CONSTRUCTION SITE HAZARD RECOGNITION SKILLS MEASUREMENT VIA EYE-TRACKING AND IMMERSIVE VIRTUAL REALITY TECHNOLOGIES

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ABSTRACT

CONSTRUCTION SITE HAZARD RECOGNITION SKILLS MEASUREMENT VIA EYE-TRACKING AND IMMERSIVE VIRTUAL REALITY TECHNOLOGIES

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Hazard recognition is considered as one of the major elements of construction site safety; however, empirical studies about hazard recognition capabilities of construction workers are limited due to nature of construction sites and difficulty of measuring this skill. This study suggests usage of immersive virtual reality systems, eye tracking, and game technologies to overcome this difficulty. In this scope; a virtual construction site with hazardous situations was designed and used in experiments, via these technologies. In these experiments, effects of levels of formal education and work experience on hazard recognition rate and speed were tested. The results show that level of education has a significant effect on hazard recognition performance. Both recognition rate (p=0.000058) and speed (p=0.021) are significantly better for more educated group of workers. Moreover, the difference in recognition rate is mostly caused by the hazards which were seen but unrecognized by the subjects. On the other hand, experience does not affect hazard recognition performance. Neither recognition rate nor recognition speed is different among the groups. However, the ratio of the unseen hazards is significantly higher (p=0.004) for more experienced group of workers. Additionally, results are also analyzed according to each hazard individually. The contributions of this study are on two fronts: Firstly, the results obtained would broaden the knowledge on hazard recognition behavior and they could help developing better and more personalized safety management and training strategies. Secondly, the methodology suggested in this study provides a practical, ethical, and feasible way of conducting safety research.

Keywords: Hazard Recognition, Virtual Reality, Eye Tracking, Game Technologies, Construction Safety, Safety Competency

ÖZ

GÖZ TAKİBİ VE SANAL GERÇEKLİK TEKNOLOJİLERİ İLE ŞANTİYELERDE TEHLİKE FARKETME YETENEĞİ ÖLÇÜMÜ

Özel, Bekir Enes
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Tehlike tanıma, şantiye güvenliğinin temel öğelerinden biri olarak kabul edilir, ancak şantiye işçilerinin tehlike tanıma yeterlilikleri konusundaki ampirik çalışmalar şantiyelerin doğası ve bu yeteneğin ölçümünün zorluğu sebebiyle sınırlıdır. Bu çalışma, bu zorlukların aşılması için imersiv sanal gerçeklik, göz takibi ve oyun teknolojilerinin kullanımını öne sürmektedir. Bu kapsamda; bu teknolojilerin yardımı ile sanal bir şantiye ortamı tasarlanmış ve deneyler için kullanılmıştır. Bu deneylerde örgün eğitim ve iş tecrübesi seviyelerinin tehlike tanıma oranı ve hızı üzerindeki etkileri test edilmiştir. Elde edilen sonuçlara göre, eğitim seviyesinin tehlike tanıma performansı üzerinde istatistiksel olarak anlamlı bir etkisi vardır. Daha eğitimli işçi grubunun tehlike tanıma oranı ($p=0,000058$) ve hızı ($p=0,021$) anlamlı oranda daha iyidir. Ayrıca, tanıma oranındaki fark büyük oranda denekler tarafından görülen ama tanınamayan tehlikelerden kaynaklıdır. Öte yandan, tecrübe tehlike tanıma performansı üzerinde bir etkiye sahip değildir. Tanıma oranı ve tanıma hızı açısından daha az veya çok tecrübeli gruplar arasında bir fark yoktur. Bununla birlikte, görülmeyen tehlikelerin oranı daha tecrübeli işçi grubu için istatistiki olarak anlamlı biçimde ($p=0,004$) daha fazladır. Bunlara ek olarak, sonuçlar her bir tehlike için de ayrı ayrı analiz edilmiştir. Bu tezin katkısı iki yöndedir: İlk olarak, elde edilen sonuçlar

tehlike fark etme davranışı hakkındaki bilgiyi genişletecektir ve daha iyi ve kişiselleştirilmiş iş güvenliği eğitimi ve yönetimi stratejileri geliştirilmesinde kullanılabilirler. İkinci olarak, tezde öne sürülen metodoloji, güvenlik araştırmaları için pratik, etik ve uygulanabilir yöntem sunmaktadır.

Anahtar Kelimeler: Risk Tanıma, Sanal Gerçeklik, Göz Takibi, Şantiye Güvenliği

To all those who lost their lives in construction site accidents

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LIST OF ABBREVIATIONS

AEC	Architecture, Engineering, and Construction
CAVE	CAVE Automatic Virtual Environment
HFT	Hazard Fixation Time
HMD	Head Mounted Display
ILO	International Labour Organization
MRT	Mean Reaction Time
PBT	Push Button Time
SGK	Sosyal Güvenlik Kurumu
TMR	Total Miss Rate
VR	Virtual Reality

CHAPTER 1

INTRODUCTION

1.1. Chapter Disposition

This first chapter contains basic information about the thesis you are reading. It aims to draw a framework for the study. The chapter starts with explaining the motivation behind the research and continues by revealing the research questions and hypotheses. After that, the aim and objectives toward these research questions are expressed. The procedure of the research is explained shortly. Lastly, the disposition of the thesis is provided.

1.2. Motivation

Construction sites are ever-changing and extremely dynamic workplaces. In more stationary workplaces like factories, occupational safety experts can deeply observe and analyze the risks in-situ and introduce permanent measures. However, constant changes in construction sites makes it impossible to take permanent measures. Furthermore, works in construction sites have unavoidable risks by their nature. For example, working at a height comes with the risk of falling down. Even though it is possible to mitigate the risks, it is not possible to completely eliminate them. Therefore; it is not possible for a construction site to become completely hazard free, at least in the foreseeable future (Sousa, Almeida, & Dias, 2014). For these reasons, construction site workers have to adapt to work in hazardous situations to be able to prevent workplace accidents (Howell, Ballard, Abdelhamid, & Mitropoulos, 2002).

Fatality rates in construction industry show that the above-mentioned adaptation is not in a desirable state right now. Hundreds of workers die or become disabled because of occupational accidents each year in construction sites around the world (International Labour Organization [ILO], 2019). Furthermore, thousands of workdays are lost due to less severe accidents (Sosyal Güvenlik Kurumu [SGK], 2017). In addition to humanitarian aspects, these accidents cost millions of dollars each year (Heinrich & Ainsworth, 1930; Waehrer, Dong, Miller, Haile, & Men, 2007). This situation has considerable negative results both socially and economically. It is clear that more effort is needed on this topic.

Hazard recognition is one of the major elements of any kind of safety management (Albert, Hallowell, Skaggs, & Kleiner, 2017). Considering the impossibility of providing hazard free construction sites as explained, hazard recognition skills become even more important for construction site workers. Workers need to recognize the existing hazards to be able to mitigate the risk. Yet still, even the most experienced workers fail to successfully recognize all the hazards (Perlman, Sacks, & Barak, 2014). Therefore; two main motivational factors for this study are (1) very high accident rates in construction sites and the severity of their results, and (2) the need for improvement in hazard recognition capabilities of construction site workers.

A possible enhancement of adaptation of construction site workers to hazardous situations can be achieved through improvement of hazard recognition skills of them. Of course, this improvement requires a deep understanding of recognition process. However, safety science has a core dilemma in itself. The very reason it exists is unsafe conditions in any environment and the need for increased safety in these conditions. On the other hand, the same unsafe conditions also make it very hard to conduct experiments on the safety problems. Therefore, the number of empirical studies remains rather limited. As a result, there is a lack of systematical correlational evidence on safety subjects (Hopkins, 2014).

This thesis focuses on this gap. The aim is to contribute to the enhancement of our understanding on the hazard recognition process of construction site workers. For this purpose, eye movements and push-button responses of subjects during the hazard recognition process are examined. Above mentioned dilemma is solved via virtual environments. Detailed explanations of these metrics and systems are given in "3.2.Methodology" section of this thesis.

1.3. Aim & Objectives

The main aim of this study is to deepen our knowledge on hazard recognition capabilities of construction site workers to contribute to the effort on lowering the accident rates in construction sites. Objectives toward this aim are listed as:

- Designing a feasible and ethical research methodology for construction worker safety behavior researches
- Examining the effect of level of education and level of experience on hazard recognition performance
- Exploring potential uses of virtual reality head mounted displays (HMD) and eye trackers in construction safety studies

1.4. Research Questions

This study focuses on four questions:

- Q1: Does rate of recognition of hazards increase as the level of formal education increase?
- Q2: Does rate of recognition of hazards increase as the level of experience increase?
- Q3: Does hazard recognition speed increase as the level of formal education increase?
- Q4: Does hazard recognition speed increase as the level of experience increase?

Therefore, the null hypotheses are:

- $H_0$1: Rate of recognition of hazards is not affected by level of education.
- $H_0$2: Rate of recognition of hazards is not affected by level of experience.
- $H_0$3: Hazard recognition speed is not affected by level of education.

- $H_0$4: Hazard recognition speed is not affected by level of experience.

Accordingly, the alternative hypotheses are:

- H_a1: Rate of recognition of hazards increases as level of education increase.
- H_a2: Rate of recognition of hazards increases as level of experience increase.
- H_a3: Hazard recognition speed increases as level of education increase.
- H_a4: Hazard recognition speed increases as level of experience increase.

1.5. Procedure

This study consists of four main phases. These phases are; literature review, experiment design, experiment deployment, and analyses/discussion of the results.

During the literature review; Web of Science, Scopus, and Google Scholar databases were searched on different combinations of the key phrases "construction safety", "hazard recognition/identification/detection", "(immersive) virtual reality", "eye tracking/movements", and "safety management". More than 150 relevant publications were selected, categorized, and reviewed. Information on the gaps in the literature are identified and theoretical base of this study was structured with the help of the reviewed studies.

The second phase is the experiment design phase. A virtual environment that represents two different scenes in a construction site and a training scene were created. One of the scenes is an indoor scene and the other one is an outdoor scene. The virtual construction site and majority of the objects used in the site were modelled in SketchUp. Some of the objects were downloaded from Unity Asset Store and modified. The virtual environment was created and arranged for experiments in Unity, a widely used software tool for game design.

The third phase is the experiment deployment. The experiments were carried out with twenty nine construction professionals with varied levels of formal education and work experience. Each subject attended the experiment individually. After instructions and a short questionnaire, the equipment was worn by the subject and the experiment routine was started by a researcher. The experiment was initiated with a training session and after its completion, the subjects were asked to push a button when they saw a hazard while their eye movements were recorded. When the experiment was completed, the subjects were asked to fill in a short questionnaire to evaluate the experiment design.

The fourth and final phase is the analyses and discussion of the results. In this phase; data from eye tracker and push-button feedback were superimposed on a timeline for each subject. Qualitative and quantitative analyses were conducted on these data. Outcomes of the analyses were discussed. Additionally, feedback gathered from the subjects via questionnaire and post-experiment interviews have been considered for future refinements and improvements of the experiments design.

1.6. Thesis Disposition

This thesis is organized in five chapters. The first one is the Introduction, which includes the introduction thesis and draws a framework for the research.

The second chapter is Literature Review. This review starts with basic information about construction safety. After that, it covers relationship between construction safety and hazard recognition in terms of role and importance of hazard recognition in preventing accidents. Recent studies about measuring hazard recognition skills of workers are also presented. The review continues with studies about usage of digital technologies on the field of construction safety. After that, virtual reality (VR) systems and eye tracking technology is reviewed. They are explained briefly and studies on their usage in architecture, engineering, and construction (AEC) industry; safety studies; and hazard recognition are reviewed. Moreover, eye tracking in immersive VR systems is reviewed in terms of hardware and existing studies. The review is concluded with a critical analysis of the literature.

The third chapter of the thesis is Methodology. Materials and methods used for the research are described in detail in this chapter. Selection and features of the research population are described. Tools and technologies have been used for the research are explained. Design of the experiment setup in virtual and real worlds are told in detail. Data collection methods are indicated. Information about how the experiments are conducted is given.

The fourth chapter is the Results. In this chapter the data gathered from the experiments and several analyses are presented. These results and analyses are interpreted and discussed. Research questions are answered and hypotheses are tested. Results from the analyses are compared with previous studies. Moreover, the validity of the experiment setup and HMDs as construction safety research tools are discussed.

The fifth and the final chapter is the Conclusions. This chapter includes a brief summary of the study and inferences of it. Limitations are mentioned and recommendations for further research are given in this last chapter.

CHAPTER 2

LITERATURE REVIEW

2.1. Chapter Disposition

This chapter includes the relevant information from the scientific literature. The chapter contains five topics which are “2.1. Construction Safety”, “2.2. Virtual Reality Systems”, “ 2.3. Eye Tracking Technology”, “2.4. Eye Tracking in Virtual Reality”, and “2.5. Critical Analysis of the Literature”.

Construction Safety topic gives general information about construction safety and gets into more detail under its subtopics of “2.1.1. Hazard Recognition”, and “2.1.2. Digital Technologies in Construction Safety”. The second topic, “2.2. Virtual Reality Systems” covers prominent studies in literature under subtopics of “2.2.1. Virtual Reality in Architecture, Engineering, & Construction Sector”, “2.2.2. Virtual Reality in Safety Studies”, and “2.2.3. Virtual Reality in Hazard Recognition”. The topic also includes general information about virtual reality systems. After that there is “2.3. Eye Tracking Technology” topic. It is comprised of general information about eye tracking and three subtopics which are “2.3.1 Eye Tracking in Architecture, Engineering, & Construction Sector”, “2.3.2. Eye Tracking in Safety Studies”, and “2.3.3. Eye Tracking in Hazard Recognition”. The fourth topic is “2.4. Eye Tracking in Virtual Reality”. This topic briefly mentions the hardware that enables eye tracking in VR. Also, some relevant studies are briefly mentioned. The final topic of this chapter is “2.5. Critical Analysis of the Literature.” In this topic, existing trends, point of views, strengths and weaknesses of the literature is analyzed and discussed.

2.2. Construction Safety

Construction sites are dangerous. There are hundreds of journal articles opening with this premise and there are all kinds of supporting evidence for it. If you are a construction site worker in Europe, your probability to die because of an occupational accident is three and a half times higher than the average of other sectors (EuroStat, 2019a). The situation is not so different in other parts of the world as the risk is 4-fold higher in Argentina, 14-fold higher in Israel, 4.5-fold higher in Japan, 3-fold higher in USA, and 3.5-fold higher in Egypt (ILO, 2019). Not only fatality rates but also the rate of accidents with high severity is also considerable. In Europe, construction sites are responsible for 14% of all accidents resulted with amputation (EuroStat, 2019b). Economic damage is another important aspect of occupational accidents. Comprehensive studies show that, billions of dollars are lost due to occupational accidents in construction sites every year (Heinrich & Ainsworth, 1930; Waehrer et al., 2007; Yılmaz & Kanıt, 2018). Even though many studies have been conducted and many others are being carried out, construction industry is still far behind of others in terms of prevention of severe occupational accidents and further research is required in the area (Sousa et al., 2014; Z. Zhou, Goh, & Li, 2015).

2.2.1. Hazard Recognition

Hazard recognition is a vital part of operational safety in many different areas not only in construction sites (Abbas, Mneymneh, & Khoury, 2018) but also in traffic (Harbeck, Glendon, & Hine, 2017), aerospace industry (Jiang, Li, & Tao, 2016), energy plants (Paltrinieri, Tugnoli, & Cozzani, 2015) and many other fields. To be able to mitigate the risks caused by a hazard, a worker first must be able to realize and recognize the hazard. The very first step of risk management is hazard recognition (Moreno & Cozzani, 2017). Consequences of unrecognized hazards could be extremely disastrous (Albert et al., 2017).

