reported above, leading to lowering the MAR user's task performance. By the same token, in any complex construction environment, workers need to use more cognitive resources to observe actual and possible environmental changes at construction sites. Therefore, future research should confirm the validity of the above results through a field experiment, as well as with a wider variety of MAR systems.

3.6 CONCLUSIONS

In the AEC industry, MAR is widely considered to support its users' cognitive capability via the superimposed information it provides. However, such information may lead to cognitive overload and thus could adversely effects on the performance of tasks. Also, the limited user's field of view that comes with MAR use could limit his/her ability to notice events in their surroundings. Therefore, this study compared the impact of two distinct types of MAR (i.e., handheld and head-mounted systems) on construction professionals' CL, TP, and SA, relative both to each other and to paper-based techniques. While the rebar-framework design information provided via a superimposed virtual rebar model in MAR-assisted inspection appeared to decrease the inspectors' CL associated with the information-seeking (e.g., the number of rebars required; proper spacing) and processing (e.g., identifying missing or superfluous rebars in the actual rebar framework), it negatively impacted their performance in dangerous surroundings. The head-mounted MAR device we used, in particular, decreased its users' understanding of the surrounding environment and increased their inspection-task completion times, as compared not only to paper-based inspection but also to its tablet-based counterpart. As such, the key contribution of this research is that both of the main existing modalities of MAR-based inspection influence CL, TP and SA – for the most part, negatively.

Despite the aforementioned limitations of this study, several theoretical and practical implications can be derived from the results. The findings of both our experiments can contribute to the body of knowledge that a given information-presentation format can influence construction practitioners' cognitive workload and performance during MAR-supported tasks. Also, the findings of the research could provide a better understanding of MAR cognitive issues. In addition, the findings of our research would guide the design and usage of MAR systems for construction tasks, and this could possibly enhance the human cognitive functioning at construction worksites by better utilization of MAR systems.

3.7 CHAPTER SUMMARY

This chapter compared the impact of two different types of MAR system i.e., handheld and head-mounted system on construction professionals' CL, TP, and SA. The results indicate the superimposed virtual rebar model in MAR-assisted inspection would decrease the inspector' CL. However, the limited user's field of view of HoloLens-based AR inspection could limit user' ability to notice events in their surrounding.

CHAPTER 4

HOW IMMERSIVE VIRTUAL REALITY SYSTEM FEATURES IMPACT BEHAVIOR CHANGE FOR SAFETY? A STRUCTURAL EQUATION MODELING APPROACH

4.1 INTRODUCTION

Construction safety trainings are often provided by Architecture, Engineering & Construction (AEC) firms to improve the hazard recognition skills of their workforce (Demirkesen and Arditi, 2015) and to change their unsafe behavior (Shi et al., 2019). A recent research study (Jeelani et al., 2017) has found that traditional training methods such as paper-based teaching, videos, and online materials mostly used two-dimensional static images captured from real construction sites for training purposes, which could not capture the real dynamic nature of constriction site operation. Moreover, the traditional training programs are also expensive to set up as it require expert trainers and equipment' availability (Vahdatikhaki et al., 2019). More importantly, understanding of safety is commonly provided through conventional training programs to workers, but knowledge alone is usually not enough to fully improve workers' commitment to safety elements and safety awareness in the complex construction environment (Kiral et al., 2015).

This chapter is based on unpublished study.

Abbas, A., Seo, J., Ahn, J., Luo, Y., Lee, G., and Wyllie, M. (2021). "How Immersive Virtual Reality Training System Features Impact Behavior Change for Safety? A Structural Equation Modeling Approach." Accident Analysis & Prevention (Elsevier) (Under submission process).

Therefore, in order to address these limitations of traditional training methods, currently, immersive virtual reality (IVR) based training has been proposed for construction workforce training as it allows to immerse participants in the situation that might otherwise too dangerous to experience at the construction sites (Jeelani et al., 2017; Sacks et al., 2013). In addition to the benefit of IVR that can create safe and cost-effective training environments, it can also provide unique safety training experiences to workers (e.g., immediate guidance, empathy building, experiencing consequences, future projection, feedback, and emotional self-regulation) as behavior change interventions (Dirksen et al., 2019). Moreover, the features of the virtual environment, such as visual interface, immersion, interaction, and presence, allow various situations that may help to enhance the workers' safety awareness in a physically safe environment (Avveduto et al., 2017).

Although, the previous studies have validated the effectiveness of virtual environment-based training through different perspectives such as by evaluating the learning outcomes (Lee et al., 2010; Makransky and Petersen, 2019; Meyer et al., 2019), risk perception, and decision making (Leder et al., 2019), motor, cognitive and emotional impact (Mirelman et al., 2020) and by evaluating immersion, spatial presence and interaction with the different IVR-based training system (Grabowski and Jankowski, 2015). Unsurprisingly perhaps, the learning performance and technical advancement of virtual reality-based training environments have taken center stage in such research, which in most cases has ignored that the ultimate goal of safety training is to change the users' unsafe behavior. As behavior change is a complex process (Norcross et al., 2011), and mediation effect of various important psychological factors (PF) such as presence, motivation, enjoyment, and self-efficacy are involved in changing human behavior (Morris et al., 2012; Skarin et al., 2019). Therefore previous studies (Choudhry and Fang, 2008; Yu et al., 2017) have identified the difficulty of achieving behavioral changes among workers towards safety in the complex construction environment

This study intends to identify the mediating effect of IVR system features on the behavior change outcomes, which was mediated by important psychological factors that are presence, motivation, enjoyment, and self-efficacy. To achieve this research objective, we conducted experimental studies to perform the forklift operator training in the immersive virtual environment. The reason of the selection of forklift operator training in the IVR environment is that because a recent study by Ahn et al. (2020) has mentioned that forklift operator safety training delivered through traditional methods have limitations in influencing operators' unsafe safety behavior. As a result, high injury and fatality rates are frequently observing by many occupational health and safety regulators and authorities around the world with forklift operations. For this purpose, our one group was performing the forklift operator training in the immersive virtual environment using VR gear (virtual reality headset, pedal, steering wheel, and joystick) whereas the second group was performing the IVR-based training through a VR headset and a computer keyboard. At each experimental session, participants response was collected through a questionnaire about IVR system features, psychological factors, and the impact of IVR system features on behavior change (i.e., behavioral intention, learning, and satisfaction). The results were analyzed through the structural equation modeling (SEM) approach. By understanding how the IVR system features influence the psychological factors and their relationship with behavioral intention, we could better design the IVR-based training programs in a cost-effective way.

4.2 BACKGROUND

4.2.1 Preview works on IVR-based training

(Bailenson et al., 2008) define that the IVR environment provides the user a virtual three-dimensional multi-physical environment and perceptually constantly gives a feeling of presence or a user feel that he/she exists within this virtual reality environment. Many of the researchers in the past have tested IVR based training for construction. Sacks et al. (2013) tested IVR-based training environment for construction stone cladding work and for cast-in-situ concrete work. This research simulated construction site environment through cave automatic virtual environment (CAVE) and found that IVR based training environment could be more effective for learning and identifying construction safety risks compared with the conventional training method. However, this research only found a distinct benefit of IVR-based training environment for cast in situ and cladding work but did not find a clear benefit of using IVR based training for general construction site safety. Mo et al. (2018) developed the construction site safety environment using BIM and virtual reality headset for the home builder. This research demonstrates virtual environment efficiency and accuracy for designing the IVR-based training program. And lastly, (Shi et al., 2019) tested IVR-based training for construction safety and utilized a motion tracking feature and a multi-user IVR system where participants could walk between two high rise buildings in a hazardous construction situation. This research found that IVR-based information with positive consequences encourages people to follow the demonstration in a virtual environment based hazardous situation. However, this research does not provide evidence on how IVR system features could be effective for training purposes compared with other training methods.

In the other domains, IVR-based training is also inspiring to influence the users' performance therefore many of the studies have been investigated IVR-based training potential in different domains. In the area of psychology, Alshaer et al. (2017) tested the virtual reality-based wheelchair simulator with different field of view of VR devices and with immersive and non-immersive conditions. This research found that design factors of VR-based environment such as display type, field of view, and self-avatar presence impact on user's perception, behavior and driving performance. However, this research measured the participants' behavior through implicit performance in the IVR environment. In the medical sector, Bhushan et al. (2018) reviewed the adoption of VR to improve the quality and safety of training. This research found that a VR-based environment can help novices to achieve competency in endoscopy by practicing the routine and complex cases in VR-based 3D realistic scenarios. In firefighting, Çakiroğlu, and Gökoğlu (2019) proposed an IVR-based behavior skills approach to teach basic behavior skills for fire safety. This research found that the sense of presence in the IVR based environment could play a crucial role in the virtual environment to improve the behavior skills towards fire safety. In the area of transportation, Feldstein, and Dyszak (2020) tested the street crossing decisions ability within a IVR setup and in a real environment. This research found that detection of approaching vehicles was significantly lower for crossing decisions in the IVR environment than for crossing decisions in the real environment. In the agriculture sector, Gonzalez et al. (2017) developed and assessed a tractor driving simulator with IVR for training to reduce tractor overturns accidents. This research found that the use of IVR for training purposes increases the perception of risk and safety for novice and expert users of tractors. In the area of chemical manufacturing, Kwok et al. (2019) developed a virtual emergency drill environment and used a VR HMD device. This research has found that the IVR environment could make crisis management training more flexible as it allows trainees to refine their skills according to their mistakes in each iteration. In the mining sector, Pedram et al. (2020) used the IVR environment to provide vocational safety training for underground mining activities. This research found IVR-based learning is positively impacted by features of the IVR system (realism and co-presence), by the learning experience (immersion, presence, social presence), and by the usability of IVR system (usefulness and ease of use). And, lastly in the automation and robotics sector, (Roldán et al., 2019) tested an IVR-based training system for industrial operators in the assembly task. This research found that the IVR-based training environment is better in terms of mental demand, perception, learning and performance against conventional training alternatives training.

4.2.2 Theories of behavior change

Although there are a large number of theories and approaches towards behavioral change, the following theories have been accepted by many researchers studying people's behavior. Social cognitive theory (Bandura, 1986), the theory of planned behavior (Ajzen, 1991), transtheoretical model/stages of change model (Prochaska and Velicer, 1997), and Fogg behavior model (Fogg, 2009).

The social cognitive theory (Bandura, 1986) combines theories and process from cognitive, behavior, and emotional models of behavior change and explains human behavior continually interact with environmental factors and personal factors. From the perspective of the theory of planned behavior (Ajzen, 1991), behavioral intention is the most significant cause of behavior change. This theory adopts a cognitive approach to defining behavior based on a person's attitudes and beliefs and developed from the theory of reasoned action (Hill et al., 1977) which defined intention to perform is the top predictor of human behavior. The transtheoretical model/stages of change model (Prochaska and Velicer, 1997) identified five stages of change such as pre-contemplation (unaware of the problem and not thinking about the behavior), contemplation (aware of the problem, and deliberating about change in the near future), preparation (planning to make change), action (exercise the desired the behavior), and maintenance (works to maintain the behavior change). This theory combines the process and principles of behavior change and evolved from a comparative analysis of twenty-five major theories of psychotherapy (Glanz et al., 2014). And, according to the Fogg behavior model (Fogg, 2009), three factors, i.e., motivation, ability, and triggers, influence a person's behavior change. All these three factors must be present at the same time for the behavior change to occur.