Due to their ever changing environment and nature of the works involved in construction projects; construction sites cannot be totally hazard free (Sousa et al., 2014). Hazardous nature of construction sites is a generally accepted condition among the practitioners and academia (Swuste, Frijters, & Guldenmund, 2012). Furthermore, even construction project features that seem unrelated at the first sight like site restrictions, time limitations, subcontracting methods, procurement methods, or design complexity contribute generation of hazardous conditions and makes it even harder to eliminate hazards (Manu, Ankrah, Proverbs, & Suresh, 2010). Considering it is not possible to eliminate all hazards in a construction site, workers' ability to detect the hazards in time and act accordingly becomes very important to prevent accidents (Fang & Cho, 2015). Even the most successful safety management examples are not capable of providing a totally hazard free workspace for construction workers; thus, in order to be safe, construction site workers have to learn how to work in acceptably hazardous environments (Howell et al., 2002).

Even though the relationship between construction safety and hazard recognition is clear, number of empirical studies which focus on measuring hazard recognition skills of construction site workers are very limited (Dzeng, Lin, & Fang, 2016). Two main reasons for this gap might be (1) the very reasons make a construction site a dangerous place for workers also make them unsuitable places for scientific studies; and (2) a lack of a practical methodology for measuring hazard recognition skills.

A very comprehensive series of studies firstly introduced and tested three novel strategies to improve hazard recognition skills by a team of researchers; (1) a technique for pre-task safety meetings (Albert, Hallowell, & Kleiner, 2014a), (2) a serious game named SAVES (Albert, Hallowell, Kleiner, Chen, & Golparvar-Fard, 2014), and (3) a digital site display (Albert, Hallowell, & Kleiner, 2014b). After field observations of more than 3000 hours, the research team concluded even though their implementations significantly increased the rate of identification of hazards, the rate was still far from satisfactory and further improvements were needed; moreover, the authors noted that the greatest limitation of their researches is difficulty of the observations in site and limited validity of sole observation and they point out that improved methodologies in this regard would be beneficial (Albert et al., 2017).

Scientific literature related to hazard recognition is reviewed more comprehensively in upcoming topics.

2.2.2. Digital Technologies in Construction Safety

The attention of academia on construction safety has been very limited until 2002. In any year before 2002 there were no more than 10 construction safety studies; however, as shown in Figure 2.1, a rapid and steady increase has started after 2002 (Z. Zhou et al., 2015). Similarly, total number of studies that adopt digital technologies between 1986 and 2002 was only 24; on the other hand, after 2002 and especially between 2008 and 2012 (Table 2.1), and after 2012 (Figure 2.2) number of these studies became significantly higher and digital technologies became increasingly important tools for construction safety studies (Golizadeh, Hon, Drogemuller, & Hosseini, 2018; Z. Zhou, Irizarry, & Li, 2013)

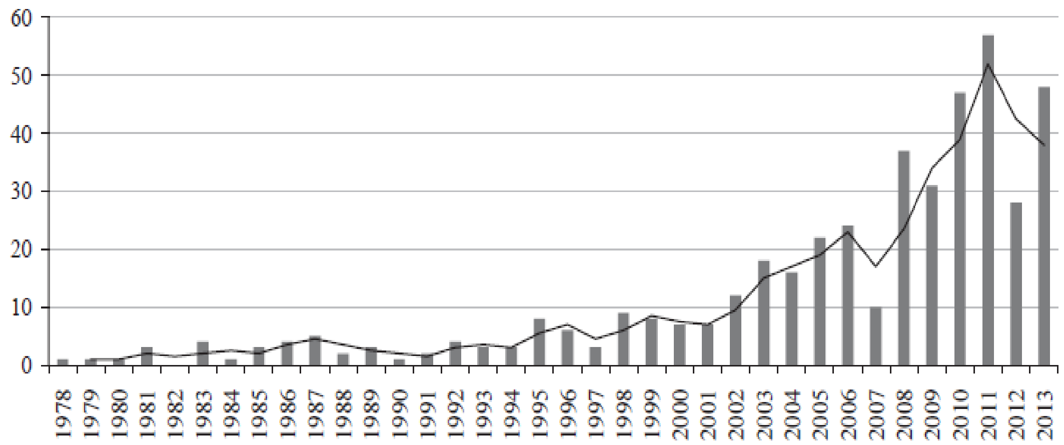

Figure 2.1. Number of construction safety publications according to year

(Source: Z. Zhou et al., 2015)

Table 2.1. *Number of construction safety studies that use digital technologies from 1986 to 2012*

Years	*Number*
1986	1
1987	0
1988	0
1989	1
1990	1
1991	0
1992	3
1993	0
1994	4
1995	3
1996	3
1997	1
1998	1
1999	2
2000	4
2001	0
2002	5
2003	2
2004	1
2005	4
2006	5
2007	4
2008	12
2009	6
2010	17
2011	20
2012	19

Source: (Z. Zhou et al., 2013)

These increases might be related to increased awareness on occupational safety, new governmental regulations, and increased availability of digital technologies in last two decades.

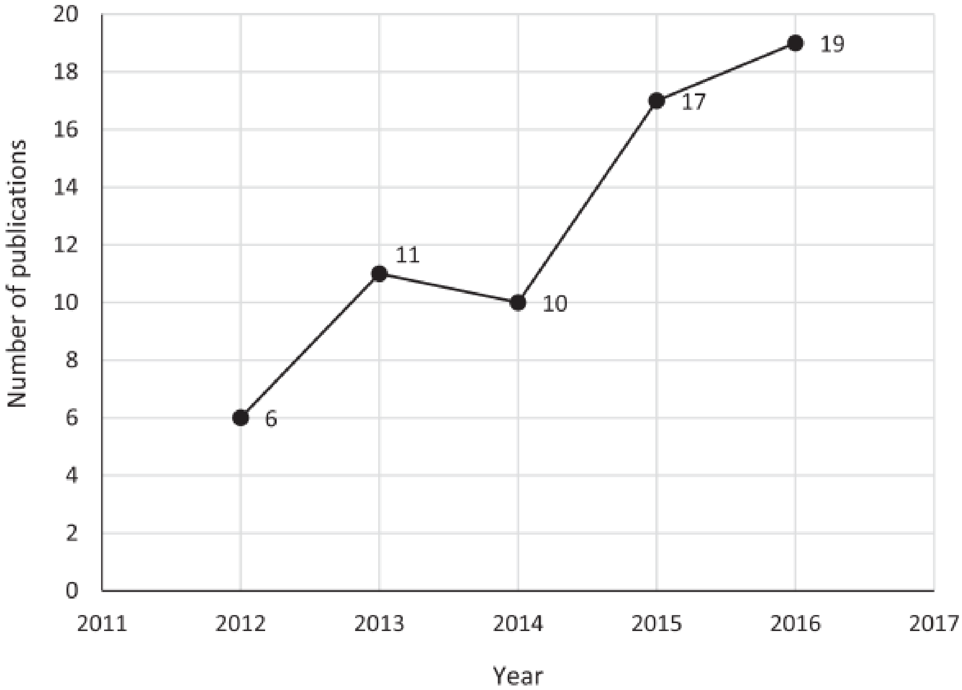

Figure 2.2. Number of construction safety studies that use digital technologies from 2012 to 2016 (Source: Golizadeh et al., 2018)

A review study by W. Zhou, Whyte, and Sacks (2012) states that many different types of digital technologies has been used by construction safety researchers. They group them according to their approaches (Table 2.2). It should be noted that, even though their article does not mention any eye tracking studies, a small number of studies were conducted after the publication of this review study.

Table 2.2. *Types of technologies/approaches used by construction safety studies*

Tool/Project	*Approach*	*Technology*
H&S competence assessment	Assessment of duty-holders competence	Online databases
Construction Safety and Health Monitoring System	Monitor project performance	Online databases
Design for Safety Process	Simulation and review of construction process for design related safety issues	VR
Virtual Construction Laboratory	Simulation and review of innovative processes	VR
MBA-black building	Safety planning considering environmental conditions	GIS, entity-based 4D CAD
Decision Support System	Assist monitoring and control of operations	GIS
Patterns Execution and Critical Analysis of Site Space Organization	Critical space–time analysis	Entity-based 4D CAD
Rule-based 4D system	Rule-based	Entity-based 4D CAD
Mäntylinna building	Visualization	BIM-based 4D CAD
Safety Analysis of Building in Construction	Structural analysis	BIM-based 4D CAD
Construction Hazard Assessment with Spatial and Temporal Exposure	Construction job safety analysis and evaluation of operational risk levels	Entity-based 4D CAD
Computer image generation for job simulation	Simulation for job safety analysis	VR
Automated obstacle avoidance support system	Sparse point cloud	Laser range scanning technology
Real-time proximity and alert system	Generate active warning or feedback in real time	Wireless & RFID communication
WiFi-based indoor positioning system	Indoor positioning	Wireless & RFID communication
Video rate range imaging system	Detect, model, and track the position of static and moving obstacles	Video laser range scanning technology

(Adapted from: W. Zhou et al., 2012)

2.3. Virtual Reality Systems

The term Virtual Reality (VR) was first offered in 1989 by Jaron Janier who was CEO of VPL research, a VR systems manufacturer (Krueger, 1991). Even though it is possible to use the term even for computer screens, since they are also virtual realities; the generally accepted definition of the term includes immersive environments based on HMDs, immersive screens, body tracking systems and binaural sound systems which generates illusion of being inside of an artificial environment rather than being an external observer of that environment (Steuer, 1992). The main purpose of VR is to generate a medium called virtual world or virtual environment in which people can share a very wide spectrum of experiences. Moreover, just like virtual reality, the term virtual environment can also be used for worlds in other digital means or even novels (Craig, Sherman, & Will, 2009). Therefore, it is beneficial to indicate that in this thesis the term VR is used for defining immersive systems and the term virtual environments is used for defining the computer-generated environment that provides a digital space for VR experiences.

Two main methods of generating visual stimuli in VR are HMDs and immersive screens (Loomis, Blascovich, & Beall, 1999). An HMD is a dual screen display that is attached to the head of the users, placed in front of their eyes (Craig et al., 2009) These screens show slightly different views of the virtual environment to provide stereoscopic visual stimuli for increased sense of presence. The first VR system was an HMD by Philco Corporation which is called The Headsight. The Headsight was invented in 1961 and it was followed by the Sword of Damocles by Ivan Sutherland in 1968 (Singh & Singh, 2017). Sword of Damocles HMD had a 40° field of view and a crude optical system. The system, shown in Figure 2.3, was too heavy that it had to be hung on the ceiling (Sutherland, 1968). These frontier applications were followed by several other systems, which were mainly used for military purposes, pilot education, and astronaut education; but their technical capacities were very limited and their costs were too high to become widespread (Aimakhanova, 2014).

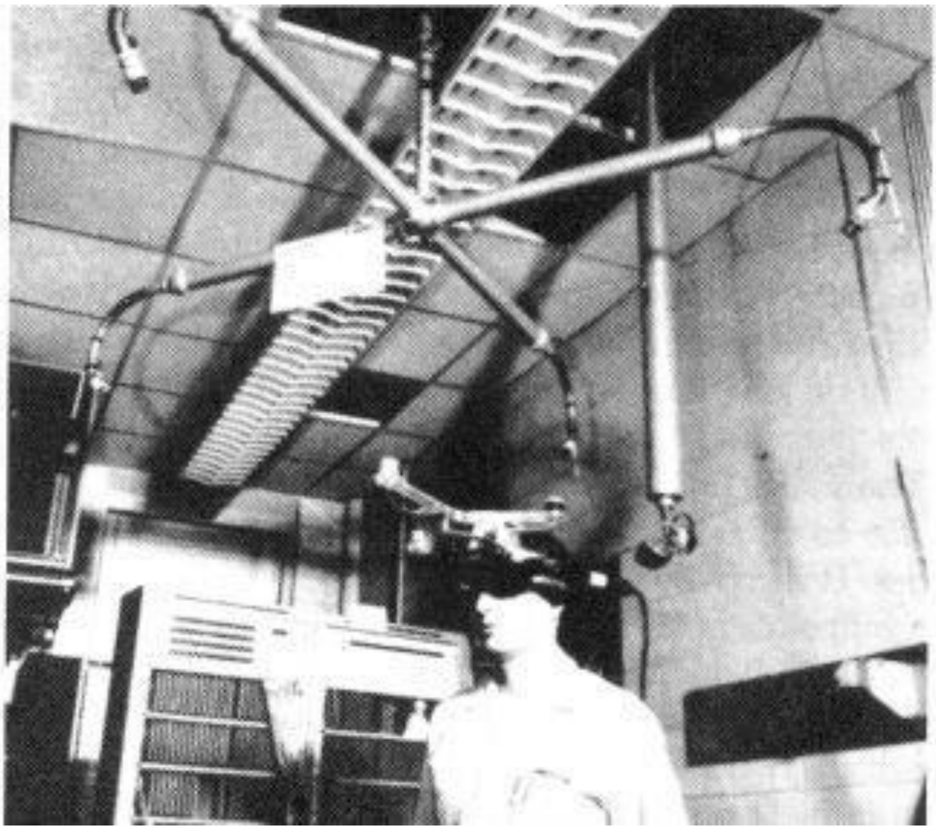

Figure 2.3. Sword of Damocles HMD VR system

(Source: Sutherland, 1968)

Even though the early versions of HMDs could not become widespread research tools or consumer electronics; there has been a reemergence of VR systems with the introduction of the new generation of HMDs in recent years. This new generation HMDs have arguably lower costs and higher portability than the previous ones (Beattie, Horan, & McKenzie, 2015). This new generation also has advanced technological features like built-in head tracking systems, much higher resolution, wider field of view, and integrated sound systems. (Anthes, Garcia-Hernandez, Wiedemann, & Kranzlmuller, 2016). Therefore, they are capable of providing requirements of generating a VR (visual stimuli, body tracking, and binaural sound systems) even by themselves, without any additional equipment.

The other VR type is immersive screen. The most prominent immersive screens are CAVE systems. CAVE is box shaped small room. Virtual environment is projected to its walls via multiple projectors and stereo shuttered glasses are used to mimic depth (3D). The visuals change in real time according to viewing angle of the user to provide immersiveness (Cruz-Neira, Sandin, & DeFanti, 1993). According to the first CAVE designers the name CAVE is both acronym of CAVE automatic Virtual Environment and a reference to Plato's cave allegory (Cruz-Neira et al., 1993). The walls of the cave are translucent and visuals are projected from the outside as seen in the Figure 2.4. Not only CAVEs but also large curved screens called dome screens are considered as VR systems and used for providing immersive virtual environments (Meir, Parmet, & Oron-Gilad, 2013).

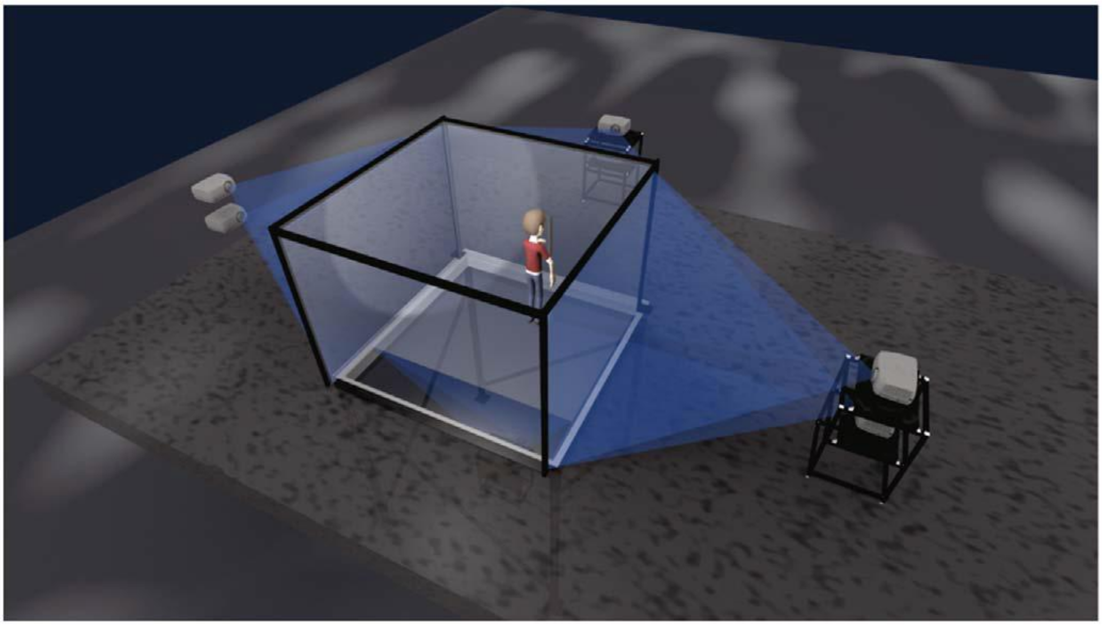

Figure 2.4. A three sided typical CAVE system.

(Source: Meißner et al., 2017)

2.3.1. Virtual Reality in Hazard Recognition Studies

A recent review names hazard recognition as one of the most important study areas for VR in construction studies, yet still number of studies are limited (Li, Yi, Chi, Wang, & Chan, 2018). Furthermore, some of the studies mentioned in this review use methodologies that cannot be considered as VR in recent literature since they lack required level of immersiveness. Hence there is a vast potential in this area.

In an attempt to test usability and validity of VR systems as a means for hazard recognition and risk perception measurement in construction site workers and to understand differences of capabilities of different populations such as construction site supervisors, safety directors and inexperienced engineering students; Perlman, Sacks, and Barak (2014) compared traditional design drawings/site photographs and a CAVE system. The authors note that VR offers a unique and practical solution to conduct experiments in hazardous sites and confirms its validity as a hazard recognition study tool according to the results of their experiments. The results show that the group that inspected the construction site via VR were able to detect hazard more efficiently than those who inspected via design drawings and site photographs. Moreover, even though the supervisors have much more experience than the students, they were not able to detect significantly more hazards then the students. The article also states that the results may be affected by the locality of the population and suggests further research in different locations.

In another experiment that used a CAVE system, Sacks et al. (2015) proposes VR to be used as a medium for collaboration of designers for construction site safety consideration. Even though the main purpose is to test willingness of the designers to make changes in the design for a safer construction, the authors also were able to measure hazard recognition capabilities of designers in virtual environments.

There are also several hazard recognition studies that use non-immersive VR systems; as mentioned earlier, it is possible to call a system VR even when the virtual environment is experienced via standard computer screens. However, this thesis refers

VR as immersive systems like HMDs or CAVEs; thus, screen-based VR studies are out of scope of this review. For example, Park and Kim (2013) introduces an interface called SMVS which provides improved communication between safety managers, construction managers and the workers and users interact with the system via screens. Another example is a study in which researchers design a system for improved recognition of hazard in the pre-construction stage and this system is interacted via screens too (Hadikusumo & Rowlinson, 2002).

Naturally, construction is not the only field that safety researchers use VR (Özel & Pekeriçli, 2018b). For example; Meir, Oron-Gilad, and Parmet (2015) used an immersive dome screen to understand hazard recognition skills of pedestrian children of different ages to be able to understand the development of these skills throughout time. In another study, effectiveness of VR systems in hazard recognition and risk assessment in manufacturing industry were examined (Puschmann, Horlitz, Wittstock, & Schütz, 2016). The authors concluded that VR systems offer a successful alternative to document based methods.

2.3.2. Virtual Reality in Other Safety Studies

VR systems have been used in safety studies in many fields including production (Reis, Duarte, & Rebelo, 2015) mining (Grabowski & Jankowski, 2015), nuclear plant safety (Henrique da Silva et al., 2015), and chemical industry (Manca, Brambilla, & Colombo, 2013).

In a study on construction safety; Irizarry and Abraham (2005) used a CAVE based VR for training of the steel erection workers. The authors underline that VR gives chance to gain experience of the most hazardous conditions without any risk. They also state otherwise impossible level of controllability of variables is possible for researchers with VR systems. The article also indicates that it is possible to use the system they have designed to evaluate the effect of different conditions on performance and safety of the workers. A similar approach was adapted by Building Management Simulation Centre in Netherlands where a curved immersive screen is used for training users in a virtual construction environment (De Vries, Verhagen, & Jessurun, 2004).

Sacks et al. (2015) conducted a series of experiments on architects via a CAVE system in several virtual environments to test feasibility of designing for safer construction sites. The research investigated the capability and willingness of designers to contribute to safety management of construction sites.

A mixed reality system which uses an HMD to provide realistic visual stimuli in combination with physical objects to provide tactile stimuli to generate a realistic training simulator for skilled workers is introduced in a recent article (Bosché, Abdel-Wahab, & Carozza, 2016). The authors indicate that there is a gap between traditional training methods and real construction site and VR based training methods can help narrowing this gap.

2.3.3. Virtual Reality in Architecture, Engineering, and Construction Industry

Visuals have always been a very crucial tool for humankind to think and understand the world around, and they are even more important for architects since visuals are irreplaceable tools for communicating with both themselves and the other people (Laseau, 2001). One of the biggest challenges for an architect is to understand the effects of a design on its users. It is a very serious problem for even the most experienced of architects (Kalay, 2005). Moreover, trying to communicate about 3D space via 2D media like computer screens or drawings results a conflict and disconnectedness (Kwon, Choi, Lee, & Chai, 2005). A study reported that their experiments showed subjects ability to understand 3D qualities of spaces are limited when they interact with the model via computer screens (Sun, Fukuda, Tokuhara, & Yabuki, 2014). Moreover, our current perception of human behavior in a building before its construction is merely based on extrapolation, method of predicting performance of the design based on previous examples, and considering every design problem is unique, extrapolation method causes a gap between the problem and the solution in most situations (Hong, Schaumann, & Kalay, 2016).

VR may offer some solutions to above mentioned problems. Du, Zou, Shi, and Zhao, (2018) noted that VR is getting more and more attention from AEC industry and it has a good potential to improve workflows. They introduced their system called BVRS which is an automation tool for instant real time synchronization between BIM models and virtual reality. The authors point that even though the system needs further improvements, their initial tests show the system provides instant conversion of BIM models into virtual environments so that stakeholders of a project can communicate efficiently.

Paes, Arantes, and Irizarry (2017) argue that what would justify widespread usage of immersive VR in AEC industry is its superiority to non-immersive digital systems in supporting design practices. To be able to show the validity of their claim, they designed an experiment to compare spatial perception of subject via a desktop system and a VR system. The results of the experiments on people from different ages and different professions showed that subjects' spatial perceptions are better and levels of presence are higher in VR systems.

Another study tested validity of VR to evaluate the usability of patient rooms in hospitals (Dunston, Arns, Mcglothlin, Lasker, & Kushner, 2011). The researchers conducted experiments with a physical model of a patient room and a CAVE based virtual room. The results show that the virtual room has enough fidelity to be used for testing usability of patient rooms. The authors indicate VR could be a practical and cost-efficient way of testing architectural design alternatives.

In a study with the main purpose of understanding the effect of atria on spatial exploration of users in a museum building, similar experiments were conducted in both real life and in an HMD based VR system. The authors tell that there is a very high correlation between the results obtained from two experiments (Lazaridou & Psarra, 2017). According to these results the research team suggests that VR systems are valid tools for architectural studies.

There are also some VR design tools that provide immersive design environments. These environments have reported to have certain positive effects on the design process which are enriched inspiration and generation, efficient and enjoyable design experience, better delivery of semantic and emotional attributes to the end-user, and increased originality (Rieuf, Bouchard, Meyrueis, & Omhover, 2017).

2.4. Eye Tracking Technology

In contemporary literature, eye tracking is noted as the technology of determining eye movements of a subject with information gathered via electronic devices (Duchowski, 2007). Even though there are a number of different technologies, pupil-corneal reflection method, which is based on the fact that corneal reflection is always stationary while the pupil move and can be used as an anchor point to determine the gaze direction, is adopted by most of the eye tracking devices (Morimoto & Mimica, 2005). There are two basic states of an eye which eye trackers follow: fixations and saccades. Other measures are usually derivations of these two. Fixations are when pupil is stationary and focused, information is gathered during fixations; on the other hand, saccades are quick ballistic movements of the pupil and it is assumed that no information gathered during saccades (Palmer, 1999). Fixation location reveals focus of attention while fixation duration provides information about cognitive load (Tsai, Hou, Lai, Liu, & Yang, 2012). It is a valid methodology for estimation of visual focus that is used widely for scientific researches (Krucien, Ryan, & Hermens, 2017) in fields like customer preferences and advertising (Balcombe, Fraser, Williams, & McSorley, 2017), driver focus (Topolšek, Areh, & Cvahte, 2016), gaming (Polonio, Di Guida, & Coricelli, 2015), or user experience design (Tonbuloğlu, 2013).

2.4.1. Eye Tracking in Hazard Recognition Studies

Validity as an attention measuring tool of eye tracking over other methods are mentioned in several studies (Di Stasi, Contreras, Cándido, Cañas, & Catena, 2011; Khan et al., 2012; Popien, Frayn, von Ranson, & Sears, 2015). Eye tracking has three main advantages: (1) it does not distract the subjects, (2) data gathered with eye tracking is less likely to be biased, and (3) it is possible to detect points of attention that the subjects themselves are not aware of (Djamasbi & Hall-Phillips, 2014). Moreover, Thomas & Lleras (2007) reported their study on problem solving shows that there is an implicit link between eye movement patterns and spatial cognition and it is possible to improve task performance by manipulating eye movements.

One of the frontier studies about usage of eye tracking for hazard recognition in construction sites notes that; even though importance of hazard recognition in construction safety is underlined by many studies, there is a gap in the literature in empirical studies about measurement of hazard recognition skill (Sneha, Hasanzadeh, Esmaeili, Dodd, & Fardhosseini, 2015). The same research team (minus Sneha) tells in another article that their field experiments and comparison of results from these experiment with traditional tests show that eye-tracking is a valid tool for measurement of situational awareness in a construction site (Hasanzadeh, Esmaeili, & Dodd, 2016). Additionally, authors note eye trackers gather data without distracting the subjects. The second study also gives results showing how experience and perception of the situation affect eye movement patterns of workers.

To investigate the relationship between risk perception and gaze patterns of construction site workers, Habibnezhad et al. (2016) formed two groups of workers with high and low risk perception. Construction site images with hazard were shown to the groups and their eye movements were recorded. The results showed that there were significant differences in the gaze patterns of workers with different risk perceptions.

Hazard recognition is vital for construction safety, yet still current methods does not allow transfer of hazard recognition expertise from experienced workers to less experienced ones. Dzeng et al. (2016) suggest usage of eye trackers as a means for this transfer. For this purpose, the authors prepared an experiment setup which includes 2D still images that contain several hazards selected as a result of examination of 350 construction site accidents. These hazards were grouped as obvious and non-obvious. Subjects were divided into two groups according to their level of experience and asked to detect hazards in those images. Meanwhile, an eye tracker was used to record the eye movements of the subjects. The results show that work experience may not increase hazard recognition accuracy and miss rate since there is not a significant difference; however experienced workers are faster to detect hazards. The article also mentions that the prices of eye trackers have become affordable recently and their wide spread usage could be feasible.

Another article also underlines importance of the hazard recognition in construction safety and lack of a reliable method for measuring hazard detecting skills of workers (Fang & Cho, 2015). The study introduces a different method for gaze tracking. Instead of using an eye tracker, this method tracks movement of the head and its velocity to approximate where the subject is looking. Initial test of the proposed system with gaze tracking during simple abstract tasks were successful; however, further improvements are required.

After a series of eye tracking experiments with construction site photos and images artificially created according to these photos; Pinheiro, Pradhananga, Jianu, and Orabi (2016) claim eye-tracking could be an efficient means for evaluating effects of safety training on construction workers and develop better accident prevention strategies. Moreover, authors also state that data from eye trackers make way for deeper understanding of safety perception of construction workers. The article also points the need for further research with 3D visuals and additional data gathering techniques.

Fujita, Nakamura, and Kushiro (2017) have developed a video and eye tracking based hazard recognition training tool for construction workers. The authors claimed that this interactive and dynamic training tool would perform better in training than traditional methods. Experiments on experienced and novice workers were conducted with the tool and the results were discussed.

In a recent study, Jeelani, Han, & Albert (2018) have developed a system that uses a mobile eye tracker to help safety training and safety management. The system localizes the workers and their gazes in three-dimensional reconstruction of the construction site and analyzes it to determine visual attention of the users. This data is compared to predefined hazards in the site, so that workers' behavior can be better understood and personal safety feedback can be provided.

In addition to construction safety, eye trackers are beeing used on other fields for hazard recognition studies like road safety (Chapman, Underwood, & Roberts, 2002; Hosking, Liu, & Bayly, 2010). Di Stasi et al. (2011) state that eye tracking technology have been used successfully for measuring differences of hazard recognition skills of experienced and novice motorcycle riders and improvements in their recognition skills after a training program; furthermore, authors suggest it to become a part of road safety trainings. Another study claims that experience have positive effect on recognition of hazard on traffic and it could be related to their different eye scan patterns; moreover, these scan paths may be used for safety training (Hosking et al., 2010).

2.4.2. Eye Tracking in Other Safety Studies

There are several studies which have employed eye tracking technology successfully in safety related studies and confirmed its validation as a safety study tool. In one example eye tracking used along with 4 psychology tests to compare different interfaces for petrochemical plant safety monitoring (Ikuma, Harvey, Taylor, & Handal, 2014). Sharma, Bhavsar, Srinivasan, and Srinivasan (2016) adopted eye tracking technology successfully to acquire data about cognitive abilities of control room operators in chemical plants. Similarly, another study adopted remote eye trackers to be able to gather data to use in prediction of human error in chemical plant monitoring; so that it would be possible to act proactively against accidents or develop enhanced training methods for the operators (Kodappully, Srinivasan, & Srinivasan, 2016).

Another study employs eye trackers to collect data about employer attention like above mentioned studies but in healthcare sector (Henneman et al., 2017). The study tested if there is a relation between eye movement patterns of nurses and their surveillance abilities with the help of a head mounted eye tracker. The results show that there is a positive correlation between fixation durations and surveillance quality of nurses.

Seneviratne and Molesworth (2015) successfully used eye tracking methodology to measure effectiveness of employing different strategies like include humor or celebrities in preflight safety briefings. The data gathered with eye trackers analyzed in terms of total observation time percentage, first look away, and total look away number. This information was used for determining effectiveness of different strategies on groups with different gender and flight experience.

Road safety is another field that eye trackers have been used efficiently. In one study an eye tracker system with three cameras had been mounted on front panel of a car to be able check effects of different lighting conditions on highway tunnel safety (He, Liang, Pan, Wang, & Cui, 2017). The research team used the information gathered via eye trackers to analyze level of tension and visual workload of the drivers to understand their reactions to lighting conditions. Another study in road safety field focus on hazard reaction time of drivers and their mood (Zimasa, Jamson, & Henson, 2017). The research team analyzed data from a head mounted eye tracker and concluded that sadness significantly increases hazard reaction time.

2.4.3. Eye Tracking in Architecture, Engineering, & Construction

Number of studies that adopt eye tracking technology on AEC industry is rather low. Knowledge about this technology and recognition on its potential uses are limited (Yousefi, Karan, Mohammadpour, & Asadi, 2015). The literature can be roughly divided into two groups: studies that focus on visual focus of professionals or laymen on built environment and their differences; and studies that try to measure lighting comfort with eye tracking parameters such as pupil size, openness of the eye, and direction of gaze (Özel & Pekeriçli, 2018a).

In one of the earliest studies that belongs to the above mentioned first group; Weber, Choi, and Stark (2002) conducted a series of experiments with simple architectural models of rooms with windows, columns, and stairs. The research team prepared different arrangements of architectural elements in the room models and examined the differences they resulted in gaze patterns of the viewers. Differences between the actual models and their photographs were also discussed. The study revealed several preferences while viewing the models like primacy of left visual field or preference on horizontal and vertical elements. However, this is a very early study conducted with an invasive setup including a headrest, chin rest, and a bite bar.