Among these aforementioned behavior change theories, the transtheoretical model/stages of change model was extensively applied to behavior change model because it comprehensively conceptualized a process that involves a series of behavior change stages, and this model has also proven useful in conceptualizing and guiding the behavior change in several fields such health, psychology, sociology, and communication (Norcross et al., 2011).

4.2.3 Knowledge gaps

Dixon (2008) said that generally, many studies explained the various behavior change theories in detail however, they do not include how the latest technologies such as IVR can change the users' unsafe behavior. As the transtheoretical model change model comprehensively conceptualized a process that involves a series of behavior change stages. Therefore, by using the transtheoretical model a conceptual framework of the behavior change outcomes and their casual relationships in the IVR-based training environment was developed for this research (as shown in Figure 4.1). The original transtheoretical model comprises five stages of change such as pre-contemplation (unaware of the problem and not thinking about the behavior), contemplation (aware of the problem and deliberating about change in the near future), preparation (planning to make change), action (exercise the desired the behavior), and maintenance (works to maintain the behavior change). However, for this research, the first two-stage of behavior change (pre-contemplation and contemplation) were incorporated into the conceptual framework (as shown in Figure 4.1). In this framework, the IVR system features influence the behavior stages indirectly through the mediation of psychological factors (PF) such as presence, motivation, perceived enjoyment, and self-efficacy. Finally, the dependent variables pre-contemplation (learning knowledge) and contemplation (behavioral intention) are based on the transtheoretical model defined by (Morris et al., 2012).

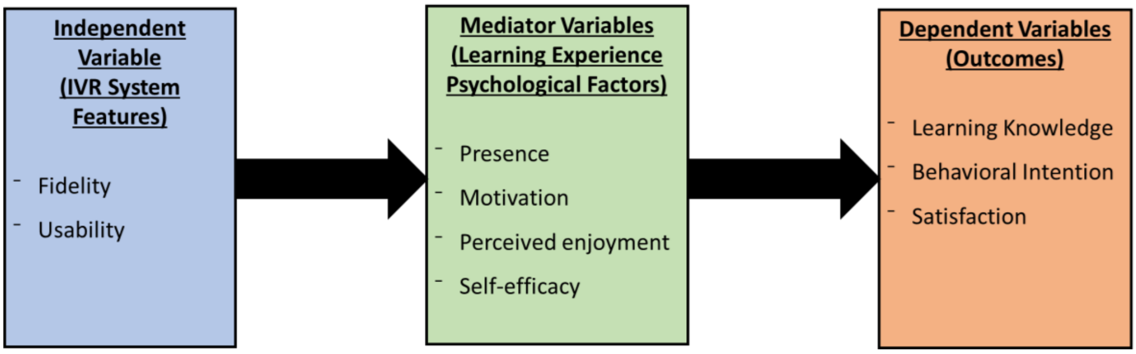


Figure 4.1 Conceptual Framework of the Behavior Changes Outcomes and Their Causal Relationship with IVR System Features

Based on the above conceptual framework, a research model is developed for evaluating how the IVR system features impact on behavior change outcomes, as shown in Figure 4.2. This model addresses the constructs and their causal relationship. The hypothesized model consists of the constructs (1) IVR system features which are measured by control, fidelity, and usability; (2) presence; (3) motivation; (4) perceived enjoyment; (5) self-efficacy; and (6) behavior change outcomes which are measured by satisfaction and stages of behavior change model (Prochaska et al., 1998) such as (contemplation) learning knowledge and (preparation) behavioral intention. The hypotheses based on this research model are summarized in Table 4.1.

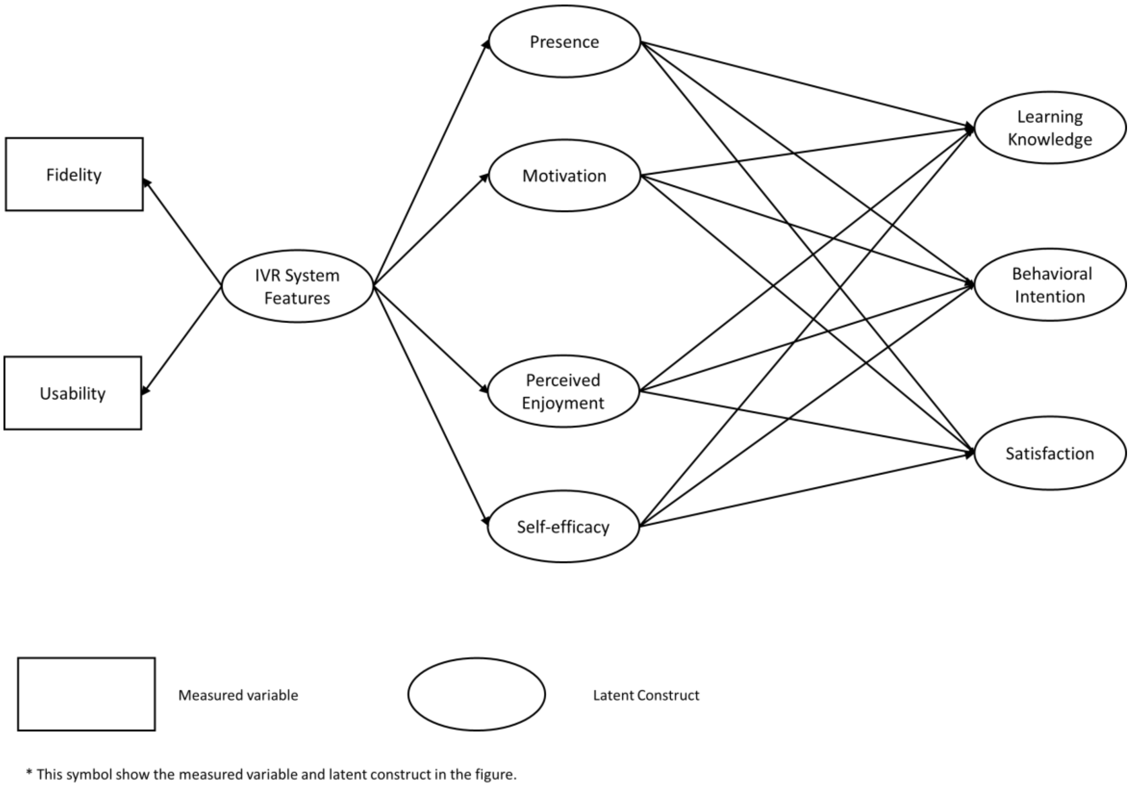


Figure 4.2 Research Model

Table 4.1 Table List of the Hypotheses Included in the Research Model

Hypotheses	References

H1: VR system features are significantly related to presence.	Lee et al. (2010), Makransky, and Lilleholt (2018) and Makransky, and Petersen (2019)
H2: VR system features significantly related to motivation.	Lee et al. (2010) and Makransky, and Lilleholt (2018)
H3: VR system features significantly related to perceived enjoyment.	Makransky, and Petersen (2019) and Makransky, and Lilleholt (2018)
H4: VR system features significantly related to self-efficacy.	Pedram et al. (2020) and Shu et al. (2019)
H5: Presence is positively related to learning knowledge.	Makransky, and Lilleholt (2018)
H6: Presence is positively related to behavioral intention.	Lee et al. (2013) and Makransky, and Lilleholt (2018)
H7: Presence is positively related to satisfaction.	Lee et al. (2010) and Makransky, and Lilleholt (2018)
H8: Motivation is positively related to learning knowledge.	Makransky, and Lilleholt (2018) and Chen et al. (2014)
H9: Motivation is positively related to behavioral intention.	Makransky, and Lilleholt (2018)
H10: Motivation is positively related to satisfaction.	Makransky, and Lilleholt (2018) and Lee et al. (2010)

H11: Enjoyment is positively related to learning knowledge.	Makransky, and Lilleholt (2018), Makransky, and Petersen (2019) and Schneider et al. (2016)
H12: Enjoyment is positively related to behavioral intention.	Makransky, and Lilleholt (2018) and Schneider et al. (2016)
H13: Enjoyment is positively related to satisfaction.	Makransky, and Lilleholt (2018)
H14: Self-efficacy is positively related to learning knowledge.	Makransky, and Petersen (2019) and Chen (2017)
H15: Self-efficacy is positively related to behavioral intention.	Chen et al. (2012)
H16: Self-efficacy is positively related to satisfaction.	Canrinus et al. (2012)

The further detailed on the selection of the six constructs and their hypothetical causal relationships are described below.

4.2.3.1 IVR system features

Research has shown that virtual environment system features could influence the learning outcomes i.e., learning knowledge, behavioral intention, and satisfaction level of the user (Lee et al., 2010; Makransky and Petersen, 2019). In the present research, IVR system features are measured by fidelity and usability. Fidelity is defined as the degree to which the virtual environment configuration permits users to examine objects visually or to search for examine, and manipulate objects using their sense of touch (Witmer et al., 2005). Whereas usability is defined as the quality and accessibility of the technology in use, and it's measured by perceived usefulness and perceived ease (Davis, 1989; Makransky and Petersen, 2019). Previous research studies indicate that fidelity and usability play a significant role in mediating the experience of learning and interaction, which in turn improves learning outcomes. For example, Lee et al. (2010) and Makransky, and Petersen (2019) tested how desktop virtual reality affects learning outcomes and found that fidelity and usability could influence psychological factors (e.g., presence, motivation, etc.) which in turn affected users interaction and learning experience in the virtual environment. Similarly, Makransky, and Lilleholt (2018) used IVR simulation to identify the underlying mechanisms that impact users' emotional process during learning and found that fidelity and usability would influence the students' psychological factors (e.g., presence, motivation, enjoyment, etc.) and learning outcomes. Consistent with these previous studies, this study hypothesized that the degree of realism of the objects in the IVR environment and its perceived usefulness would effect the fidelity and usability which in turn would influence the four key psychological factors (e.g., presence, motivation, enjoyment and self-efficacy etc.) by improving their unsafe behaviour.

4.2.3.2 Presence

Presence is defined as the sense of the user to feel "being there" in the virtual reality environment (Berkman and Akan, 2019). According to (Lee et al., 2010; Makransky and Lilleholt, 2018; Makransky and Petersen, 2019), the sense of presence in the virtual environment occurs due to the virtual reality features. Furthermore, presence played a mediating role in the virtual reality environment that influence user' learning knowledge (Makransky and Lilleholt, 2018), behavior intention (Lee et al., 2013; Makransky and Lilleholt, 2018) and satisfaction (Lee et al., 2010; Makransky and Lilleholt, 2018).

4.2.3.3 Motivation

Motivation refers to a state of mind which tends to energize or activate the behavior (Kleinginna and Kleinginna, 1981). Motivation is a prominent factor in theories of behavior change (Dixon, 2008). Research studies have identified that virtual reality-based features such 3-dimensional environment, dynamic display, and closed interaction with the virtual reality contents would motivate the user (Lee et al., 2010; Makransky and Lilleholt, 2018). Ultimately, this VR-based motivation would significantly effect the user's learning (Makransky and Lilleholt, 2018), behavioral intention (Makransky and Lilleholt, 2018), and satisfaction (Lee et al., 2010; Makransky and Lilleholt, 2018).