10 years later; in a similar study by Hasse and Weber (2012) façade photographs of fourteen buildings and their digitally altered versions were shown to architects and laymen for them to evaluate the façades in terms of beauty and balance. According to the results, researchers investigated the relationship between perceived beauty, balance of mass composition, symmetry of the façade and eye movements of the viewers. The study discussed effects of symmetry on how the façades are viewed and effects of placement of façade elements on perceived balance.

In another similar study architectural photos/three dimensional drawings and their digitally manipulated counterparts were used for testing the effects of architectural elements such as stairs, signboards, people and patterns (Lee, Cinn, Yan, & Jung, 2015). Results of removal of the architectural elements, like significant decrease in horizontal saccades in columned spaces, are discussed in detail according to recorded gaze patterns of the subjects. It is also noted that architects focus on three dimensional qualities of the space more while laymen focus more on two dimensional qualities.

Cho (2016) carried out a series of experiments with a digitally generated detached house façade and recorded eye movements of subjects while viewing the façade. The author tells that viewers were mostly focused on openings (windows, doors). Also, it is indicated that reflective windows had gathered more attention. The results also suggested that there is no difference between gaze patterns of AEC professionals and laymen while viewing the house.

Iñarra Abad, Juan Vidal, Llinares Millán, and Guixeres Provinciale (2015), used three dimensional renderings from submissions to an architectural competition to analyze visual attention during architectural assessment. The researchers divided images into different areas as buildings, landscape, sky, ground, and people. The results showed that the buildings had gathered the most attention as expected and people were the second most viewed subjects even though they occupy relatively small areas in the images. Furthermore, fixation duration/area ratio is the highest on people, which underlines importance of images of people on perceiving the architectural spaces.

In a different approach (Ying Liu, Sun, Wang, & Malkawi, 2013) eye tracking was adopted to study effects of architectural cue on evacuation path finding of building occupants. Photos of junction points in the evacuation paths were shown to subjects and their gaze patterns were recorded. The results were analyzed in terms of the hierarchy of architectural cues. Moreover, effects of gender on way finding strategies were investigated.

Eye tracking is also used in landscape design researches (Nordh, Hagerhall, & Holmqvist, 2013). Goto et al. (2017) have built a Japanese garden at a hospital rooftop and measured biological responses of the Alzheimer’s disease patients including eye movements. Patients’ responses were compared to a standard rooftop garden. The results showed that visual interactions of the patients (along with the other biological responses) were significantly more positive when viewing the Japanese Garden.

Although the main function of the eye trackers is to determine the gaze direction, it is possible to track pupil size and eye openness via many eye tracker models. This feature is used for investigating effects of different lighting conditions on occupants.

Choi & Zhu (2015), used an eye tracker to record pupil sizes of subjects to understand whether the pupil size is an indicator of visual comfort. The experiments were conducted in a room where the lighting conditions were controlled by the researchers. The results show that eye tracking is a valid and reliable method for this purpose and can be used for academic studies and the application of smart lighting systems both.

Eye tracking is also used for glare assessment (Sarey Khanie, Stoll, Einhäuser, Wienold, & Andersen, 2017). The research team developed a glare prediction system based on gaze locations data from an eye tracker. The authors claim that using eye trackers instead of predicting the gaze locations could result significant improvements for glare assessment.

Another approach to detect glare problem with eye trackers were suggested by Yamin Garretón et al. (2015).The degree of eye openness was tested as glare indicator in a controlled office environment under daylight. The results showed that the data from degree of eye openness measurements are in parallel with existing glare prediction models and highly reliable.

Other than above mentioned two groups there are a small number of studies that adopts eye tracking as a drafting tool. A study (Jowers, Prats, McKay, & Garner, 2013) that benefits from eye trackers along with mouse and keyboard for drafting could be given as an example. The system uses a pre-defined library of geometric shapes to support shape exploration process of the users. The paper suggests that the system provides a flexible and dynamic geometric exploration process to the designers. The authors have indicated that the system worked successfully most of the time and the responses of the participants were positive.

2.5. Eye Tracking in Immersive Virtual Reality

Eye tracking in immersive VR is a rather unexplored area, especially for construction safety studies. Even though there are several studies that made use of eye trackers along with VR systems, none of them is on construction safety. This could be related to lack of knowledge (Yousefi et al., 2015) and expertise in AEC researchers on eye tracking and low number of VR eye trackers.

There are two types of HMD based VR eye trackers. Integrated systems and add-ons. Integrated systems are HMD which have eye trackers directly built inside as a part of them. FOVE0, which is the first hardware of this kind, has appeared in 2016 (Anthes et al., 2016). Shortly after well-known eye tracker companies like Tobii and SMI released their own products. Since SMI is acquired by Apple Inc. in 2017 (Hackett, 2017), SMI products are not publicly available anymore. Moreover, technology companies like HTC and Qualcomm are planning to release their own eye tracking HMDs in near future.

The second type of eye trackers for HMDs is add-ons. They are sold separately from HMDs and required to be set up on the befitting HMD. HTC Vive and Oculus Rift add-ons by Pupil Labs, upgrade package for Rift by SMI, and eye tracking module for Vive by Shanghai Qingtech (Wu, 2018) are examples of these equipment.

The earliest study with combination of eye tracking technology and immersive VR systems is a human computer interaction study (Tanriverdi & Jacob, 2000). The research team merged Virtual i-Glasses HMD and ISCAN eye tracker to compare interaction with eye movements and interaction with finger pointing. The results showed that eye movement interactions were significantly faster than finger pointing in all objects and significantly accurate in distant objects. Moreover, majority of the subjects reported to tell they would prefer eye movement over finger pointing as interaction method. Another early study with a very similar setup is on aircraft inspection (Duchowski et al., 2000), in which the authors combined a Virtual Research V8 HMD with ISCAN head mounted eye tracker to track gaze of the subjects in a 3D model of an aircraft cargo bay for training purposes.

In a recent study, experiments were conducted in a real world supermarket setup and the virtual version the same supermarket to affirm validity of using eye tracking in HMDs (Siegrist et al., 2019). The authors note that there were no significant differences in behavior and eye movements of the subjects in two setups. Moreover, a pilot shopping behavior study were conducted with the same VR setup.

Another HMD - eye tracking study researched effects of different subway train interior designs on gaze locations of the subjects (Wu, 2018). The author underlined that this methodology is beneficial because it provides a strong immersion, it allows data collection implicitly, and it allows total control of variables.

Another possible way to use eye tracking in VR is to use immersive screens or CAVE systems along with mobile eye trackers. In a contemporary study, Meir, Parmet, and Oron-Gilad (2013) used a 180 degrees spherical screen with diameter of 7.50 meters and a head mounted eye tracker to assess decisions of adults and children on when to cross a road. A second study by the same research group used the same tools to measure skills of adults and children to detect road hazards from pedestrian point of view (Meir et al., 2015). The research team claims that the screen is large enough to provide immersiveness. Both studies show vulnerability of children to road hazards provide information about their perception of traffic.

With a similar approach Meißner, Pfeiffer, Pfeiffer, and Oppewal (2017) suggested using eye tracking in virtual environment in shopping studies. After extensively discussing positive and negative aspects of employing eye tracking technology in desktop, real life and VR; the authors pointed that eye tracking in virtual environment solves many problems of other methods. They claim that this method provides higher flexibility and control for experiments. The research team also conducted a pilot test for combination of eye tracking and VR systems with a CAVE and head mounted eye tracker and reported that results were successful.

As an alternative approach a recent study tries to predict gaze direction from head direction data, so that it would be possible to track eye movements in VR only with an HMD without an eye tracker (Fang & Cho, 2015). Even though early tests with simple abstract objects are fairly successful, it would be harder to implement the system to complex virtual environments. Moreover, Duchowski (2007) reports that a number of previous efforts on predicting gaze direction based on head movements were mostly inconclusive.

The number of studies that employ eye trackers in VR are rather limited, particularly in safety research. However, it is a newly emerging technology and there is rapid development. There are some new hardware offerings which has recently become available or will be available soon. It would be fair to expect to see more studies using these technologies together in near future.

2.6. Critical Analysis of the Literature

There are tens of scientific articles and statistical reports from all around the world stating the need for serious improvements in construction safety. Thousands of people die or get seriously injured. Billions of dollars are lost every year. Although hazard recognition is recognized as a vital part of any safety management approach (Abbas et al., 2018); even the most experienced and educated construction site workers cannot detect all possible hazards (Perlman et al., 2014). Further studies in this field would have a positive effect on this picture.

There is a lack of systematical correlational evidence in safety studies (Hopkins, 2014) and construction safety is no exception. VR could be capable of overcoming some of the ethical practical and financial problems that cause this gap. Yet still, more research is needed to understand full potential of VR for construction safety studies (Golizadeh et al., 2018). Moreover, hazard recognition studies can especially benefit from VR systems (Li et al., 2018).

There are also some limitation factors in existing studies on hazard recognition in construction safety. A common problem in many studies is the low level of visual fidelity. Fidelity is a crucial aspect of a virtual environment. A low visual fidelity virtual environment would fall short on successfully representing the reality. Level of detail in the modeling, seamless texturing and realistic lighting are three key factors of high fidelity (Pascu, Dobrescu, Opran, & Enciu, 2014). Collecting data inside the virtual environment also poses a problem. Asking questions to the subjects or asking them to think out loud could be distracting and solemnly relying on post experiment questionnaires could be unreliable. Immersion is another aspect that some studies fell short in. Especially level of immersion in the studies that use computer screens is questionable. Furthermore, participants of some earlier studies are AEC students.

Even if these students have work experience in construction sites, it is a questionable sample to represent all construction workers.

Moreover, as indicated in the Figure 2.5, despite the fact that the ability to influence the safety of a construction site is highest in the earliest part of the project and it gets lower exponentially as the project proceeds, most of the available researches focus on construction phase rather than earlier plan or design phases (Z. Zhou et al., 2015). It is also indicated that current industry practices are not suitable for planning the safety issues at the earliest stages of a project (Swuste et al., 2012); however, spreading usage of BIM technology would change this. BIM technology allows immense amount of information to be loaded in pre-construction computer models. This information can also cover the construction phases of the buildings. Therefore, BIM makes it possible and encourages to increase the amount of decision made in the earlier stages (Yan Liu, van Nederveen, & Hertogh, 2017). This situation would increase feasibility of pre-construction phase safety planning. The system and the methodology proposed in this study allows combination of observability of construction phase in addition to timing and effectiveness of design phase thanks to high fidelity of state-of-the-art virtualization technology and early information flow of BIM.

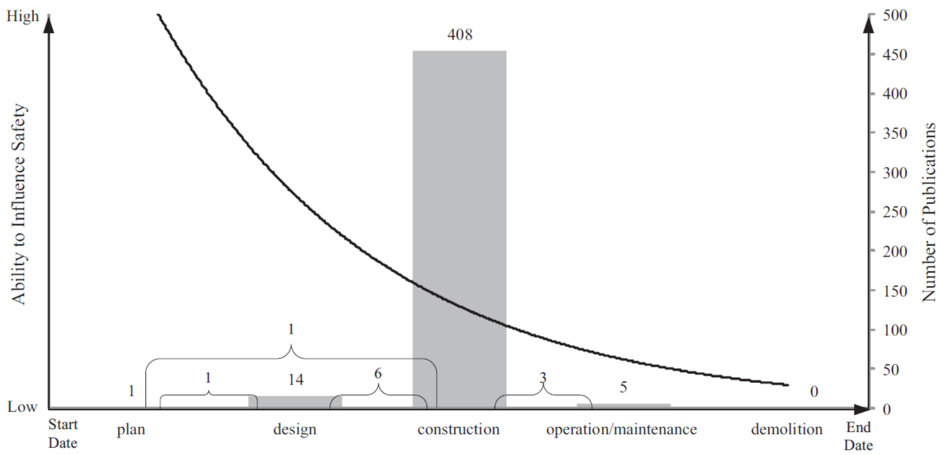

Figure 2.5. Number of studies according to project phase

(Source: Z. Zhou et al., 2015)

Another topic to be mentioned is the technical problems of HMDs. All of the HMDs available on the market are first-generation models of their brands. They still need a lot of technical improvements. Their field of views do not cover the whole human visual field. As a result, subjects view virtual environment through a black frame. Naturally, this situation decreases level of immersiveness of the subjects. The motion sickness experienced by the subjects remains to be solved (Kawai, Mitsuhara, & Shishibori, 2016). This problem is basically caused by the latency between movements of the subjects and response of the virtual environment. Better optimized virtual environments and improvements in GPU technology would solve this problem up to some extends, however it still poses a serious challenge for VR. Moreover, there is the so called “screen-door effect”. Screens inside the HMDs are viewed from a very close distance and as a result the pixels become visible to the users in some situations. This situation is called the screen-door effect (Rajesh Desai, Nikhil Desai, Deepak Ajmera, & Mehta, 2014) and it is a distraction for some subjects. Last but not the least, there is the “vergence-accommodation conflict”. In real world our eyes focus on a specific distance and rest of the visual field remains blurred. However, in HMDs whole visual field is sharply rendered and it harms the immersiveness (Hua, 2017). Moreover, since rendering a larger area instead of only the focused area is harder for GPUs, hardware requirements for VR studies increase. However, with the rapid advancement in HMD technology and exponential increase in processing power of the computers according to Moore’s Law (Moore, 1965), it may be possible to overcome these problems in the near future.

CHAPTER 3

MATERIAL & METHOD

3.1. Chapter Disposition

This chapter explains methodology of the research. It includes two topics: “3.1. Material” and “3.2. Methodology”. The first topic, Material, gives information about resources used in the research. Methodology is the second topic of this chapter. It describes the design process of the experiments and procedures followed during their execution.

3.2. Material

This topic contains information about the resources used during the research. It has three subtopics: “3.1.1. Population”, “3.2.2. Equipment”, and “3.2.3. Software”.

3.2.1. Population

The population of this study is construction site personnel. The sample includes active personnel from different professions like unskilled workers, foremen, engineers, and architects; hence, different levels of education. This population makes it possible to understand effect of formal education on hazard recognition skills. In addition to that, sample also includes workers with different level of construction site work experience to be able to measure effect of experience on hazard recognition skills.

Twenty nine construction professionals have attended to the experiments, data from two of them were not included in the research due to technical problems. There are six primary school, seven high school, one vocational school, nine university, and four post graduate school graduates in the sample. Construction work experience of the subjects varies between one and forty three years with mean of fifteen and median of eleven years.

Nineteen subjects were workers at a large residential project in Ankara. They were selected randomly among a pool of more than one hundred workers on the construction site. Six of the subjects were workers in a mid-size curtain wall manufacturing company in Ankara. Every relevant worker who was in the company headquarters during the experiments have attended to the experiments. Two of the subjects individually attended in the experiments by invitation of a researcher. The sample includes unskilled workers, skilled workers, foremen, technicians, engineers, and architects.

All subjects (except for one) stated that they receive state-regulated compulsory workplace health and safety training annually. This training has been given since 2013. It is composed of sixteen hours of theoretical and practical lectures per year. That means, a subject who has more than six years of work experience has received ninety six hours of safety training. Only two of the subjects reported that they have received extra safety training other than the state-regulated compulsory training.

Only one of the subjects stated that he had used an HMD before, the rest of the subjects told that they have had no experience with HMDs before. Verbal and written consent were given by all the subjects.

3.2.2. Equipment

The hardware used in the experiments are an HMD with eye tracking capabilities and a Bluetooth controller. HMD used is an *SMI Mobile Eye Tracking HMD.* The controller used is a *Snakebyte VR:CONTROLLER.* Both devices can be seen in Figure 3.1.