4.2.3.4 Perceived enjoyment

Perceived enjoyment is the degree to which a user finds a virtual environment pleasant, fun, and enjoyable (Makransky and Lilleholt, 2018; Tokel and İsler, 2015). Perceived enjoyment is an important factor in theories of behavior change and has been suggested as a predictor in determining the physical activity behavior change process (Kuroda et al., 2012; Lewis et al., 2015). According to Schneider et al. (2016), enjoyment is positively associated with learning knowledge and best predictor for behavioral intentions. In the virtual reality environment, research studies (Makransky and Lilleholt, 2018; Makransky and Petersen, 2019) have identified that virtual reality features are the antecedents to user' enjoyment. Research has also identified that enjoyment experience in the virtual reality environment would play a mediating role on user learning (Makransky and Lilleholt, 2018; Makransky and Petersen, 2019), behavioral intention (Makransky and Lilleholt, 2018), and satisfaction (Makransky and Lilleholt, 2018).

4.2.3.5 Self-efficacy

Self-efficacy refers to an individual's confidence in their ability to complete a specific task (Bandura, 1977). Self-efficacy is a major factor in theories of behavior change (RGN and RGN, 2002). In several behavior change areas, for example, weight control (Linde et al., 2004), tobacco use (Martin et al., 2010), and exercise behavior (Slovinec D'Angelo et al., 2014), self-efficacy has been shown to be a prominent factor for behavior change. In the virtual reality environment research studies (Pedram et al., 2020; Shu et al., 2019) have mentioned that virtual reality features are the antecedents to user' self-efficacy.

4.2.3.6 Learning knowledge

Learning knowledge (contemplation) is the behavior change stage in which human starts recognition of the problem, put initial consideration on behavior change, and gather information about possible solutions and actions (Morris et al., 2012; Prochaska et al., 1998). Research studies have shown the psychological factors such as presence (Makransky and Lilleholt, 2018), motivation (Makransky and Lilleholt, 2018), enjoyment (Makransky and Lilleholt, 2018; Makransky and Petersen, 2019), and self-efficacy (Chen, 2017; Makransky and Petersen, 2019) would impact on the user' learning.

4.2.3.7 Behavioral intention

Behavioral intention (preparation) is the behavior change in which human self-examine the decision, reaffirm the need, desire to change behavior, and complete the final pre-action steps (Morris et al., 2012; Prochaska et al., 1998). Previous research in other domains has shown that behavioral intention antecedent to user behavior. For example, understanding the behavioral intention to use mobile banking leads towards the first step of the behavior change process (Luarn and Lin, 2005). Past studies have shown that psychological factors such as presence (Lee et al., 2013; Makransky and Lilleholt, 2018), motivation (Makransky and Lilleholt, 2018), enjoyment (Makransky and Lilleholt, 2018; Schneider et al., 2016), and self-efficacy would impact on the user' behavioral intention.

4.2.3.8 Satisfaction

Satisfaction is described as ‘‘an intrinsic positive consequence emerging from behavior that fulfills the expectations of an individual” (Corral-Verdugo et al., 2016; Skarin et al., 2019). The previous research on satisfaction has shown that satisfaction influences behavior in other domains. For example, satisfaction during travel intervention programs leads to greater travel behavior change (Skarin et al., 2019). Past research has also mentioned that the psychological factors such as presence (Lee et al., 2010; Makransky and Lilleholt, 2018), motivation (Lee et al., 2010; Makransky and Lilleholt, 2018), enjoyment (Makransky and Lilleholt, 2018) and self-efficacy (Canrinus et al., 2012) would impact on the user' satisfaction level.

Items to measure fidelity, usability, presence, motivation, perceived enjoyment, self-efficacy, behavior intention, learning knowledge, and satisfaction were developed based on previous studies, as listed in Table 4.2. All items were measured with a five-point Likert scale with (1) strongly disagree, and (5) strongly agree.

Table 4.2 Questionnaire Items and Sources

Constructs	Measurement Items	Code	Sources
Fidelity	1. I was able to easily move in the virtual environment.	Fid 1	(Witmer et al., 2005)

	2. I was able to accurately touch the control devices’ buttons to interact with the virtual environment.	Fid 2	
	3. I was able to easily identify objects through physical interaction, like lifting the object by forklift.	Fid 3	
Usability	1. IVR-based training is simple and easy for me.	Usb 1	(Davis, 1989)
	2. It is easy for me to interact with IVR-based environment.	Usb 2	
	3. IVR-based training allowed me to progress at my own pace.	Usb 3	
Presence	1. My interaction with the IVR-based simulation environment seemed natural.	Pr 1	(Sutcliffe et al., 2005)
	2. I was engaged in the virtual environment experience.	Pr 2	
	3. I was involved in the experiment task to the extent that I lost track of time.	Pr 3	
Motivation	1. I was motivated to do this forklift operator training in IVR environment.	Moti 1	(McAuley et al., 1989; Pedram et al., 2020)
	2. I was motivated to attain forklift operator performance goals in the IVR environment.	Moti 2	

	3. I was motivated to be a part of this forklift operator training in IVR environment.	Moti 3	
Perceived enjoyment	1. I enjoyed IVR based forklift operator training.	Enj 1	(Tokel and İsler, 2015)
	2. I found the IVR environment for forklift operator training purposes was pleasant.	Enj 2	
	3. I have fun using IVR based forklift operator training.	Enj 3	
Self-efficacy	1. I am confident that I can understand the concepts related to forklift operator training in the IVR environment.	Effic 1	(Makransky and Petersen, 2019)
	2. I am confident that I can do forklift operator training exercises in the IVR environment.	Effic 2	
	3. I am confident that I can improve the skills of forklift operator in the IVR environment.	Effic 3	
Learning knowledge	1. IVR-based training helps me to understand about safe operation of forklift.	Lear 1	(Lee et al., 2010)

	2. I am more interested to learn the topics in the IVR environment.	Lear 2	
	3. I gained a good understanding of the basic concepts of the forklift operator training in the IVR environment	Lear	
Behavioral intention	1. I am able after this IVR-based training to anticipate unsafe forklift operator actions.	Inten 1	Self-developed
	2. The information provided in the virtual environment helps me to improve my unsafe behaviour (e.g., check the surrounding before moving forklift, not operate the forks while the forklift is moving, etc.)	Inten 2	
	3. This IVR-based training influences my intention to perform the save forklift operation tasks.	Inten 3	
Satisfaction	1. I was satisfied with this IVR-based training environment.	Satis 1	(Chou and Liu, 2005)
	2. I was satisfied with the variety of forklift operator training aspects that were covered in the IVR environment.	Satis 2	
	3. I was satisfied with the immediate information gained by IVR-based training.	Satis 3	

4.3 RESEARCH METHODS

This study aims to understand the impact of the IVR environment on safety training outcomes and safety behavior intention. Two experiments were performed. In each session, participants completed the forklift operator tasks in the IVR environment and could get feedback from the IVR system based on his/her actions in the virtual environment. One experiment was performed the forklift lift operator tasks in the IVR environment through the VR gears (pedal, steering wheel, and joystick), whereas the second experimental group performed the same forklift operator task with the help of a computer keyboard and joystick. At each experimental session, participants' response was collected through a questionnaire about IVR system features, learning experience, and the impact of IVR system features on behavior change outcomes. The procedure of each experiment is explained below in greater detail.

4.3.1 Participants

A sample of total sixty Ph.D. and postdoctoral students from the faculty of construction and environment at the Hong Kong Polytechnic University was recruited for the two experiments. They were randomly divided into two groups of 30, each of which would perform forklift operator tasks in the immersive virtual environment through VR gears/ keyboard. The majority of the respondents had a driving experience and have working experience in the construction industry of at least one year. In addition, all participants have heard about virtual reality, but only very few of the respondents have used any virtual reality-based tool, device, or application before.

4.3.2 Experimental procedures

First, before each experimental session, we collected the participants' background information through a survey and then provided them brief instructions about the study's purpose and how to perform the forklift operator task in the IVR environment through. Then, participants of the two groups were performed the forklift operator tasks in two experimental sessions as shown in Figure 4.3. All participants in both sessions were equipped with Samsung HMD Odyssey, a head-mounted display device to provide an immersive experience in the virtual environment. In addition to the VR head-mounted device, a Logitech G29 Driving Force racing wheel and pedals were used as input devices for steering, acceleration and breaking the virtual forklift in the experimental session A. The system also used a Logitech 3D Pro joystick to mick the levers to operate the forks (e.g., raise, tilt, shift, and lower). Experiment B was performed the same forklift operator task with a computer and joystick, as shown in Figure 4.3. In both experiments, the IVR training simulator was demanding from participants to perform four scenarios i.e., basic introduction about the forklift operation in the IVR environment, forklift introduction scenario, operating the fork and picking up a pallet scenario. At the end of the experiment, participants response was collected through a questionnaire about IVR system features, learning experience, and impact of IVR system features on behavior change outcomes.

Figure 4.3 Experimental Procedure

4.3.3 Design of IVR-based forklift operator training

This IVR-based training simulator was designed using a laptop (CPU: Intel Core i7-10750H, RAM: 16 GB; Graphics: NVIDIA GeForce RTX 2060) running on Windows

10 operating system 64 bit. The forklift training scenario used in the study was developed using Unity 3D (https://unity.com), a multi-platform game engine. Particularly, the training simulator is designed in such a way so that the user can learn the most basic forklift operation skills step by step as he/she goes through the scenarios in sequence. In this training simulator, users are required to perform four scenarios, i.e., forklift introduction scenario, basic steering scenario, forks introduction scenario, and picking up a pallet scenario. The tasks included in each scenario are mentioned in Table 4.3.

Table 4.3 Task Included in Each Scenario

Scenario	Task Included
Forklift introduction scenario	Changing forklift gears
	Driving forward
	Reversing
Basic steering scenario	Forward steering
	Backward steering
Forks introduction scenario	Raising the forks
	Tilting the forks
	Shifting the forks

	Driving after moving the forks
Picking up a pallet scenario	Approaching a pallet
	Lifting the pallet

In addition, in each scenario, the system was constantly providing instructions on how to operate a forklift safely and providing feedback messages on how he/she was performing (as shown in Table 4.4). This system was also checking the user's actions to ensure that he/she was complying with all safety regulations embedded in the VR training simulator, and if the system finds that the user was tacking an unsafe action an instantaneous violation or warning message appeared. Particularly, these safety regulations were designed based on the safety guideline developed by US Occupational Safety and Health administration and SafeWork South Australia mentioned in (Ahn et al., 2020)' research.

Table 4.4 Tasks That Instructs the User About Forklift Operation and Safety Practices in the IVR Environment

Further, the safety requirement was working in IVR-based simulation which was demanding following from the user. (1) check surrounding before forklift driving (2) drive slowly (3) looking in the direction of travel (4) no operation of forks while moving (5) load pallet correctly (6) no collision (7) approach pallet safely (8) check surrounding at corner (9) check pallet secured (10) travel with forks at a lowest safe height. The details of each safety requirement are mentioned in Table 4.5.

Table 4.5 Safety Requirements in IVR-based Simulation

Safety Requirements	Details
Check the surroundings before forklift driving	The IVR system was designed in such a way that was demanding from the user to check the surroundings (by looking left and right) before driving the forklift. In case the user stops driving for more than 10 seconds then the IVR system was warning the user to check again the surroundings and a violation was raised when the user continues to drive even after receiving the warning.
Drive slowly	The IVR system was designed to check continuously check whether the participants were driving at a safe speed. It warns the participant if they were traveling at an unsafe speed (e.g., over 5 km/h) and a violation was raised when the participant exceeds the speed limit which was set at 8 km/h in the IVR simulation environment.
Look in the direction of travel	The IVR system was designed in such a way that was demanding from the users to look in the direction of travel while the forklift was moving. It warns the participants if they were not looking in the direction of travel while moving and a violation was raised if they continue to look away from the direction of travel after warning.