SMI Mobile Eye Tracking HMD is a basically a Samsung Gear HMD with eye trackers integrated inside it. The one used in this research is coupled with a Samsung Galaxy S7. It is capable of 60 Hz binocular eye tracking with 0.5° accuracy. It has 96° field of view (SensoMotoric Instruments, 2019).

Figure 3.1. Snakebyte VR:CONTROLLER (left), SMI Mobile Eye Tracking HMD (right)

Conducting safety research with HMDs and virtual environments provides numerous advantages. Most prominently, ethical limitations regarding to exposing the subjects to unsafe conditions mostly disappears. In a real construction site, researchers cannot ask the subjects to tour a hazardous site or intentionally insert hazards in a site (Perlman et al., 2014), but in VR it is possible without any problem. Moreover, experimenting directly on the field restricts manipulation opportunities of environmental variables. On the other hand, virtual environments can be freely and easily adjusted according to the researcher purposes.

Additionally, collecting data on the field experiments requires an enormous amount of effort (Albert et al., 2017). Yet still, even this enormous effort would be bound by site limitations due to priority of the actual job on the site. However, in a virtual site, data collection process is much less restricted. Besides, it requires relatively less effort. Moreover, a degree of automation in data collection is possible.

Another advantage of VR is its relatively low cost. Conducting experiments in real world could be costly. However, a VR experiment setting requires a much lower budget and is more practical. This will allow researchers to increase the sample size, test more variables, conduct experiments more easily and increase the repeatability of the experiments (Bernardes, Rebelo, Vilar, Noriega, & Borges, 2015). However, initial cost of VR hardware also should be considered. Especially, eye tracking enabled VR settings are quite expensive Moreover, their accessibility is limited since they are not consumer electronics like standard HMDs.

Finally, HMD eye trackers are completely non-invasive. User experience of eye tracker enabled HMDs are the same with the standard HMDs except for a very short (~15 seconds) calibration period. It is even possible for the subjects to remain blind to eye tracking.

One of the common problems the researchers face in VR studies is bringing the workers to a remote, fixed location (Sacks, Perlman, & Barak, 2013). Using a mobile system solves this problem. HMD used in this study does not require any supportive hardware and experiments can be conducted at wherever the subjects are located.

A particular problem with SMI Mobile Eye Tracking HMD is the lack of support from its manufacturer. SMI was acquired by Apple Inc. in 2017 (Hackett, 2017). As a result, SMI Mobile Eye Tracking HMD does not get updates anymore. Older versions of the software had to be used in this study for this reason.

Snakebyte VR:CONTROLLER is used as controller in the study. It is a standard Android Bluetooth game controller designed to be used for VR applications. The controller is used as movement controller, as hazard recognition pushbutton by the subjects and as room changer, as eye tracking calibration starter for experiment attendants.

Finally, two questionnaires were used in the experiments, are explained in “3.2.2 Experiment Design”. Questionnaires and their translations into English can be found in Appendix II.

3.2.3. Software

Software were benefitted in two stages of the study. The first one is the design of the virtual environment. The virtual environment was generated in Unity. Unity is a game engine software by Unity Technologies ApS. Due to the limitations caused by the fact that SMI Mobile Eye Tracking HMD does not get updates, instead of the newest version, an older version of Unity (5.6.6f2) was used. Unity was preferred since the HMD used in the study is designed to be used with Unity. Moreover, Unity provides capable and flexible tools for gathering data. Also, Unity is free for non-commercial scientific researches.

Majority of the 3D models used in the virtual environment were modelled in SketchUp. It is a 3D digital modelling software by Trimple Inc.. SketchUp was chosen over the alternatives due to its practicality and suitability to low poly modelling. “Pro” version of the SketchUp had to be used for interoperability reasons. 5.6.6f2 version of the Unity software is not compatible with SKP or STL file types that “Free” version of Unity can export.

Adobe Photoshop is used for editing materials used for the models in virtual environments. Photoshop is a raster image editing software by Adobe Inc.. Photoshop is preferred because of its strength in editing tools and familiarity of the research team to the software.

Some of the assets used in the virtual environment are readymade assets downloaded from *Unity Asset Store.* Some of these assets required some editing in their models. FBX Converter by Autodesk is used for converting meshes of these assets from FBX to DXF so that they can be imported to SketchUp.

The second stage included software is data analysis. Data gathered in virtual environment were transferred to Microsoft Excel. Data were filtered and analyzed in Excel to test the hypotheses that are explained earlier.

3.3. Methodology

The methodology of the study can be divided into four phases: literature review, design of the experiments, execution of the experiments, and analysis of the results. In the following topics these phases will be explained in detail.

3.3.1. Literature Review

To be able to identify the gaps in the literature, to have a general understanding and knowledge base on related topics, and to acquire the required knowledge for the study; a comprehensive literature review is conducted as the first phase of this study. Many keyword combinations similar to those below are used in Web of Science, Scopus, and Google Scholar to find relevant scientific papers:

(("virtual reality" OR "immersive virtual reality" OR “VR” OR “IVR” OR "hmd" OR “CAVE” OR "head mounted display") AND (“safety” OR "safety science" OR "hazard" OR "danger" OR “risk”))

(("eye tracking" OR "eye gaze" OR "eye movement*") AND (“architecture” OR “construction” OR “AEC”))

(("eye tracking" OR "eye gaze" OR "eye movement*") AND (“construction safety”))

Among the results, more than 150 relevant journal articles, conference papers, or books were selected. These are categorized according to their relevance, importance and possible contributions to this study. All of the selected articles, conference papers, or books are reviewed in different levels of detail.

3.3.2. Experiment Design

The main tool of the experiments is the virtual environment. In addition to the virtual environment, the experiment includes a pre experiment form that asks for basic information about the subjects to group them according to their level of education and experience, and a short post experiment interview for future refinements and improvements of the experiments design.

The virtual environment consists of three scenes that the subjects get into respectively. The first scene (Figure 3.2) is for familiarization of the subjects to VR, HMD, controls, and the general setup of the system. It is a 10x10x4m room with only four objects inside. These are a 3D “panik yapma” (“don’t panic” in Turkish) writing, two cubes (blue and yellow), and a red sphere, all floating.

The second scene (Figure 3.3) is an L shaped room with roughly dimensions of 12x12x4m in a construction site. It has windows on three side and a large hole in the ground next to the windowless wall. There is a closed are on one corner with dimensions of 4x4x4m. The scene has several hazardous and non-hazardous objects inside.

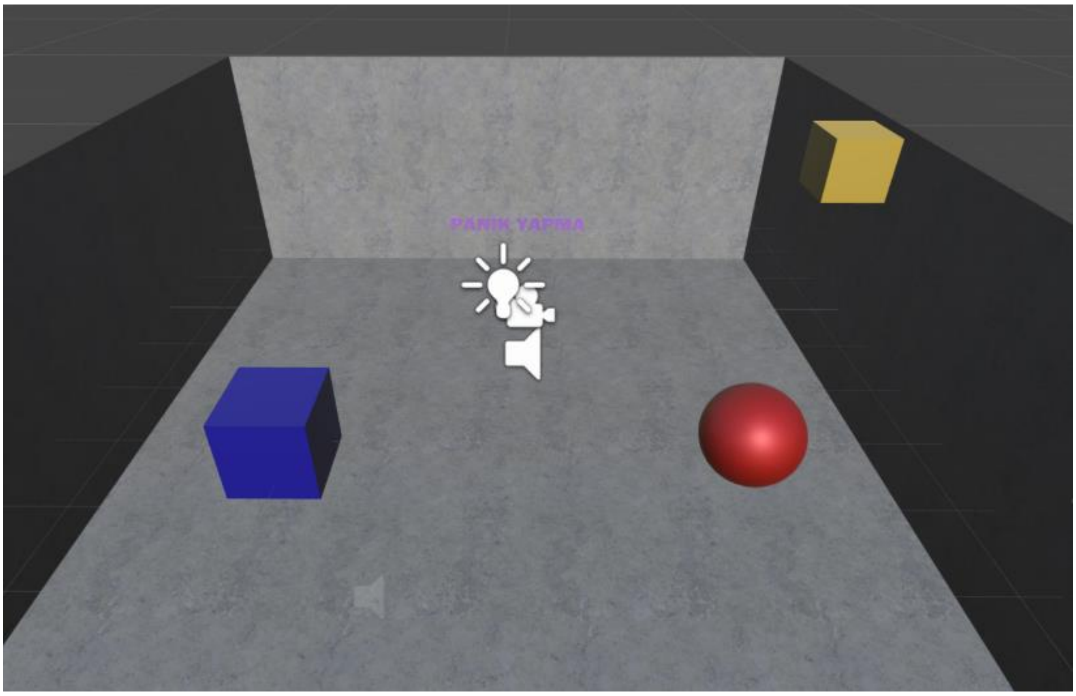

Figure 3.2. Scene 1

The third scene (Figure 3.4) is a top floor of a construction site with dimensions of 12x12m. It has a roofing that covers one third of it with 4m height. The side with the roofing also has a windowless wall. There is a closed area on one corner under the roof with dimensions of 4x4x4m. There are three unfinished columns with starter bars in this scene. Three sides other than the one with wall has safety railings. This scene also has several hazardous and non-hazardous objects inside.

Figure 3.3. Scene 2, hazards marked

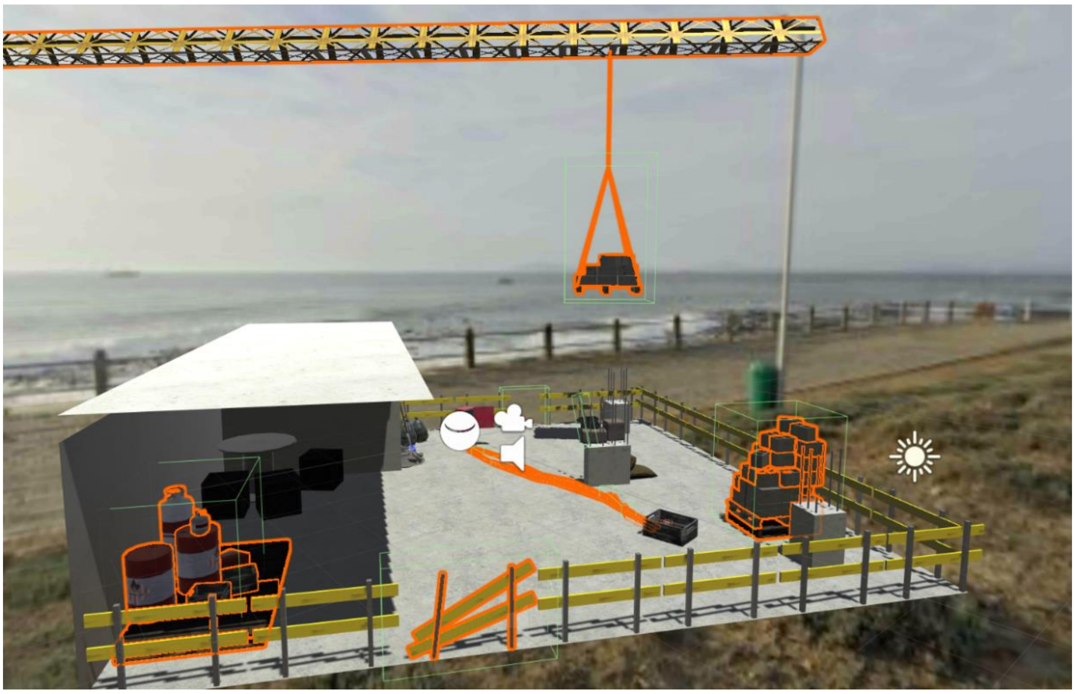

Figure 3.4. Scene 3, hazards marked

The second and third are the scenes in which data is gathered. There are several hazardous situations in these scenes. The *central events* causing the construction site accidents are identified and well known for some time (Swuste et al., 2012). The relationship between the central events and hazards are also well-established and agreed upon. A comprehensive list of these central events and hazardous situations that represent these events were prepared to be used for the second and third scenes. A number of publications were benefited from for the preparation of this list (Albert et al., 2017; Dzeng et al., 2016; Hughes & Ferrett, 2007; Perlman et al., 2014; Swuste et al., 2012). The list can be seen in Table 3.1. Images of the hazard models can be seen in Figure 3.5 and Figure 3.7. Lighting in these images were increased and adjusted to generate clearer images. In the experiment environment, lighting conditions are different and adjusted to be more realistic. Larger versions of these images can be found in Appendix I.

Descriptions and explanations of the hazards in the virtual environment is as follows:

Bucket on Windowsill: Nothing must be placed on the windowsills before the glazing are installed. A bucket can contain heavy objects like cement or pebbles. It can fall down outwards and injure workers outdoor.

Unsecured Tools on Mobile Scaffolding: Tools must not be left on scaffoldings. Especially not on mobile scaffoldings because they are less stable and it is easier for the tool to fall down. In this instance, the tools are left very close the edge the increase the risk and make it possible for the subjects to notice them.

Unsecured Chainsaw on the Ground: Machinery must never be left unsecured in construction sites. Chainsaw blades are dangerous even if the engine is not working. Moreover, the noise of the chainsaw is much lower when it is not throttled. So, it is possible for a working chainsaw to be unnoticed by a worker because of the ambient noise and the worker can contact a working chainsaw.

Table 3.1. *List of central events and hazardous situations*

Central Event	Hazard	Scene
Fall from Height	Unsecured Shaft Opening	2
	Ladder Propped on the Wall	2
	Unsecured Edge	3
	Broken Safety Railing	3
Contact with a Falling Object	Unsecured Tools on Mobile Scaffolding	2
	Bucket on Windowsill	2
Contact with Toppling Down Objects	Stacked Wooden Crates	2
	Stacked Bricks	3
Contact with Electricity	Damaged Power Cord	3
Contact with Machinery	Unsecured Chainsaw on the Ground	3
Contact with Vehicles	Hoist (Lifting Brick Stack)	3
Exposure to Extreme Heat	Gas Tanks	3
Exposure to Harmful Substance	Harmful Substance Tanks	2
Trip / Fall to Same Level	Wooden Planks (with nail on one) on the Ground	2
	Lifted Power Cord on the Ground	3
Strike Against Something	Unsecured Bent Rebar	3

Harmful Substance Tanks: Harmful chemicals are used for many construction tasks like painting, fine construction works, or cleaning. Those chemicals can cause short- and long-term harms on lungs, skin, mouth, or eye. In this instance, adhesive material containers like tanks, cans, and bottles are used. Adhesive material warning is placed on one of the tanks. The existence of the adhesive material containers is already a hazardous situation. Moreover, these containers are stacked in an unbalanced way.

Wooden Planks (with nail on one) on the Ground: There must not be any object on the ground that can cause a trip over. In this instance, three planks placed on each other as a hazardous situation. Moreover, there is a nail on the top plank.

Unsecured Shaft Opening: All openings must be enclosed with safety railings. In this instance, a shaft opening with three sides has railings only on one side. Two other sides are left unsecured. Workers can fall down and get injured or heavy objects can fall down and injure the workers below.

Ladder Propped on the Wall: Ladders must have proper precautions to prevent them falling. In this instance, the ladder must have had a slipping prevention either on top or the bottom. Moreover, the ladder is placed very close to an unsecured window. Also, the angle of the ladder with the ground is less them optimal angle.

Stacked Wooden Crates: Every stack poses a risk of toppling down. In this instance, six wooden crates (75x75x75cm) are placed on top of each other. A stack this high (375cm) is already a hazard. Moreover, the stack is unbalanced and contents of the crates are unknown. Thus, the risk is increased.

Flammable Tanks: Existence of flammable and combustible materials poses a hazard. Fire is particularly dangerous in construction sites since fire protection equipment are usually installed in very late periods of a construction. In this instance, these materials are too exposed to possible heat sources by construction task such as welding, cutting or worker actions like smoking. Also, they are placed on a wooden container and very close to wooden crates that can easily spread the fire. Moreover, the liquid container at the right side is not properly secured.

Hoist (Lifting Brick Stack): Hoisting during the work is objects is always a dangerous task. Workers can be struck by the hoisted object or the hoisted object can fall on the workers. In this instance, a stack of bricks is hoisted on top of the working area. The stack is not properly secured and hoisted too close to the working area.

Broken Safety Railing: All openings must be enclosed with safety railings and these railing must be in good shape. In this instance, the railing is broken and cannot function properly. Workers can fall down and get injured or heavy objects can fall down and injure the workers below.

Bent Rebar: Exposed rebars pose a danger and should be covered with safety caps. In this instance, the rebar is without a safety cap, at the eye level, and bent outwards. Workers, machinery, or construction materials can strike against the rebar.

Stacked Bricks: Every stack poses a risk of toppling down. In this instance the risk is greater because the height of the concrete brick stack is too high (2m) and the brick is not stacked decently. Moreover, the stack is too close to the edge of the building. Bricks can fall down and injure the workers outdoor.

Damaged Power Cord: Power distribution boxes are used in construction sites as portable electricity distributers for machinery. Since there are lots of equipment in the construction sites that can easily damage either the box itself or the cords, they must be checked regularly. In this instance the box is in good shape but the one of the cords is broken off. There is a risk of getting struck by electricity.

Lifted Power Cord on the Ground: There must not be any object on the ground that can cause a trip over. In this instance two power cords are lifted from the ground in a way that workers or machinery can trip over.

Unsecured Edge: All openings must be enclosed with safety railings. In this instance there is a 1m gap between two railings. Workers can fall down and get injured or heavy objects can fall down and injure the workers below.

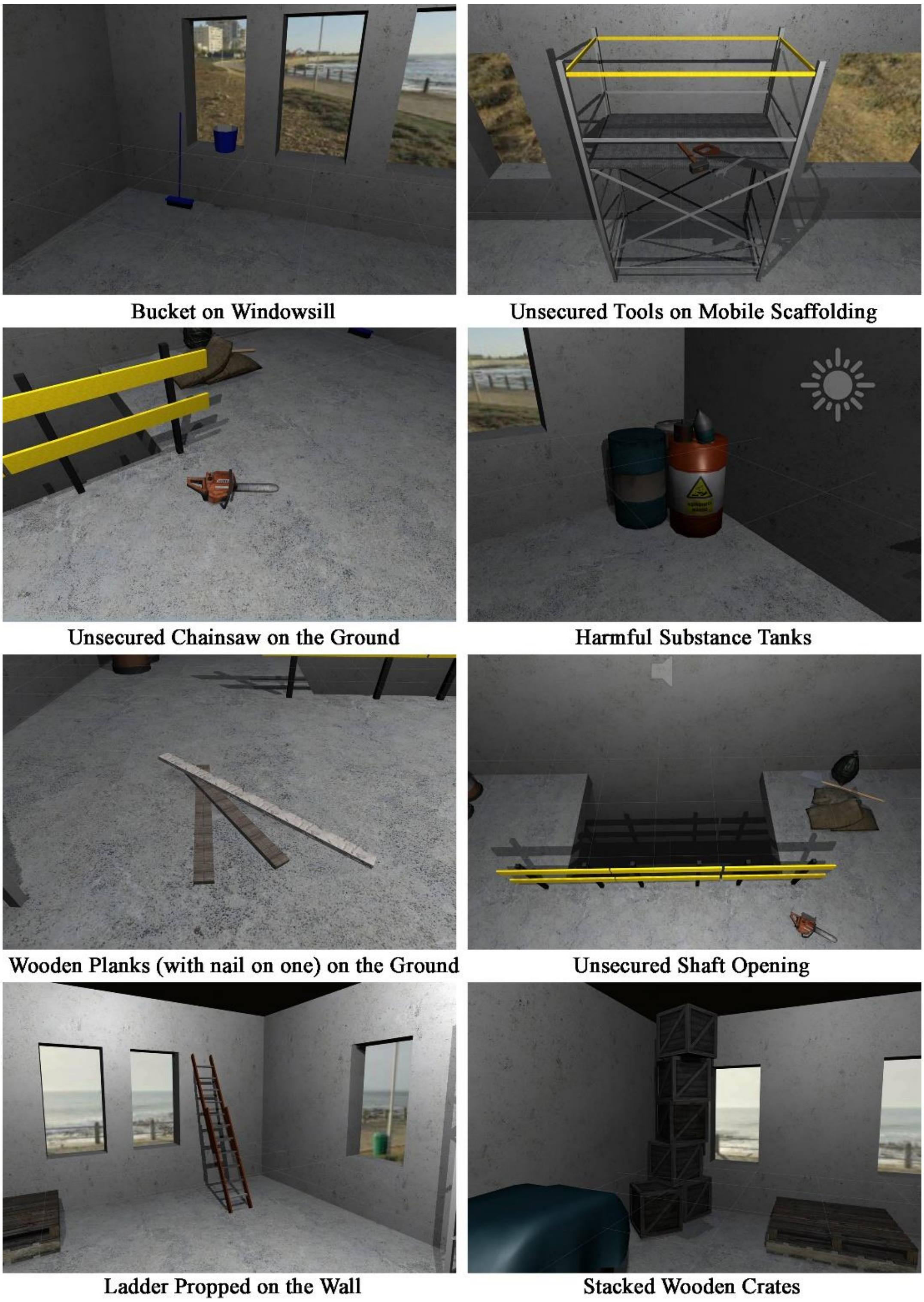

Figure 3.5. Hazardous situation models in the Scene 2

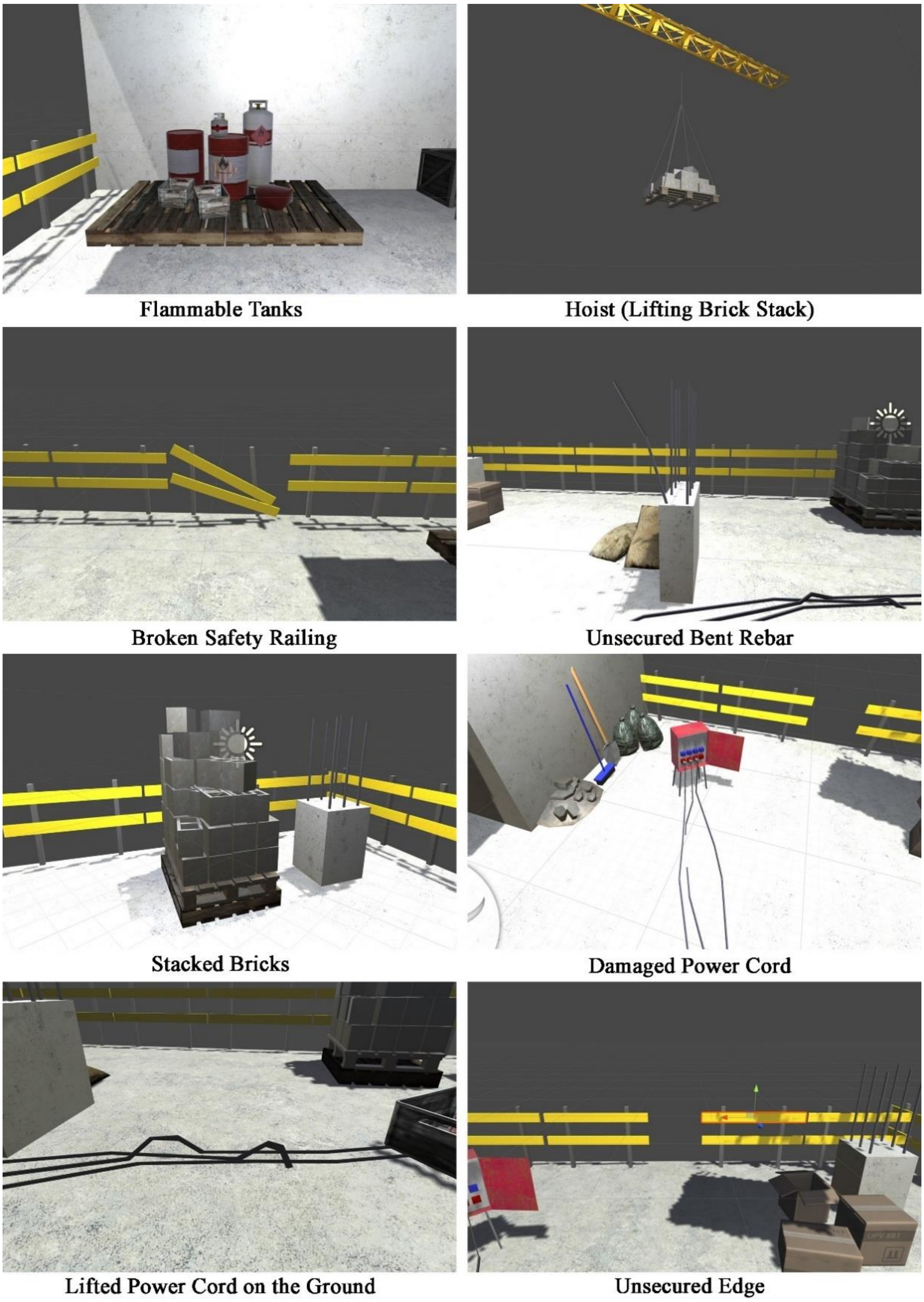

Figure 3.6. Hazardous situation models in the Scene 3

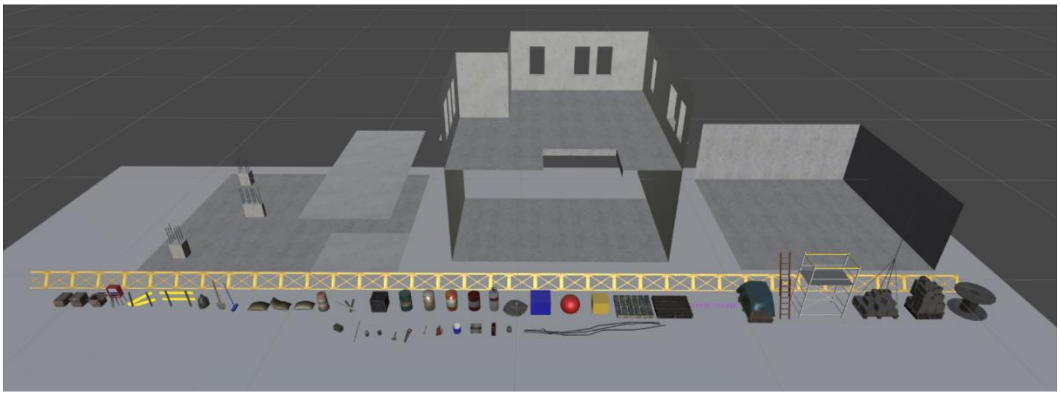

Figure 3.7. Objects used in the scenes

There are fifty unique construction site objects in the virtual environment. Most of these are used in multiple instances for different scenes in various sizes/directions/arrangements. The objects are either created for this study by the research team or downloaded from the *Unity Asset Store*. In some cases, downloaded objects required editing to fit geometrical style and color palette of the virtual environment or to fit specific needs of the experiments or to become low poly. Mesh editing are done in SketchUp and material editing is done in Photoshop. These objects can be seen in the Figure 3.6.

The objects created by the research team are modelled in SketchUp. They are exported as 3DS files since 5.6.6f2 version of Unity cannot import SKP files. These models are imported to Unity as assets. Models are covered with materials in Unity.

HMD used for the experiments is powered by a mobile device. Hence, while increasing the fidelity of the virtual environment, the load on the GPU was needed to be considered. Several precautions are taken for this.

First of all, every game object in all scenes have low poly meshes. To provide an increased fidelity, most of these low poly objects have normal maps which are generated from high poly versions of them. Also, a spherical HDRI of a low-density urban area (Figure 3.8) is wrapped around the scene as skymap to increase fidelity with low processing cost. A texture with transparent alpha channel is used in the crane. As a result, crane which is a complex object and would normally require hundreds of polygons, was modeled with only ten polygons. Pixel density of the used HMD is rather low. To lower the effect of this problem, 8X anti-aliasing is applied. Finally, number of light sources was kept as low as possible. The second scene (indoor setting) has one directional light to simulate the sun and one point light to simulate indoor light. The Third scene has one directional light to simulate the sun. Both scenes also include a reflection probe for more realistic reflections and light distribution. Also, very subtle environmental lighting is used for preventing very high dynamic contrast. Additionally, to lower to load in the CPU, update function, which is called once per frame, is used as little as possible in scripts.

Figure 3.8. Spherical HDRI used as skymap

(Source: Zaal, 2018)

Ambient sound is reported to have a significant positive impact in fidelity of a virtual construction site (Lu & Davis, 2016). Moreover, it is indicated that sound also has a significant effect on safety decisions of the subjects. Therefore, a realistic construction site ambient sound (The Sound Gallery, 2016) is added to all scenes. For increased immersion, when the scene is changed the ambient also sound changes.

To be able to provide a more fluid experiment sequence, all experiment scenes explained above are located inside a single Unity scene under different parent objects. When the scene is needed to be changed, parent object that contains the desired scene gets enabled while the others gets disabled via a script.

Two sets of data are collected in VR. The first one is the time of the fixations on hazardous objects and the second one is the pushbutton time. To collect the first set of data, a script that continuously casts a ray is used. When the ray is collided with the colliders which are defined on the hazardous areas the time passed until the beginning of the experiment is recorded. This time will be called hazard fixation time (HFT) from now on.

The second set of data is collected when a subject has recognized a hazard. The subjects are asked to push a button when they recognize a hazard. When the button is pushed, the time until the beginning of the experiment is recorded. This time will be called pushbutton time (PBT) from now on.

A Bluetooth game controller is used for subject interactions in VR. There are two type of interactions available for subjects via this controller. The first one is the pushbutton they need to press when they see a hazard. All of the frontal buttons on the right side of the controller is assigned for this task. Normally, subjects are asked to press the lowermost button on the right side; however, subjects cannot see the controller. It is possible for them to accidentally press adjacent buttons. Hence, all the frontal buttons on the right side are assigned for hazard recognition task.

The second interaction available via the controller is walking in virtual environment. Left bumper button is assigned for this task. Bumper button is used for this task so that the subjects would use different fingers (right thumb for hazard recognition, left index finger for movement) for different interaction types. This way it would be easier and more instinctive for the subjects to differentiate these two interactions. The button configuration can be seen in Figure 3.9. Movement is controlled by a script. While the left button is pressed, subjects is transformed forward in the direction of the game camera. When the button is released, the subject stops. This way, the subject can move forward by pressing the button. The movement is kept as simple as possible for the subjects to adapt to the VR as quick as possible and experience less nausea.

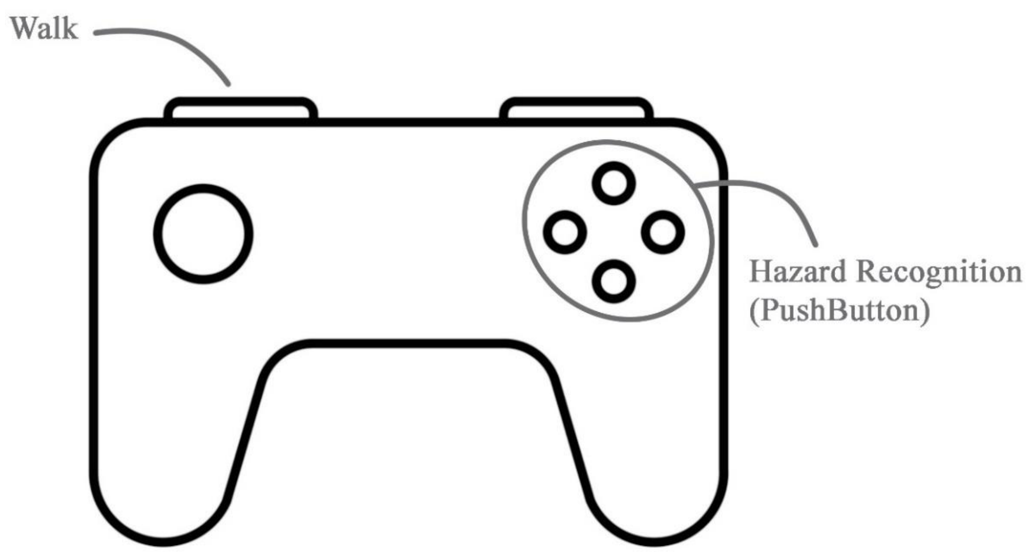

Figure 3.9. Button configuration of the controller used in the experiment

Two short questionnaires are prepared for the study. One of them is pre-experiment and the other is post-experiment. The pre-experiment questionnaire collects demographic information required for the study such as level of education, level of experience, and job. It also includes a short briefing on the experiment. The post-experiment questionnaire consists questions for the subjects to evaluate the virtual environment and make suggestions. both questionnaires take less than a minute to complete. The questionnaires and their translations into English can be seen in the Appendix II.