No operation of forks while moving	The IVR system was designed to check no operating the forks (e.g., raising, lowering, tilting, or shifting the forks) while the forklift is moving. It was giving a warning to the participants if they were operating the forks while moving.
Load pallet correctly	The IVR system was designed to check the pallet is correctly loaded onto the forks when the participant attempts to lift a pallet in a virtual environment. It was giving a warning to the user if the pallet was not correctly loaded.
No collision	The system was checking if the forklift collides with any objects in the surrounding (e.g., walls or objects) and a violation was raised if the participant ignores this collision.
Approach pallet safely	The system was checking whether the forklift has approached the pallet at a safe speed, and a violation was raised if the forklift collides with the pallet at high speed.
Check the surrounding at the corner	The IVR system was designed in such a way that was demanding from the participant to check surroundings at the corner (by looking left and right). A violation was

	raised if he/she did not check both their left and right surrounding at the corner.
Check pallet secured	The system was checking whether the pallet is safely secured on the forklift and was giving the warning to the users if they were attempted to drive with a pallet when it was not fully secured.
Travel with forks at a lowest safe height	Lastly, the system was also checking whether the user was driving with the forks at a safe height and was giving the warning to the user in the IVR environment if he/she was driving and the forks were at an unsafe height.

4.4 FINDINGS

First descriptive analysis was performed to check the difference between the IVR gears-based group and keyboard-based group. Table 4.6 shows the overall mean score of the IVR system feature was higher with VR gears (3.71) experimental settings than in keyboard-based (3.54) experimental settings. In terms of psychological factors, presence, motivation, and enjoyment were slightly higher in IVR-gears based group. However, the self-efficacy mean score was higher in the keyboard-based group (4.01) than VR gears group (3.98). In terms of behavior change outcomes factors (learning knowledge, behavioral intention, and satisfaction) were observed slightly higher with IVR gears compare with the keyboard-based group.

Table 4.6 Table Descriptive Analysis of the Variables Between the Two Groups

Constructs	Items	Experiment A (VR gear-based group)		Experiment B (Keyboard based group	
		Mean	SD	Mean	SD
IVR SF	Fid1	3.67	0.99	3.34	1.09
	Fid2	3.56	1.04	3.23	1.07
	Fid3	3.70	0.87	3.83	0.98
	Usb1	3.66	1.06	3.50	1.10
	Usb2	3.83	0.98	3.46	1.12
	Usb3	3.86	1.07	3.89	0.99
	Overall IVR SF	3.71	1.00	3.54	1.05
Pr	Pr1	3.63	0.80	3.73	0.52
	Pr2	4.20	0.71	3.89	0.80
	Pr3	3.76	0.81	3.82	0.74
	Overall Pr	3.86	0.77	3.81	0.68
Moti	Moti1	4.15	0.78	4.13	0.73

	Moti2	4.30	0.70	4.17	0.68
	Moti3	4.19	0.71	4.10	0.71
	Overall Moti	4.18	0.70	4.13	0.70
Enj	Enj1	4.26	0.63	4.16	0.79
	Enj2	4.16	0.74	4.03	0.69
	Enj3	4.23	0.67	4.26	0.82
	Overall Enj	4.22	0.68	4.15	0.76
Effic	Effic1	4.10	0.71	4.03	0.66
	Effic2	4.03	0.71	4.06	0.69
	Effic3	3.83	0.83	3.93	0.58
	Overall Effic	3.98	0.75	4.01	0.64
Lear	Lear 1	4.33	0.66	4.36	0.61
	Lear 2	4.30	0.70	3.93	0.98
	Lear 3	4.26	0.69	4.16	0.74
	Overall Lear	4.30	0.68	4.15	0.78
Beh. Inten	Inten 1	4.13	0.73	3.80	0.88
	Inten 2	4.43	0.62	4.30	0.87

	Inten 3	4.20	0.66	4.13	0.70
	Overall Inten	4.25	0.67	4.07	0.83
Satis	Satis 1	4.37	0.56	4.33	0.75
	Satis 2	4.13	0.68	4.03	0.85
	Satis 3	4.43	0.50	4.30	0.65
	Overall Satis	4.31	0.58	4.22	0.75

Note. IVR SF = IVR system features; Pr = Presence; Moti = Motivation; Enj = Perceived enjoyment; Effic = Self-efficacy; Lear = Learning knowledge; Beh. Inten = Behavioral intention; Stais = Satisfaction, SD = Standard deviation.

After analyzing the descriptive analysis, hypotheses were tested through SEM. Mainly, there are two techniques to SEM, the covariance-based SEM (CB-SEM) and the variance-based partial least-squares SEM (PLS-SEM) technique. Different from CB-SEM, PLS-SEM can be used for small sample sizes and non-normality data. This advantage of PLS-SEM over CB-SEM is inspiring the construction engineering, and management researchers to use it for a small sample size. For example, Zhao, and Singhaputtangkul (2016) used PLS-SEM with a sample size of 35 participants to examine the influence of firm characteristics of enterprise risk management within Chinese construction organizations. Darko et al. (2018) utilized PLS-SEM to investigate the impact of different types of barriers, divers and promotion techniques on green building technologies adoption with a sample size of 43 participants. Thus similarly, the present research adopted PLS-SEM, using SmartPLS (v. 3.3.2) to test the research hypotheses and validate the hypothetical structural model.

Based on (Hair Jr et al., 2014) research, after specifying the measurement and hypothetical structural model, the reliability and validity of the measurement items within the measurement model must be assessed. Reliability denotes the extent to which measurement of constructs with multi-scale expose the accurate scores of the constructs relative to the errors (Hulland, 1999). Cronbach's alpha coefficient and composite reliability score were used to examine the internal consistency reliability of measuring each construct. The composite reliability score should be above 0.70 (Hair et al., 1998), and Cronbach's alpha coefficient (Darko et al., 2018) should be above 0.70. As Table 4.7 indicates, all Cronbach's alpha coefficient and composite reliability scores were above 0.70, showing an acceptable level of internal consistency of the measurement items.

After reliability assessment, validity which comprises the convergent validity and discriminant validity of the constructs must be evaluated (Darko et al., 2018). For an acceptable level of convergent validity, each measurement item necessary to have a factor loading of 0.5 or higher (Hulland, 1999), and the average variance extracted (AVE) of each construct should also be 0.50 or higher (Fornell and Larcker, 1981). Factor loading denotes the bivariate correlations between measurement items by which the measurement items are linked to the constructs (Hair Jr et al., 2014). Whereas AVE can be stated as the grand mean value of the square loadings of a set of measurement items and is equivalent to a construct's features (Darko et al., 2018). First, we measured the factor loading score of all measurement items and found that one item Pr3 was lower than 0.50. The measurement items with low factor scores can be deleted because their contribution to the explanatory power of the model would be insignificant, thus could bias the estimating of the other measurement items (Darko et al., 2018; Nunnally, 1978). So, this item (Pr3) was deleted from the list of measurement items. After the deletion of these measurement items, the analysis was rerun to make sure the reliable and valid measurement model was achieved. As Table 4.7 shows, all factor loadings and AVEs were above 0.50 which gives proof of convergent validity of the constructs. An AVE above 0.50 shows that the constructs explains more than 50% of the variance in its measurement items, which is acceptable.

Table 4.7 Measurement Model Evaluation

Construct	Item	Factor Loading	Cronbach's Alpha	Composite Reliability	AVE
IVR SF	Fid1	0.772	0.894	0.919	0.655
	Fid2	0.808			
	Fid3	0.786			
	Usb1	0.831			
	Usb2	0.891			
	Usb3	0.760			
Pr	Pr1	0.645	0.701	0.738	0.591
	Pr2	0.875			
Moti	Moti1	0.805	0.800	0.882	0.714

	Moti2	0.903			
	Moti3	0.824			
	Enj1	0.881			
Enj	Enj2	0.912	0.844	0.906	0.763
	Enj3	0.824			
	Effic1	0.854			
Effic	Effic2	0.884	0.808	0.885	0.719
	Effic3	0.804			
	Lear 1	0.789			
Lear	Lear 2	0.744	0.706	0.919	0.630
	Lear 3	0.844			
	Inten 1	0.805			
Beh. Inten	Inten 2	0.870	0.762	0.863	0.678
	Inten 3	0.794			
	Satis 1	0.929			
Stais	Satis 2	0.786	0.842	0.904	0.759
	Satis 3	0.892			

Note. IVR SF = IVR system features; Pr = Presence; Moti = Motivation; Enj = Enjoyment; Effic = Self-efficacy; Lear = Learning knowledge; Beh. Inten = Behavioral intention; Stais = Satisfaction; AVE = Average variance extracted.

After performing the convergent validity test, the discriminant validity test was performed. Discriminant validity tests whether a construct assesses what is originally intended to assess. In other words, discriminant validity tests the extent to which a construct is different from other constructs. To assess discriminant validity, cross-loadings of the measurement items were checked. Table 4.8 shows each measurement item had the highest loading on its corresponding constructs, thus indicate each construct is actually differing from one another and valid for the structural path modeling (Darko et al., 2018).

Table 4.8 Cross Loadings of Measurement Items

Construct	Item	IVR SF	PR	Moti	Enj	Effic	Lear	Beh. Inten	Stais
	Fid1	**0.772**	0.437	0.279	0.364	0.380	0.424	0.409	0.278
	Fid2	**0.808**	0.432	0.313	0.399	0.418	0.422	0.288	0.243
IVR SF	Fid3	**0.786**	0.491	0.420	0.559	0.548	0.564	0.539	0.347
	Usb1	**0.831**	0.537	0.310	0.278	0.589	0.384	0.327	0.194
	Usb2	**0.891**	0.586	0.352	0.397	0.576	0.443	0.398	0.251

	Usb3	**0.760**	0.480	0.279	0.354	0.419	0.390	0.368	0.131
Pr	Pr1	0.332	**0.645**	0.216	0.332	0.265	0.280	0.311	0.230
	Pr2	0.586	**0.875**	0.419	0.507	0.381	0.502	0.381	0.296
	Moti1	0.425	0.438	**0.805**	0.667	0.581	0.467	0.401	0.425
Moti	Moti2	0.303	0.392	**0.803**	0.576	0.458	0.528	0.581	0.510
	Moti3	0.248	0.251	**0.824**	0.485	0.394	0.384	0.460	0.309
	Enj1	0.357	0.592	0.627	**0.881**	0.488	0.492	0.524	0.502
Enj	Enj2	0.449	0.458	0.577	**0.912**	0.480	0.496	0.606	0.474
	Enj3	0.446	0.421	0.594	**0.824**	0.436	0.452	0.498	0.529
	Effic1	0.605	0.366	0.397	0.383	**0.854**	0.557	0.455	0.516
Effic	Effic2	0.512	0.394	0.557	0.484	**0.884**	0.482	0.474	0.467
	Effic3	0.362	0.321	0.513	0.528	**0.804**	0.390	0.392	0.288
	Lear 1	0.430	0.334	0.403	0.318	0.440	**0.789**	0.641	0.526
Lear	Lear 2	0.440	0.484	0.400	0.491	0.420	**0.744**	0.521	0.529
	Lear 3	0.454	0.430	0.499	0.481	0.498	**0.844**	0.661	0.580
Beh. Inten	Inten 1	0.360	0.409	0.476	0.534	0.341	0.581	**0.805**	0.512

	Inten 2	0.363	0.354	0.468	0.544	0.529	0.363	**0.870**	0.614
	Inten 3	0.494	0.353	0.477	0.460	0.415	0.494	**0.794**	0.533
	Satis 1	0.197	0.316	0.467	0.522	0.441	0.626	0.617	**0.929**
Satis	Satis 2	0.071	0.168	0.393	0.333	0.298	0.477	0.501	**0.786**
	Satis 3	0.459	0.377	0.447	0.595	0.564	0.666	0.626	**0.892**

Note. Bold values show that each measurement item had the highest loading on its respective construct; IVR SF = IVR system features; Pr = Presence; Moti = Motivation; Enj = Perceived enjoyment; Effic = Self-efficacy; Lear = Learning knowledge; Beh. Inten = Behavioral intention; Stais = Satisfaction.