A voluntary participation form and a post-experiment briefing form were prepared. Both forms can be found in Appendix II in Turkish and English. To prevent any bias, the subjects were not informed about the eye tracking before the experiment. This information is given to the subjects in the post-experiment briefing form.

3.3.3. Experiment Procedure

Experiments were carried out in three different locations, METU School of Informatics Building, a large-scale residential construction project in Ankara, and headquarters of a mid-scale curtainwall manufacturing company. There were always two researchers present during the experiments to run the experiments and assist the subjects. Photographs taken in different locations during the experiments can be seen in Figure 3.10.

Figure 3.10. Photographs taken during the experiment in different locations

Description of the experiments is as follows: The experiment starts with a short briefing. First the subjects are asked to read and sign a form they participate to the experiment voluntarily. After that the subject are asked to fill the pre-experiment questionnaire. When they are done, HMD is mounted in the heads of the subjects. Firstly, the subjects enter the scene 1. In the beginning there is only the writing is enabled and the rest of the object are disabled. After they get familiarized with the VR, they are asked to look at the floating writing in the middle and adjust the focus of the HMD, and position of the HMD on their heads until they feel most comfortable and the vision is sharpest. When they are done, the eye tracker calibration is started. Then the controller is given to the subjects and the function of the buttons are explained. When they are familiar with the buttons rest of the objects in the room (two cubes and a sphere) are enabled. Subjects are asked to find these objects and push the hazard recognition button when they do. When they are done, subjects are asked to move around the room. When they are comfortable with all the aspects of the VR, subjects are sent to the Scene 2.

Subjects are asked to find the hazards in Scene 2 and push a button on the controller when they do. After the subjects are done, they are sent to Scene 3. If a subject still hasn't done after spending five minutes in the scene, they are told the time is up and sent to Scene 3. Same procedure applies for Scene 3. VR part of the experiment is over after the subjects are done in Scene 3. Subjects are relieved of the HMD and the controller and asked to fill the post-experiment questionnaire. When questionnaire is completed the experiment is over. Whole process takes approximately ten minutes.

Before the scene switches, subjects were asked to move to the middle of the room and look at a specific location. These locations are arranged in a way that when the scene is changed the subjects will not be looking at directly or close to a hazard in the next scene.

Experiment procedure guide that was followed in the experiment can be seen below.

1. Invite the subject in the room

2. Brief the subject on the basics of the experiment
3. Ask the subject to *read and sign the voluntary participation form*
4. Ask the subject to *fill the pre-experiment questionnaire*
5. Start the experiment on the HMD
6. Ask the subject to *wear the HMD* and help them do
7. Ask the subject to *turn around and look around the virtual room*
8. Ask the subject to *look at the floating writing* and adjust the focus of the HMD via the scroll on top of the HMD
9. Ask the subject to *adjust the position of the HMD until they feel most comfortable and the vision is sharpest*
10. Tell the subject that the *HMD will start an automated adjustment system and ask them to follow the red dot and tell when the process is finished*
11. Start the eye tracking calibration
12. Give the controller to the subject and show the required buttons and explain their functions
13. Enable the red sphere, blue cube, and yellow cube.
14. Ask the subject to *find those objects and push the hazard recognition button when they do*
15. Ask the subject to *move around in the room*
16. Tell the subject that *the preparations are completed and the experiment can start whenever they feel comfortable in VR*
17. When the subject is ready, tell *they will be sent to a new scene and when they are done with recognizing the hazards in that scene, they can ask the be sent to the third scene*
18. Ask the subject to *move approximately to the middle of the room and look at the floating writing*
19. Enable Scene 2
20. When the subject is done and asked to be moved to the third scene, ask the subject to *move approximately to the middle of the room and look at the safety railings*.

21. If the subject has not asked to be moved to the third scene after 5 minutes, tell the *time for the second scene is up* and *they will be sent to the third scene*. Ask the subject to *move approximately to the middle of the room and look the safety railings*
22. Tell the subjects that *they can tell when they are done recognizing the hazards in the next scene*
23. Enable Scene 3
24. When the subject tell they are done, tell *the experiment is over*
25. If the subject has not told that they are done after 5 minutes, *tell the time is up and the experiment is over*
26. Take the controller from the subject
27. Help the subject to remove the HMD
28. Ask the subject to *fill the post-experiment questionnaire*
29. Ask the subject to *read the post-experiment briefing form*
30. Walk the subject out of the room
31. Record the subject number, time, and date on the questionnaires
32. Staple the questionnaires together and file them

CHAPTER 4

RESULTS & ANALYSES

4.1. Chapter Disposition

In this chapter, results of the experiments and analyses of these results are presented. Types of data gathered are explained in the “4.2. Data Disposition” topic. Analyses based on level of education, level of experience, and individual hazards are presented in the following topics respectively.

4.2. Data Disposition

Two types of data were gathered from all subjects during the VR experiments. These are PBT and HFT. PBT is when a subject pressed the button to indicate a hazard. HFT is when the gaze of a subjects is fixated on a hazard.

PBT and HFT are superimposed on a timeline to understand the time passed between a subject saw a hazard and recognized it. PBT during or just after (less than 1 second) a fixation is accepted as recognition of the fixated hazard. The time passed between corresponding PBT and HFT is the *reaction time* for the fixated hazard.

Eye tracking algorithms provided by SMI to be used in Unity were utilized when detecting fixations. A ray is cast continuously in the direction of the gaze of the subject. Whenever this ray starts to hit one of the colliders placed on the hazards and whenever it stops hitting, timings and the name of the hazard are recorded. Total duration of the hit is calculated as the time between the beginning of the hit and end of the hit to understand whether the hit is a fixation or a saccade. Micro breaks between the hits caused by blinks or resolution problems of the eye tracker are fixed manually afterwards. The time log is kept by Unity; since Unity runs within the HMD hardware, time log is recorded by the HMD. Crosscheck mechanisms are placed to make sure PBT and HFT always use the same time log.

Generally, minimum fixation duration is accepted as 200ms, however this duration increases due to nature of the stimulus and its context. In this study, the stimulus and the environment are complex and the cognitive process of recognizing a hazard is a heavy one. Hence, minimum fixation duration for the recognition of a hazard is accepted as 500ms, similar to a previous study (Dzeng et al., 2016). The fact that subjects recognized simple geometric forms in the training scene (Scene 1) as quick as 200ms but none of the subjects were able to recognize a hazard faster than 500ms throughout the experiments validates this decision.

Reaction times for each hazard are calculated (PBT minus HFT) for each subject. The arithmetic mean of the reaction times for a subject is called Mean Reaction Time (MRT). MRT is the indicator of how fast a subject can recognize hazards.

If the subject does not fixate on a hazard or fails to recognize it after the fixation and does not push the button, it is called a *miss*. The ratio of the misses to the total number of hazards is called Total Miss Rate (TMR). TMR is the indicator of with what percentage a subject fails to recognize construction site hazards.

A PBT that does not correspond to any HFT is a misrecognition. Misrecognitions are not evaluated in this study. Moreover, some subjects pushed the button more than once for the same hazard. In those cases, PBTs after the first one are not evaluated.

In some cases, subjects had missed a hazard first; however, when they fixate on the same hazard after some time, they recognized it as a hazard. In these cases, reaction time is calculated as total duration of the first fixation plus the second fixation duration until the pushbutton reaction.

Eye tracking also enables analysis of whether a hazard is truly missed or seen by the subject and still missed. If there is a fixation on an unrecognized hazard it is called seen&missed, if not it is called a true miss.

Analyses made to test the hypotheses are based on MRTs, TMRs, true miss rates and seen&missed rates of different subject groups. Moreover, secondary analyses were made based on reaction times to specific hazards.

4.3. Results on Effect of Formal Education

To analyze the effect of formal education the subjects were divided onto two according to their level of education. The first group (Less Educated) is the workers with a high school or lesser formal educational degree. The second group (More Educated) is the workers with higher education, either a university degree of a vocational college degree. Workers with post-graduate degrees are also in this group. There are thirteen subjects in the first group and fourteen in the second. One tailed T-test was applied to the results of the groups to understand if the differences are statistically significant.

Mean TMR of the Less Educated Group is 44.4% and of the More Educated Group is %26.1% as shown in the Figure 4.1. The difference found to be statistically significant with p value of 0.000058. It indicates more educated people recognize hazards with a significantly higher percentage than less educated people.

Mean MRT of the Less Educated Group is 2.9 seconds and of the More Educated Group is 2.2 seconds as shown in the Figure 4.2. This difference also found to be statistically significant with p value of 0.021. The results suggest more educated people recognize hazards with a significantly faster than less educated people. Results of the analyses can also be seen in detail in Table 4.1.

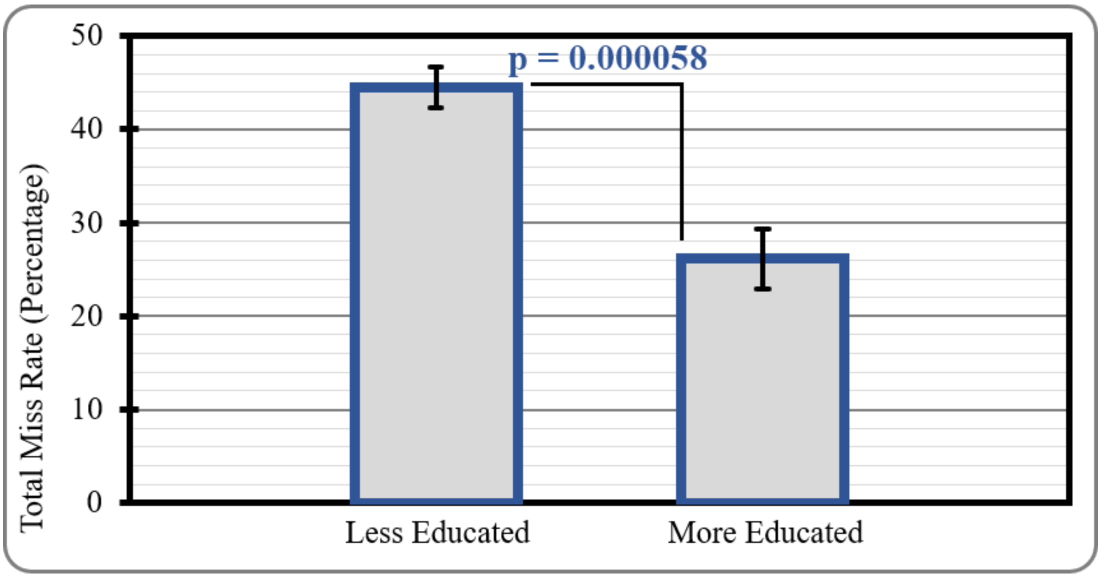

Figure 4.1. Mean TMR of Less Educated and More Educated groups

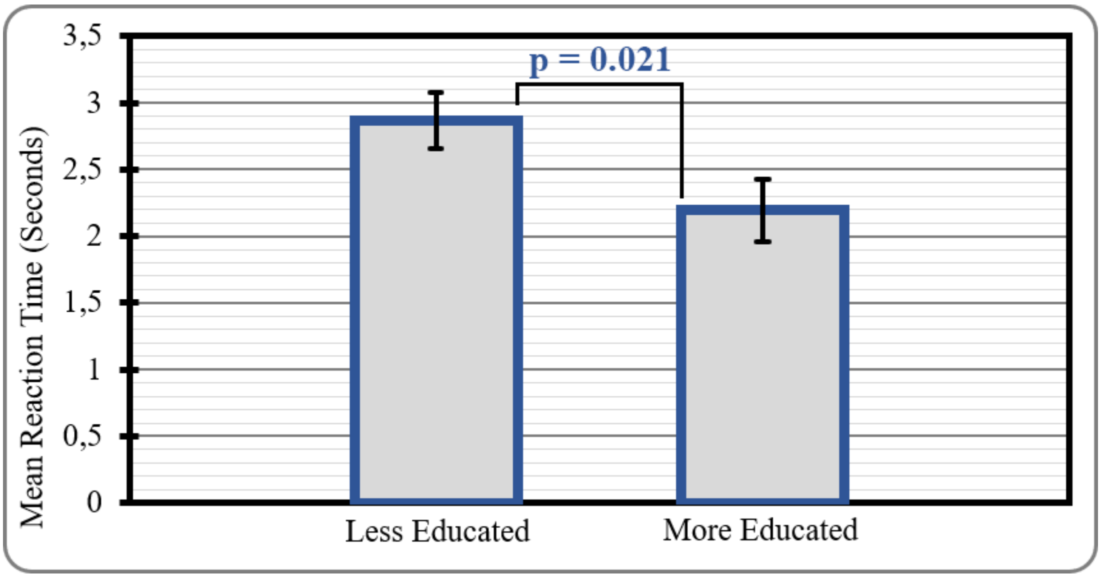

Figure 4.2. Mean MRT of Less Educated and More Educated groups

Table 4.1. *Results of the analyses on the effect of the formal education*

	Sample Group	p	t	St. Err.	Mean	n
Total Miss Rate	Less Educated	0,000058	4,7	3,22	44,46%	13
	More Educated			2,19	26,14%	14
Mean Reaction Time	Less Educated	0,021	2,13	0,21	2,87 s	13
	More Educated			0,23	2,19 s	14
Seen & Missed	Less Educated	0,0005	4,16	2,59	25,21%	13
	More Educated			2,87	11,05%	14
True Miss	Less Educated	0,28	1,1	2,59	19,25%	13
	More Educated			2,86	15,01%	14

To further analyze the effect of education the sample is divided into four groups according to their level of education as Primary, Secondary, Tertiary, and Post Graduate. Mean TMR of the groups can be seen in Figure 4.3 and mean their mean MRT can be seen in Figure 4.4. Positive Effect of formal education on hazard recognition performance is visible in both figures.

There are eight subjects in group Primary, eight in Secondary, eleven in Tertiary, and four in Post Graduate. Mean TMR for Primary is 48.9%, for Secondary is %40.7%, for Tertiary is 28.9%, and for Post Graduate Group is 19.25%. Mean MRT for Primary is 3.2 seconds, for Secondary is 2.6 seconds, for Tertiary is 2.27 seconds, and for Post Graduate is 2 seconds.