After verifying the reliability and validity of the measurement model, the significance path coefficient score must be assessed to test the hypotheses inside the structural model (Darko et al., 2018). Path coefficients indicate the hypothesized connections linking the constructs (Hair Jr et al., 2014). For this purpose, the bootstrapping technique (Davison and Hinkley, 1997) was utilized. Bootstrapping is a flexible method useful for assessing the distribution of any statistic of any type of distribution (Darko et al., 2018; Jack et al., 2001). Table 4.9 shows the bootstrapping results for the model. The higher the path coefficient value, the stronger the impact of an independent variable on the dependent variable (Aibinu and Al-Lawati, 2010). Darko et al. (2018) suggest that a path coefficient range from 0.1 to 0.3 shows a weak impact, 0.3 to 0.5 indicates a moderate influence, and

0.5 to 1.0 demonstrates a strong impact on the dependent variable (Darko et al., 2018). As shown in Table 4.9, hypothesis H1, H3, H4 had a path coefficient ranging from 0.5 to 1.0, indicating that IVR system features would put a strong influence on the dependent variables (presence, perceived enjoyment, and self-efficacy). Also, the results of the path IVR system features to presence, motivation, enjoyment, and self-efficacy had t-value greater than 1.96, implying that these were statistically significant at the 0.05 level. Also, the path of perceived enjoyment to behavioural intention and ssatisfaction was found statistically significant. Therefore, hypotheses H1, H2, H3, H4, H7 (a) and H7 (c) were supported. In contrast, the results did not fully support for other hypotheses because they had path coefficient ranging from 0.1 to 0.5 with t-values below 1.96. The detailed structural equation mode depicting the influence of each construct on behavior change outcomes is illustrated in Figure 4.4. The values inside the circle in Fig. 4 are scores of coefficients of determination (R^2).

Table 4.9 Structural Model Evaluation

Hypothetical path	Path coefficient	t-Value	*p-Value*
H1: IVR SF → Pr	0.621	6.927	0.000*
H2: IVR SF → Moti	0.387	3.106	0.000*
H3: IVR SF → Enj	0.479	4.605	0.000*
H4: IVR SF → Effic	0.598	7.255	0.000*
H5: Pr → Beh. Inten	0.099	0.717	0.473

H6: Pr → Lear	0.255	1.861	0.063
H7: Pr → Satis	0.022	0.141	0.888
H8: Moti → Beh. Inten	0.195	1.086	0.278
H9: Moti → Lear	0.194	1.102	0.270
H10: Moti → Satis	0.099	0.526	0.599
H11: Enj → Beh. Inten	0.330	1.965	0.049*
H12: Enj → Lear	0.119	0.711	0.477
H13: Enj → Satis	0.376	2.224	0.026*
H14: Effic → Beh. Inten	0.193	1.534	0.125
H15: Effic → Lear	0.289	1.833	0.067
H16: Effic → Satis	0.271	1.779	0.075

Note. * The path coefficient is significant at $p < 0.05$; IVR SF = IVR system features; IVR SF = IVR system features; Pr = Presence; Moti = Motivation; Enj = Perceived enjoyment; Effic = Self-efficacy; Lear = Learning knowledge; Beh. Inten = Behavioral intention; Stais = Satisfaction.

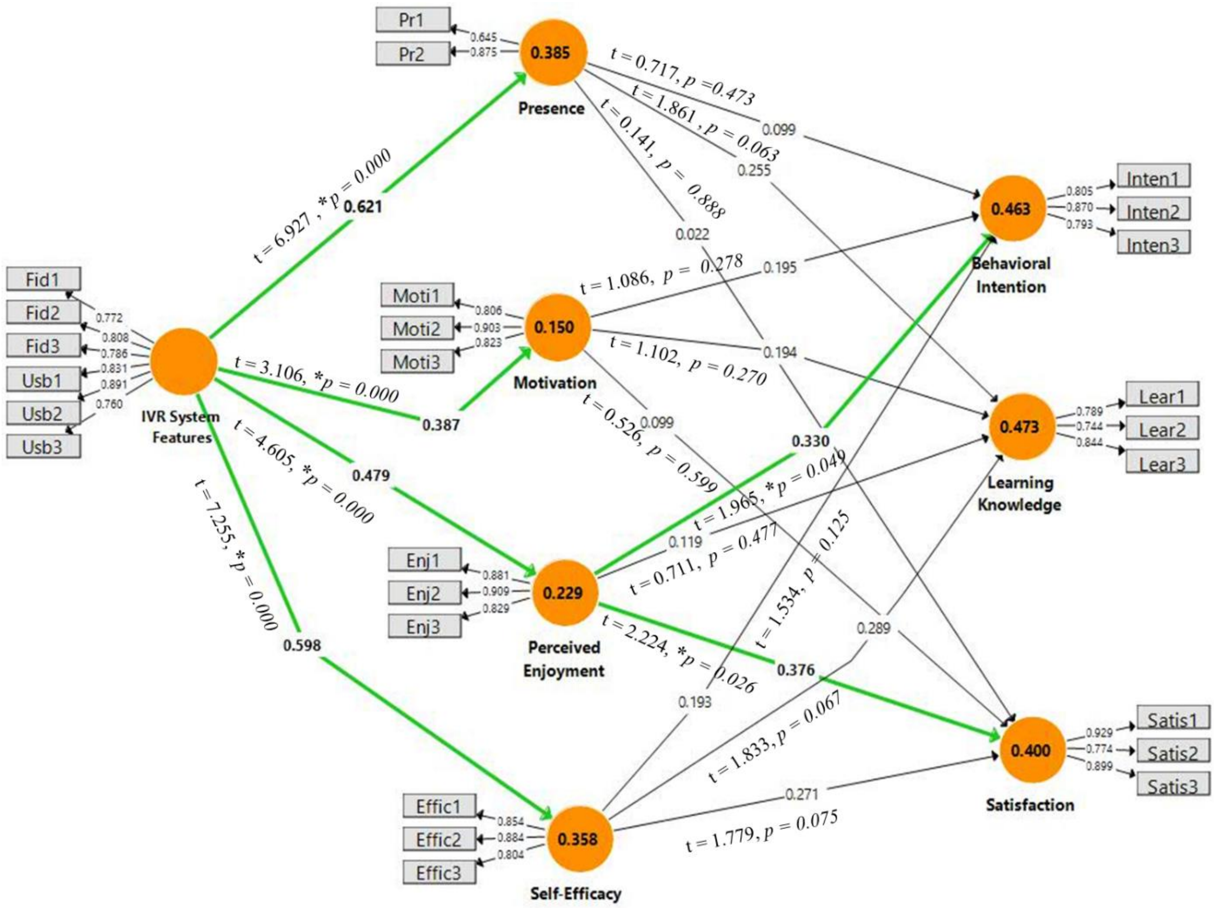


Figure 4.4 Structural Model Results

Note: highlights the significant paths; * indicates the level of significance at $p <$ 0.05.

4.5 DISCUSSION

The results supported the significant path from IVR system features to presence, motivation, perceived enjoyment, self-efficacy, and from enjoyment to behavioral intention and satisfaction.

In terms of presence, the findings of this study found that IVR system features were a significant antecedent to the presence that indicates the better the IVR system features in terms of realism, control factors, and usability, the higher level of presence the users could experience. However, unlike the results from a previous study by Lee et al. (2010), who found that presence directly predicted perceived learning outcomes using non-immersive virtual reality, the findings of this study indicate that a higher level of presence in the training environment would not exert a strong influence on users' behavior intention, learning knowledge and satisfaction. This is could be the reason of presence is a user reaction to the given level of immersion in the IVR environment, and to influence the users' behavior we could not just rely on IVR system features (e.g., realism, control factors, and usability) but should stimulate those circumstances in the IVR environment that could influence on users' emotion and emotional self-regulation then the level of presence through the IVR system features could better influence the user behavior (Dirksen et al., 2019). In terms of motivation, the findings of this study reveal that the IVR system features were significant antecedent to motivation. The realism of the safety training in the immersive environment, the immediate feedback based on the user's action, and close interaction with the IVR environment leads to motivate the users. In terms of perceived enjoyment, the findings of this study established that the IVR features affect behavioral intention and satisfaction via perceive enjoyment. It really means that virtual reality features made the safety training easier for the user as they will not get bored due to the realism of actual presence in the training scenario and would successfully complete the complex safety training with fun, which in turn, would influence their behavioral intention and satisfaction. These results are consistent with previous research (Makransky and Lilleholt, 2018) which indicates that virtual reality system features would influence the students' emotional process by increasing their perceived enjoyment in the virtual reality-based scenario which would significantly affect their behavioral intention and satisfaction. In terms of self-efficacy, the findings of this study reveal that the IVR system features were a significant antecedent to self-efficacy. This result is consistent with the findings of (Meyer et al., 2019) where their training in the IVR-based interactive 3-D environment provided distinctive experiences to users which in turn positively impact their self-efficacy. However, despite the higher influence of IVR system features on self-efficacy, there was not a significant relationship between self-efficacy and dependent variables (i.e., behavioral intention, learning knowledge, and satisfaction). This is because mostly the users of this experiment were not familiar with virtual reality devices, so arrange a one IVR based training session would not significantly influence the users' behavior so multiple training sessions would be provided to participants to influence their behavior (Meyer et al., 2019).

The findings of this study have some prominent theoretical and practical implications. First, the major empirical contribution of this paper was the finding that structural equation model significant paths best describes that IVR feature affects behavioral intention and satisfaction via perceive enjoyment. Second, this study provides a comprehensive framework for understanding the constructs involved in behavior change with the IVR training environment. Third, we highlight how the IVR system features could significantly effect various important psychological factors such as presence, motivation, enjoyment, and self-efficacy presence. The findings of this study, therefore, can be used to guide the practitioners and trainers who wish to develop and use IVR for practical training purposes. The results tell us regarding the development of IVR-based skills training tools and for software designers that they must consider the user experience by making the IVR training more and more enjoyable for the users which in turn would influence their behavioral intention and satisfaction. Also, the higher level of presence in the IVR training environment would not exert a strong influence on users' behavior, learning and satisfaction so they must create IVR-based training scenarios in which users are actually getting feedback on his/her mistakes. The timely delivery of IVR system feedback would make the training experience more enjoyable for the users and would engage the users to learn more in the safety training, which in turn would effect their behavior and satisfaction.

4.6 CONCLUSIONS

Our findings suggest that presence, motivation, perceived enjoyment, and self-efficacy are strongly influenced by features of the IVR system. The results of this study also reveal that only increasing the presence in the IVR environment system would not change the behavior change outcomes. For this purpose, we need to incorporate some features in IVR-based training programs such as stimulate those circumstances in the IVR environment that could influence users' emotions and emotional self-regulation. Also, the IVR system features would increase the users' enjoyment which would lead to provide more satisfaction during IVR-based training and impact on their unsafe behavioral intention. The findings of this research will enable construction industries' trainers and instructors to plan their safety training to make more effective use of IVR applications. The contributing IVR system features and their relationship to the behavior change outcomes had formed a framework that provides a comprehensive understanding of behavior change through IVR-based training which can be served as a tool towards achieving the higher level of behavior change outcomes. In addition, the findings of this study suggest that focusing on IVR training contents along with IVR hardware and software would be helpful to more effectively change user' unsafe behavior.

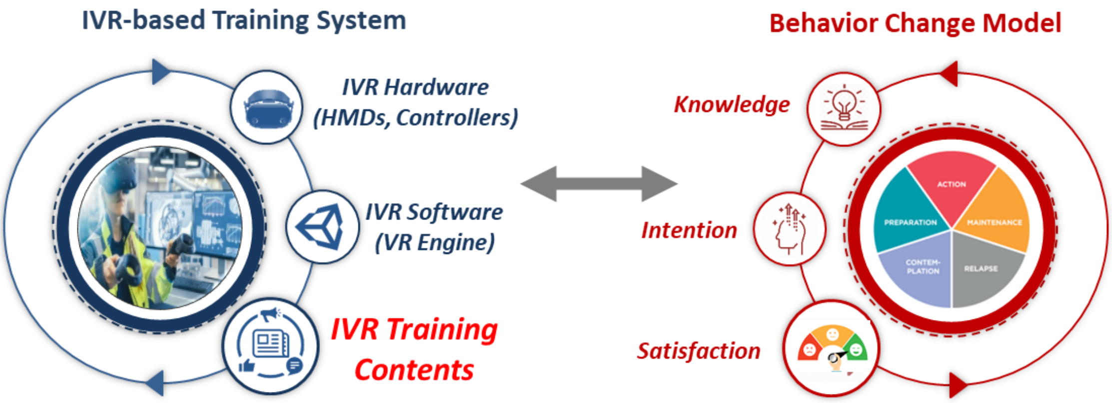


Figure 4.5 IVR-based Training for Behavior Change

Nevertheless, there are some limitations of this study that can be addressed in future research. First, the measurement items used in this study only included self-report measures so future research should use different ways of measuring the skill acquisition through IVR training with a larger sample size. Second, future research should also measure the links between the learning effectiveness measures and the operators' behavior and situation awareness in different construction scenarios. Finally, the model adopted to evaluate the behavior change inspired to the (Morris et al., 2012; Prochaska et al., 1998) behavior change model. However, only the first two levels of behavior change such as learning knowledge (contemplation), (preparation) behavioral intention, and satisfaction level, have been investigated by this evaluation. Further, studies can be conducted with forklift operators to evaluate the remaining behavior change levels (i.e., action and maintenance) and could examine the long-term impact of IVR-based training on behavior change in comparison to the traditional safety training methods. In addition, future research should also consider more factors in IVR system features (e.g., IVR training contents) and mediator variables (e.g., cognitive benefits) and then try to find out the impact of IVR-based training on user's unsafe behavior.

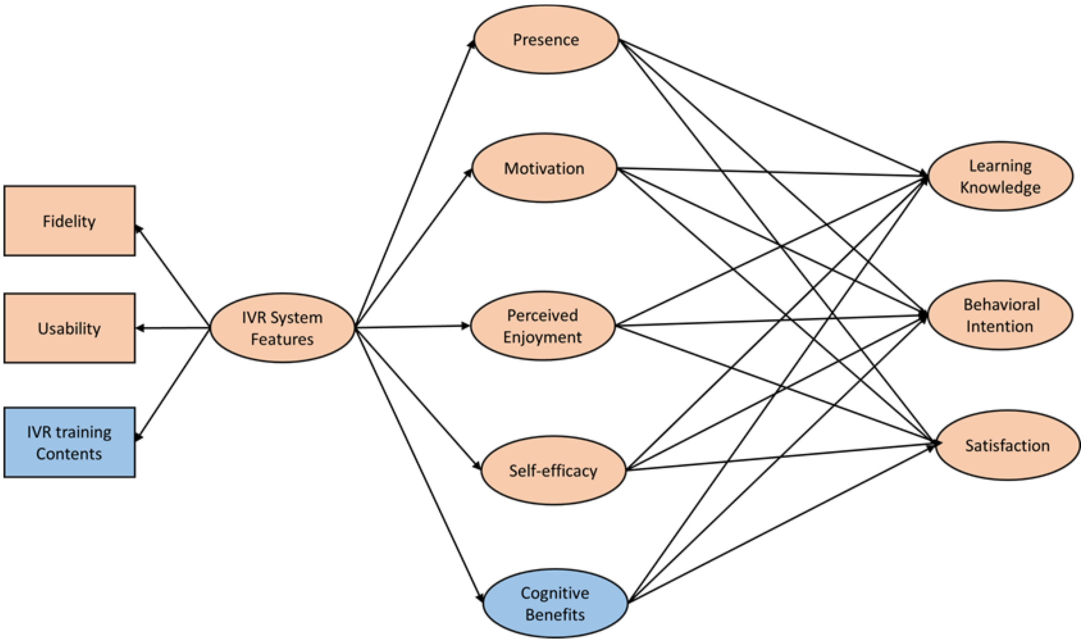


Figure 4.6 Research Model for Future Research

4.7 CHAPTER SUMMARY

This chapter provides a comprehensive framework for understanding the constructs involved in behavior change with IVR training environment. The results indicate that presence, perceived enjoyment, motivation, and self-efficacy are strongly influenced by features of IVR system. However, only a higher level of enjoyment in IVR-based training environment would influence the behavior change outcomes i, e., learning knowledge and satisfaction. The results of this study would help the development of IVR-based training and for software designers that they must consider the user experience by making the IVR training more and more enjoyable which in turn would influence user behavior intention and satisfaction.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATION FOR FUTURE WORK

5.1 INTRODUCTION

This chapter discusses a summary of the research findings and shows the limitations of this research study. It also highlights key suggestions for future research directions.

5.2 SUMMARY OF RESEARCH FINDINGS

This research mainly examines the issues of information processing in IVR/AR system and its cognitive interaction with user. Mainly, this research focused on the three IVR/AR applications, particularly to examine information acquisition (communication), information processing (cognitive task performance), and information perception (safety training). The individual studies carried out for this research project are summarized as below:

a Effectiveness of immersive virtual reality-based communication for construction projects

This research highlights the effectiveness of immersive virtual reality-based communication for construction projects. A detailed comparison of traditional FtF discussion of BIM information displayed on a monitor screen against IVR-based communication with BIM information embedded in the immersive environment was performed. The results of experiments indicate that quality of discussion, appropriateness, openness, and accuracy were found more suitable to its members to communicate in the FtF condition because it offers the group members to open-minded share the ideas with enjoyment and makes it easy to recognise their reactions or identify appropriate moments to speak. This would provide the participants' speech to take shorter than IVR exchange of the same verbal content would have taken. However, in terms of richness, IVR-based communication is considered more suitable to its members to communicate because IVR environment provided more detailed and vivid visual information to the participants, as well as a greater sense of immersion and presence than FtF communication did. The integration of face recognition trackers in the IVR environment would be helpful to increase the quality of discussion, appropriateness, openness, and accuracy of IVR-based communications.

b Impact of mobile augmented reality system on cognitive behavior and performance during rebar inspection tasks

This research revealed that the MAR system enhances the real world through the superimposition of computer-generated information while not interfering users' mobility. However, the narrowing of a user's field of view that comes with MAR use could limit users ability to notice events in their surroundings and may lead to cognitive overload and thus could adversely effect the performance of tasks. Therefore, this research understands how MAR use affects cognitive behavior, as well as task and safety performance. As a preliminary investigation, this study conducted laboratory simulations of rebar-inspection tasks and compared CL, TP, and SA of users of two types of MAR system – i.e., head-mounted and handheld compared with traditional paper-based methods. In particular, participants' CL was measured with the NASA-TLX; their TP, by completion time and the number of rebars correctly detected; and their SA, with Taylor's SART. The findings of both our experiments contribute to the body of knowledge that a given information-presentation format can influence construction practitioners' cognitive workload and performance. While the rebar-framework design information provided via a superimposed virtual rebar model in MAR-assisted inspection would decrease the inspectors' CL. In addition, head-mounted MAR device may decrease users' understanding of the surrounding environment and thus could increase their task completion times, as compared to paper and tablet-based inspection.

c How immersive virtual reality system features impact behavior change safety? A structural equation modeling approach

This study examined how IVR system features could affect behavior change outcomes. In other words, the determinants and their relationships for forklift operator training in the IVR environment that support the behavior change theory was examined. Using SmartPLS, the results supported the casual path from IVR system features to presence, motivation, perceived enjoyment, self-efficacy, and from presence, motivation, perceived enjoyment, self-efficacy to behavior change outcomes. The findings of this study have some prominent theoretical and practical implications. First, this study provides a comprehensive framework for understanding the constructs involved in behavior change with IVR training environment. Second, this research describes that IVR feature affects behavioral intention and satisfaction via perceive enjoyment. The findings of this study can guide the practitioners and trainers to better design IVR applications for practical construction training purposes. In addition, the findings of this research would help the designers to cost-effectively design the IVR training environment to impact on user's behavior.

5.3 SIGNIFICANCE AND CONTRIBUTIONS

Overall, this research highlights that human IVR/AR interaction with the users to better design the IVR/AR system and to enhance the IVR/AR applications' effectiveness. This research has advanced our understanding related to information acquisition, processing, and perception related to IVR/AR, specifically for communication, cognitive task effectiveness, and training applications. In terms of information acquisition in IVR/AR system, this research provides IVR-based communication channel can be an alternate communication channel for connecting remotely located inter-organizations. However, the quality of discussion, appropriateness, openness, and accuracy of IVR-based communications need to be enhanced. In terms of information processing in IVR/AR system, this research indicates information presentation format can influence construction practitioners' cognitive workload and performance by MAR display devices. In terms of information perception in IVR/AR system, this research reveals IVR system features affect behavioral intention and satisfaction via perceived enjoyment.

In addition, this research provides a better understanding of human cognitive aspects in IVR/ AR environment and highlights that how IVR/AR-based information visualization would help to reduce mental efforts. This research also research provides a comprehensive framework that highlights the potential factors that could affect the information processing capability of a user in IVR/AR system. The findings of this study can be used to guide the practitioners and trainers who wish to develop and use IVR/AR system for practical purposes (e.g., communication, cognitive task performance, and training).

5.4 LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

Despite the above-mentioned significance of this research, there are some limitations of this study. First, even though this research laboratory experiments tried to simulate a real construction-site experience as close as possible, however, the complexity and uncertainty of an actual construction site are very difficult to replicate in the laboratory environments. Therefore, future research studies should validate this research finding of this research at real construction site with more expert construction professionals. Second, this research examines IVR/AR interactions with users with a relatively small sample size. This can be further addressed with the larger sample size and by considering the human variability issues such as participant's age, gender, experience, etc. Third, the measurement items used in this study mainly include self-report measures. Future research could validate this research finding with other measurement techniques such as objective methods.

5.5 CHAPTER SUMMARY

This chapter summarizes the major research outcomes, overall contribution of this research in the body of knowledge and acknowledges the limitations of this research study. Directions for future studies have also been suggested. The information presented in this chapter would help the practitioners and trainers who wish to develop and use IVR/AR system for practical purposes (e.g., communication, cognitive task performance, and training). Based on this, they would better understand the human IVR/AR system interaction and thus could better design the IVR/AR applications for the construction domain.

APPENDICES

APPENDIX A CONSENT FORM TO PARTICIPATE IN RESEARCH

I ________________________ hereby consent to participate in the captioned research conducted by Dr. JoonOh Seo, an assistant professor at the Hong Kong Polytechnic University. I understand that information obtained from this research may be used in future research and published. However, my right to privacy will be retained, i.e., my personal details will not be revealed.

The procedure as set out in the attached information sheet has been fully explained. I understand the benefit and risks involved. My participation in the project is voluntary.

I acknowledge that I have the right to question any part of the procedure and can withdraw at any time without penalty of any kind.

Name of participant ____

Signature of participant ____

Name of researcher ____

Signature of researcher ____

Date ____

APPENDIX B INFORMATION SHEETS

INFORMATION SHEET A FOR PROJECT TITLE

Effectiveness of Immersive Virtual Reality-Based Communication for Construction Projects

You are invited to participate in a study conducted by Dr. JoonOh Seo, who is a staff member the Department of Building and Real Estate in The Hong Kong Polytechnic University.

This project seeks to evaluate the effectiveness of communication in the immersive virtual environments (IVEs). Participants will be involved in two experimental discussion sessions: 1) one is for discussion through face-to-face communication; and 2) the other is for discussion in the IVE. In each session, participants will be given specific discussion topics (e.g., design options for a residential or a commercial building project) and will role-play to determine the best design options through role-playing as a client, an architect, or a contractor. The length of the experiment will be around 40 minutes. Regular office rooms, Block Z at The Hong Kong Polytechnic University are chosen as test rooms. A desktop with a monitor for face-to-face communication, or a computer with virtual reality devices for communication in the IVE will be provided.

The experiment procedures are as follows.

1) Upon arrival, participants will be greeted and given the instructions. They will be asked to consent to participate in the experiment before proceeding. They are kept waiting in the rest area, where located left corner of the test room.

2) Before the experiment, the participants need to complete the participant information questionnaires and pre-survey forms firstly.

3) And then, participants will be given different specific project-related information and discussion topics according to their roles (e.g., a client, an architect, and a contractor) to facilitate discussion for design option reviews. They will be given 5 minutes to read and understand the information.

Discussion sessions for face-to-face communication

4) Three participants in a group will be seated together and will be given about 30 minutes to discuss the given discussion topics through face-to-face communication and then to determine the best design option for the project. BIM models with different design alternatives will be provided in a monitor screen.

Discussion sessions for IVR communication

4) Each participant will move to the separated rooms and will be assisted to calibrate Head Mounted Display (HMD) to ensure his or her comfort and eyesight. And then, participants will join a virtual environment using a 'Avartar'. They will be given about 30 minutes to discuss the given discussion topics through voice chatting, and then to determine the best design option for the project. BIM models with different design alternatives will be provided in a virtual environment.

5) Once the discussion ends, participants are required to accomplish questionnaires regarding communication effectiveness and learning experience.

6) Also, participants will answer post-questionnaire of presence of sense regarding IVE (only for IVE communication groups)

You have every right to withdraw from the study before or during the survey without penalty of any kind. If you would like to obtain more information about this study, please contact Dr JoonOh Seo (tel. no.: 2766-5823 / email: joonoh.seo@)

If you have any complaints about the conduct of this research study, please do not hesitate to contact Miss Cherrie Mok, Secretary of the Human Subjects Ethics Sub-Committee of the Hong Kong Polytechnic University in writing (c/o Research Office of the University) stating clearly the responsible person and department of this study as well as the HSESC Reference Number.

Thank you for your interest in participating in this study.

Dr JoonOh Seo

Assistant Professor, Department of Building and Real Estate

INFORMATION SHEET B FOR PROJECT TITLE

Impact of Mobile Augmented Reality System On Cognitive Behavior And Performance During Rebar Inspection Tasks

You are invited to participate on a study conducted by Dr. JoonOh Seo, who is a staff member of the Department of Building and Real Estate in The Hong Kong Polytechnic University.

The aim of this study is to evaluate task performance, situation awareness, and cognitive workload. Participants will inspect the steel reinforcement bars task in three experimental sessions: 1) one is for inspection through HoloLens-based augmented reality; second is for inspection through Tablet-based augmented reality; and 3) is for inspection through paper-based drawing. In each session, participants will check the eight reinforcement items, e.g. (spacing between bars, number of bars, cover spacing, no. of anchorage bars, length of anchorage bars, distance from the bottom surface, bars tied and supported and additional bars). During the experiment, participants' performance will be observed, and once this experiment ends, participants will be required to accomplish questionnaires regarding cognitive load and situation awareness.

All information related to participants will remain confidential and will be identifiable by codes only known to the researcher. You have every right to withdrawn from the study before or during the measurement without penalty of any kind. Each experimental session will take about 30 minutes.

If you would like to get more information about this study, please contact Dr. JoonOh Seo on tel. no. 2766-5823 (mobile tel. no. 6700-   ); mailing address joonoh.seo@   .

If you have any complaints about the conduct of this research study, please do not hesitate to contact Ms. Cherrie Mok, Secretary of the Human Subjects Ethics Sub-Committee of The Hong Kong Polytechnic University in writing (c/o Research Office of the University) stating clearly the responsible person and department of this study.

Thank you for your interest in participating in this study.

Dr. JoonOh Seo

Principal Investigator

INFORMATION SHEET C FOR PROJECT TITLE

<u>Project Title: How Immersive Virtual Reality System Features Impact Behavior Change Outcomes? A Structural Equation Modeling Approach</u>

You are invited to participate on a study conducted by Dr. JoonOh Seo, who is a staff member of the Department of Building and Real Estate in The Hong Kong Polytechnic University.

The aim of this study is to evaluate the impact of immersive virtual reality (IVR)-based training on users' behavior. Participants of two groups will perform the forklift operator tasks in two experimental sessions: 1) one is for performing the forklift lift operator tasks in the IVR environment though the VR gears (pedal and steering wheel) and 2) is for performing the same forklift operator task with the help of computer keyboard. In each session, participants will perform the following forklift operator tasks in the IVR environment.

- Forklift introduction
- Forks introduction
- Operating the forks
- Picking up a pallet

After the experiment, participants' responses on IVR system features, the learning experience of IVR, and behavior change outcomes will be observed through the questionnaire.

All information related to participants will remain confidential and will be identifiable by codes only known to the researcher. You have every right to withdraw from the study before or during the measurement without penalty of any kind. Each experimental session will take about 25- 35 minutes.

If you would like to get more information about this study, please contact Dr. JoonOh Seo on tel. no. 2766-5823 (mobile tel. no. 6700-); mailing address joonoh.seo@ .

If you have any complaints about the conduct of this research study, please do not hesitate to contact Ms. Cherrie Mok, Secretary of the Human Subjects Ethics Sub-Committee of The Hong Kong Polytechnic University in writing (c/o Research Office of the University) stating clearly the responsible person and department of this study.

Thank you for your interest in participating in this study.

Dr. JoonOh Seo

Principal Investigator

APPENDIX C QUESTIONNAIRE FORMS

QUESTIONNAIRE FORMS FOR PROJECT TITLE

Effectiveness of Immersive Virtual Reality-Based Communication for Construction Projects

Student Survey

Presence and Immersion Questionnaire

Please indicate your preferred answer by marking an "X" in the appropriate box of the seven-point scale.

1. How well could you concentrate on the assigned tasks or required activities?

Not well — Moderately — Very well

2. How much did the visual aspects of the environment involve you?

Not much — Moderately — Very much

3. How quickly did you adjust to the virtual environment experience?

Not quickly — Moderately — Very quickly

4. How much did your experiences in the virtual environment seem consistent with your real-world experiences?

Not much — Moderately — Very much

5. How involved were you in the virtual environment experience?

Not involved — Moderately — Very involved

6. To what degree did you feel confused or disoriented at the beginning of breaks or at the end of the experimental session?

Not confused Moderately Very confused

Student Survey
Communication Effectiveness Questionnaire

Dear Students,

The purpose of this survey is to compare the perceived effectiveness of two communication methods; a communication in person and a communication via Immersive Virtual Reality (IVR) technology. During a role-playing discussion on the new construction project in PolyU, you will experience both a direct conversation in person and an IVR technology-assisted conversation in an immersive virtual environment (IVE). The questions in this questionnaire will ask you about your communication and learning experiences with each method used in the discussion.

This questionnaire consists of four parts:
- Part A: Background information
- Part B: Communication experience during the discussion
- Part E: Suggestions and comments

Please be reminded that the data will be used **STRICTLY** for educational purposes and **NO** personal information will be disclosed at any forum.

If you have any questions about this research project please feel free to contact me (PhD Student, ABBAS Ali, ali.abbas@ , Mobile: (852) 6849) or my supervisor (Assistant Professor, Dr. JoonOh SEO, joonoh.seo@ , Tel: (852) 2766 5823.)

Part A: Background Information
Please select and tick (√) the answer that describes your background for each question.

Gender

☐ Male ☐ Female

Course

☐ Undergraduate ☐ Graduate

Major study area

☐ Architecture ☐ Engineering ☐ Construction ☐ If others, please specify: ______________

Knowledge about virtual reality (VR) before this class

☐ No knowledge ☐ Some knowledge ☐ Lots of knowledge

Previous experience with VR technology before this class

☐ No experience ☐ Some experience ☐ Lots of experience

Part B: Communication Experience during the Discussion

This part is in relation to your communication experience during the class discussion on the new construction project. Please tick (√) **only one answer** for each of the following questions that best describes your opinion.					
Group Discussion Quality					
Factor	**Scale**				
	Strongly Disagree	Disagree	Neutral	Agree	Stron gly Agree
The overall group discussion was effective to find a solution	1	2	3	4	5
The solution from the group discussion was satisfactory	1	2	3	4	5
The group members effectively shared knowledge and information about the project	1	2	3	4	5
I correctly understood the issue that I have to discuss	1	2	3	4	5
Communication Appropriateness					
Factor	**Scale**				
	Strongly Disagree	Disagree	Neutral	Agree	Stron gly Agree
Overall communication during the discussion was effective to find a solution	1	2	3	4	5
Overall communication during the discussion was relevant to the discussion topic	1	2	3	4	5
I focused when other member was speaking	1	2	3	4	5
Other members focused when I was speaking	1	2	3	4	5
I treated other members politely during communication	1	2	3	4	5
Other members treated me politely during communication	1	2	3	4	5
Communication Richness					
Factor	**Scale**				
	Strongly Disagree	Disagree	Neutral	Agree	Stron gly Agree

All topics we discussed were relevant to find a solution	1	2	3	4	5
I could provide detailed information on the subject when needed	1	2	3	4	5
I could provide vivid information on the subject when needed	1	2	3	4	5
Others provided me enough information on the subject while he/she was speaking	1	2	3	4	5
A rich amount of information was being shared during the discussion	1	2	3	4	5

Communication Openness

Factor	**Scale**				
	Strongly Disagree	Disagree	Neutral	Agree	Stron gly Agree
It was easy to communicate openly to all members during the discussion	1	2	3	4	5
I found it enjoyable to talk to other group members	1	2	3	4	5
During the discussion, there was a great deal of understanding between members	1	2	3	4	5
The group members were open to each other's different idea	1	2	3	4	5

Communication Accuracy

Factor	**Scale**				
	Strongly Disagree	Disagree	Neutral	Agree	Stron gly Agree
The information I received from others was clear	1	2	3	4	5
I often felt that other members did not understand what I was saying	1	2	3	4	5
I often had to go back and check the accuracy of the information I received	1	2	3	4	5
I often did not understand what others were saying	1	2	3	4	5
I often had to explain what I said before again	1	2	3	4	5

Part E: Suggestions and Comments

Please write down if you have any suggestions or comments about the discussion, communication methods, etc.

Student Survey
Immersive Tendencies Questionnaire
(Witmer & Singer, Version 3.01, September 1996)

Please indicate your preferred answer by marking an "X" in the appropriate box of the seven-point scale.

1. How physically fit do you feel today?

Not fit — Moderatey fit — Extremely fit

2. How mentally alert do you feel at the present time?

Not alert — Moderatey alert — Extremely alert

3. How good are you at blocking out external distractions when you are involved in something?

Not very good — Somewhat good — Very good

4. Do you ever become so involved in a television program or book that people have problems getting your attention?

Never — Occasionally — Often

5. Do you ever get extremely involved in projects that are assigned to you by your boss or your instructor, to the exclusion of other tasks?

Never — Occasionally — Often

6. Do you ever become so involved in doing something that you lose all track of time?

Never — Occasionally — Often

7. How well could you examine objects from multiple viewpoints?

Not very good — Somewhat good — Very good

QUESTIONNAIRE FORM FOR PROJECT TITLE

Impact of Mobile Augmented Reality System On Cognitive Behavior And Performance During Rebar Inspection Tasks

Student Survey

Introduction

Dear Students,

The purpose of this survey is to compare the cognitive workload and situation awareness in the augmented reality (AR) environment and paper-based instruction. During the experiment, you will perform the construction inspection task. The questions in this questionnaire will ask you about your perceived mental load and situation awareness of the surrounding environment during the experiment.

This questionnaire consists of three parts:

- Part A: Background information
- Part B: Cognitive load
- Part C: Situation awareness
- Part C: Suggestions and comments

Please be reminded that the data will be used **STRICTLY** for educational purposes, and **NO** personal information will be disclosed at any forum.

If you have any questions about this research project, please feel free to contact me (Ph.D. Student, ABBAS Ali, ali.abbas@ , Mobile: (852) 6849) or my supervisor (Assistant Professor, Dr. JoonOh SEO, joonoh.seo@ , Tel: (852) 2766 5823.)

Part A: Background Information

Please select and tick (√) the answer that describes your background for each question.

Gender

☐ Male ☐ Female

Course

☐ Ph.D. research student ☐ Postdoctoral research student

Construction industry experience

☐ No experience ☐ Only internship experience ☐ Less than 2 years ☐ 2-5 years
☐ 6-10 years ☐ More than 10 years

Previously used any augmented reality-based tool, device or application

☐ Yes ☐ No

Part B: Cognitive load

This part is related to your mental workload during the inspection task. Please tick (√) **only one answer** for each of the following questions that best describes your opinion.

Mental Demand					
Factor	**Scale**				
	Very Low	Low	Medium	High	Very High
How mentally demanding was the task?	1	2	3	4	5
Temporal Demand					
Factor	**Scale**				
	Very Low	Low	Medium	High	Very High
How much time pressure did you feel due to the rate of pace which the tasks occurred?	1	2	3	4	5
Effort					
Factor	**Scale**				
	Very Low	Low	Medium	High	Very High
How hard did you have to work (mentally) to accomplish your level of performance?	1	2	3	4	5
Performance					
Factor	**Scale**				
	Very Low	Low	Medium	High	Very High
Do you think you were successfully accomplishing what you were asked to do?	1	2	3	4	5
Frustration Level					
Factor	**Scale**				
	Very Low	Low	Medium	High	Very High
How stressed, insecure, discouraged, and annoyed were you during the task?	1	2	3	4	5

Part C: Situation Awareness

This part is related to your situational awareness of the surrounding environment during the experiment. Please tick (√) **only one answer** for each of the following questions that best describes your opinion.

Instability of the Surrounding Situation	
Factor	**Scale**

	Very Low	Low	Medium	High	Very High
How much surrounding situation was changing during experimental session?	1	2	3	4	5

Variability of Situation

Factor	Scale				
	Very Low	Low	Medium	High	Very High
How many variables (factors) were changing in the surrounding situation during experimental session?	1	2	3	4	5

Complexity of the Surrounding Situation

Factor	Scale				
	Very Low	Low	Medium	High	Very High
How much complex was the surrounding situation during experimental session?	1	2	3	4	5

Arousal

Factor	Scale				
	Very Low	Low	Medium	High	Very High
How much alert were you to observe the surrounding situation during the experiment?	1	2	3	4	5

Concentration of Attention

Factor	Scale				
	Very Low	Low	Medium	High	Very High
How much were you concentrating on the surrounding situation during experimental session?	1	2	3	4	5

Division of Attention

Factor	Scale				
	Very Low	Low	Medium	High	Very High
How much your attention was divided during experimental session?	1	2	3	4	5

Spare Mental Capacity

Factor	Scale				
	Very Low	Low	Medium	High	Very High

How much mental capacity did you had to spare in the surrounding situation?	1	2	3	4	5
Information Quantity of the Surrounding Situation					
Factor	**Scale**				
	Very Low	Low	Medium	High	Very High
How much information were you understanding about the surrounding environment during experimental session?	1	2	3	4	5
Information Quality of the Surrounding Situation					
Factor	**Scale**				
	Very Low	Low	Medium	High	Very High
How good was the quality of surrounding information, which you were understanding during the experimental session?	1	2	3	4	5
Familiarity with the Surrounding Situation					
Factor	**Scale**				
	Very Low	Low	Medium	High	Very High
How much familiar were you with the surrounding environment during experimental session?	1	2	3	4	5

Part C: Suggestions and Comments

Please write down if you have any suggestions or comments about the experiment.

QUESTIONNAIRE FORM FOR PROJECT TITLE

Project Title: How Immersive Virtual Reality System Features Impact Behavior Change Outcomes? A Structural Equation Modeling Approach

Student Survey

Questionnaire Form

Dear Students,

The purpose of this survey is to understand the impact of immersive virtual reality (IVR) based training on human behavior. During the experiment, you will perform construction forklift operator tasks. The questions in this questionnaire will ask you about your IVR-based training experience and its potential impact on human behavior.

This questionnaire consists of five parts:

- Part A: Background information
- Part B: IVR system features
- Part C: IVR training experience
- Part D: Impact on human behavior
- Part E: Suggestions and comments

Please be reminded that the data will be used **STRICTLY** for educational purposes, and **NO** personal information will be disclosed at any forum.

If you have any questions about this research project, please feel free to contact me (Ph.D. Student, ABBAS Ali, ali.abbas@ , Mobile: (852) 6849) or my supervisor (Assistant Professor, Dr. JoonOh SEO, joonoh.seo@ , Tel: (852) 2766 5823.)

Part A: Background Information

Please select and tick (√) the answer that describes your background for each question.

Gender

☐ Male ☐ Female

Position

☐ Ph.D. research student ☐ Postdoctoral research student ☐ Research Assistant

Construction industry experience

☐ No experience ☐ Only internship experience

☐ Professional experience of less than 2 years

☐ Professional experience of 2-5 years

☐ Professional experience of 6-10 years

☐ Professional experience of more than 10 years

Do you have driving experience / driving license

☐ Yes ☐ No

Previously heard about virtual reality

☐ Yes ☐ No

Previously used any virtual reality-based tool, device, or application

☐ Yes ☐ No

Part B: Immersive virtual reality (IVR) system features

This part is related to the IVR system features. Please tick (√) **only one answer** for each of the following questions that best describes your opinion.

Fidelity

Factor	**Scale**				
	Very Low	Low	Medium	High	Very High
I was able to easily move in the virtual environment.	1	2	3	4	5
I was able to accurately touch the control devices' buttons to interact with the virtual environment	1	2	3	4	5
I was able to easily identify objects through physical interaction, like lifting the object by forklift.	1	2	3	4	5

Usability

Factor	**Scale**				
	Very Low	Very Low	Very Low	Very Low	Very Low
IVR-based training is simple and easy for me.	1	2	3	4	5
It is easy for me to interact IVR-based environment with.	1	2	3	4	5
IVR-based training with allowed me to progress at my own pace.	1	2	3	4	5

Part C: IVR training experience

This part is related to your IVR-based training experience during the experiment. Please tick (√) **only one answer** for each of the following questions that best describes your opinion.

Presence

Factor	Scale				
	Very Low	Low	Medium	High	Very High
My interaction with the IVR-based simulation environment seemed natural.	1	2	3	4	5
I was engaged in the virtual environment experience.	1	2	3	4	5
I was involved in the experiment task to the extent that I lost track of time.	1	2	3	4	5
Motivation					
Factor	**Scale**				
	Very Low	Low	Medium	High	Very High
I was motivated to do this forklift operator training in IVR environment.	1	2	3	4	5
I was motivated to attain forklift operator performance goals in the IVR environment.	1	2	3	4	5
I was motivated to be a part of this forklift operator training in IVR environment.	1	2	3	4	5
Perceived enjoyment					
Factor	**Scale**				
	Very Low	Low	Medium	High	Very High
I enjoyed IVR based forklift operator training.	1	2	3	4	5
I found the IVR environment for forklift operator training purposes was pleasant.	1	2	3	4	5
I have fun using IVR based forklift operator training.	1	2	3	4	5
Self-efficacy					
Factor	**Scale**				
	Very Low	Low	Medium	High	Very High
I am confident that I can understand the concepts related to forklift operator training in the IVR environment.	1	2	3	4	5
I am confident that I can do forklift operator training exercises in the IVR environment.	1	2	3	4	5
I am confident that I can improve the skills of forklift operator in the IVR environment.	1	2	3	4	5
Learning knowledge					
Factor	**Scale**				
	Very Low	Low	Medium	High	Very High

IVR-based training helps me to understand about safe operation of forklift.	1	2	3	4	5
I am more interested to learn the topics in the IVR environment.	1	2	3	4	5
I gained a good understanding of the basic concepts of the forklift operator training in the IVR environment.	1	2	3	4	5
Behavioral intention					
Factor	**Scale**				
	Very Low	Low	Medium	High	Very High
I am able after this IVR-based training to anticipate unsafe forklift operator actions.	1	2	3	4	5
The information provided in the virtual environment helps me to improve my unsafe behavior (e.g., check the surrounding before moving forklift, not operate the forks while the forklift is moving etc.)	1	2	3	4	5
This IVR-based training influences my intention to perform the save forklift operation tasks.	1	2	3	4	5
Satisfaction					
Factor	**Scale**				
	Very Low	Low	Medium	High	Very High
I was satisfied with this IVR-based training environment.	1	2	3	4	5
I was satisfied with the variety of forklift operator training aspects that were covered in the IVR environment.	1	2	3	4	5
I was satisfied with the immediate information gained by IVR-based training.	1	2	3	4	5

Part E: Suggestions, and Comments

Please write down if you have any suggestions or comments about the experiment.

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