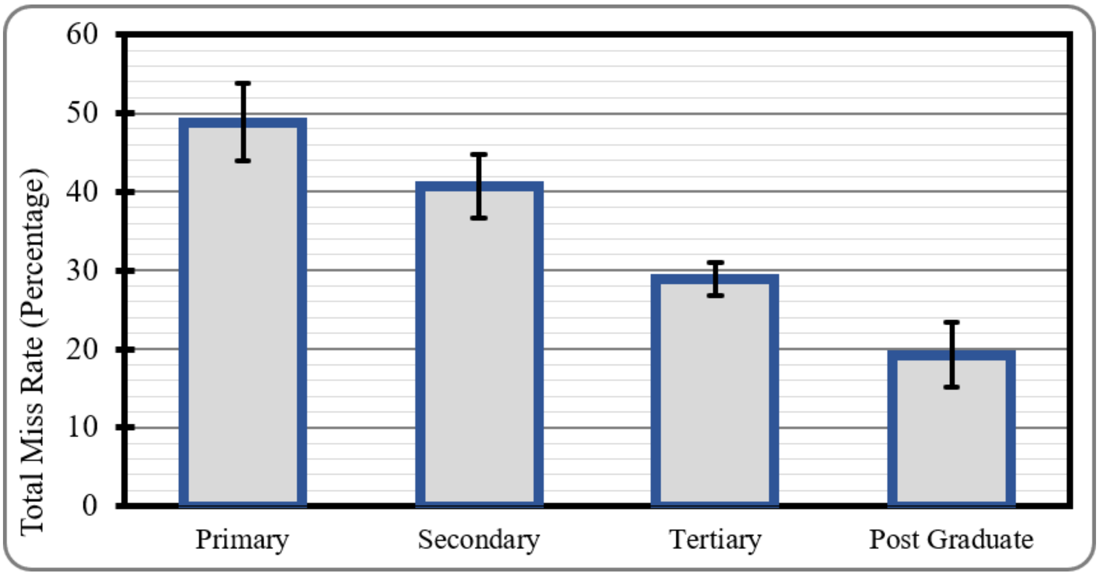

Figure 4.3. Mean TMR of Primary, Secondary, Tertiary and Post Graduate groups

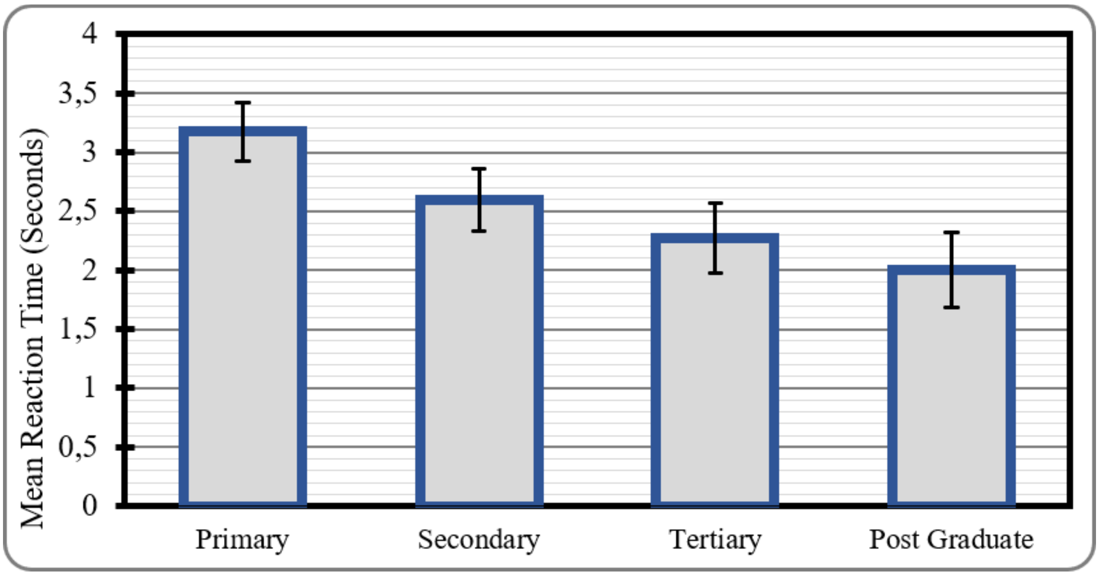

Figure 4.4. Mean MRT of Primary, Secondary, Tertiary and Post Graduate groups

4.3.1. True Miss or Seen&Missed According to Education

The rate of True Miss, which is when the subject’s eye did not fixate on the missed object, and the rate of Seen&Missed, which is when the subject’s eye fixated on the missed hazard but the subject did not recognize it as a hazard, are given below in Figure 4.5 for Less Educated and More Educated groups. Two tailed T-test was applied to the results of the groups to understand if the differences are statistically significant.

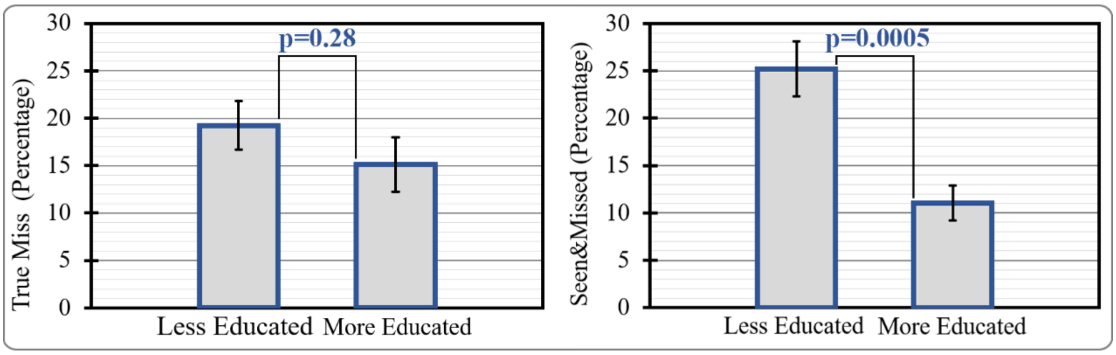

Figure 4.5. Rate of True Miss and Seen&Missed for More Educated and Less Educated groups

Mean rate of True Miss of the Less Educated Group is 19.2% and of the More Educated Group is 15.1%. However, the difference is not statistically significant with p value of 0.28.

Mean rate of Seen&Missed of the Less Educated Group is 25.2% and of the More Educated Group is 11%. The difference is statistically significant with p value of 0.0005.

The results were also analyzed according the groups Primary, Secondary, Tertiary, and Post Graduate. Rates of True Miss can be seen in Figure 4.6 and rates of Seen&Missed can be seen in Figure 4.7.

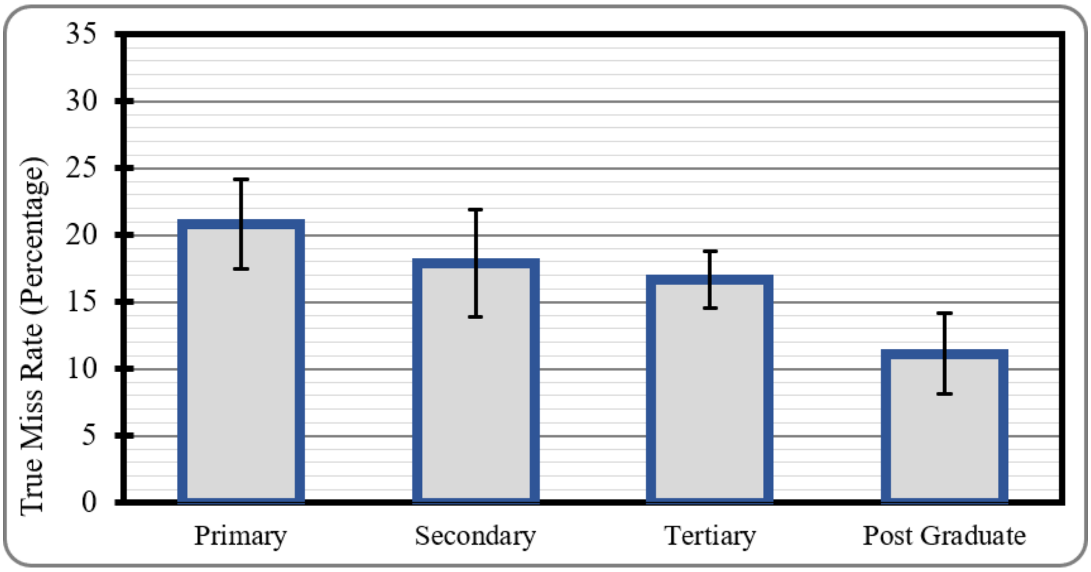

Figure 4.6. Rates of True Miss for groups Primary, Secondary, Tertiary, and Post Graduate

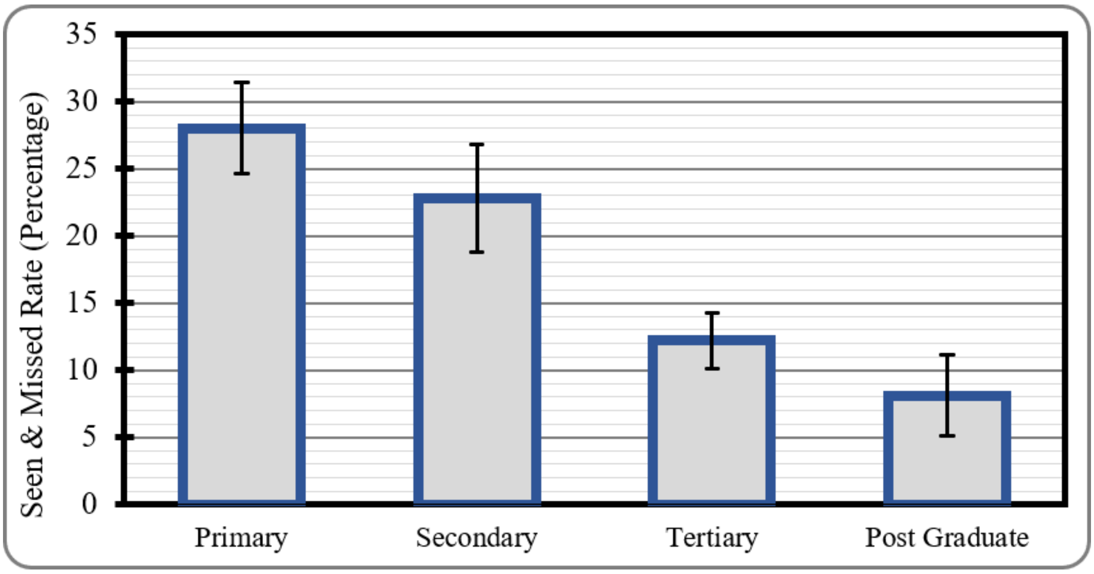

Figure 4.7. Rates of Seen&Missed for groups Primary, Secondary, Tertiary, and Post Graduate

Mean rate of True Miss of the group Primary is 20.8%, Secondary is 17.9%, Tertiary is 16.7%, and Post Graduate is 11.15%. Mean rate of Seen&Missed of the group Primary is 28.2%, Secondary is 22.8%, Tertiary is 12.2%, and Post Graduate is 8.1%.

4.4. Results on Effect of Experience

To test the effect of work experience, the subjects are divided into two groups. The first is the More Experienced Group and the second is the Less Experienced group. To make sure the effect of level of education does not affect the results, the Less Educated and the More Educated groups were divided into two as less experienced and more experienced separately, and then, resulting groups are combined to form the Less Experienced Group and the More Experienced Group. There are thirteen subjects in the Less Experienced Group with mean 6.2 years of experience. There are fourteen subjects in the More Experienced Group with mean 23.4 years of experience. One tailed T-test was applied to the results of the groups to look for statistically significance.

Mean TMR of the Less Experienced Group is 32.2% and of the More Experienced Group is 37.6% as shown in the Figure 4.8. The difference found to be statistically non-significant with p value of 0.15.

Mean MRT of the Less Experienced Group is 2.6 seconds and of the More Experienced Group is 2.6 seconds as shown in the Figure 4.9. This difference also found to be statistically non-significant with p value of 0.48. Analyses on the results are summarized in Table 4.2.

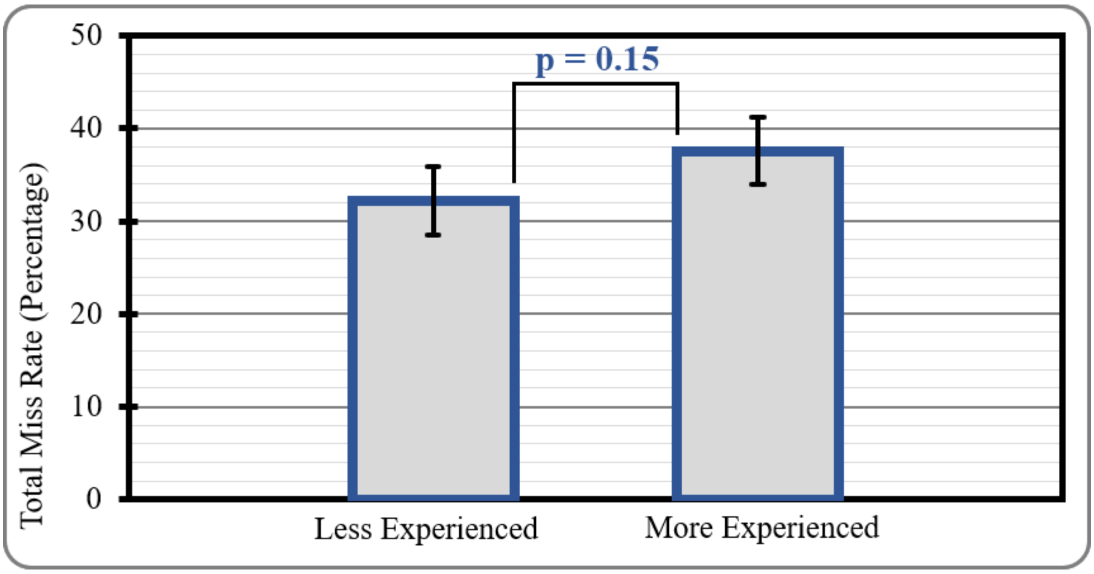

Figure 4.8. Mean TMR of Less Experienced and More Experienced groups

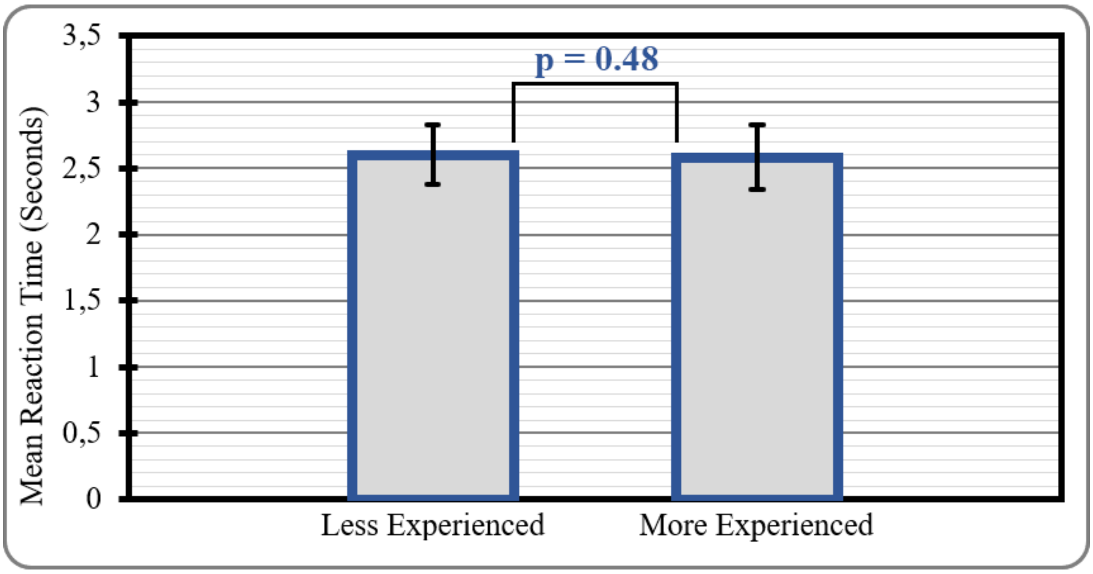

Figure 4.9. Mean MRT of Less Experienced and More Experienced groups

Table 4.2. *Results of the analyses on the effect of the work experience*

	Sample Group	p	t	St. Err.	Mean	n
Total Miss Rate	Less Experienced	0,15	-1,04	3,39	30,38%	13
	More Experienced			3,65	39,21%	14
Mean Reaction Time	Less Experienced	0,48	0,05	0,23	2,60 s	13
	More Experienced			0,24	2,58 s	14
Seen & Missed	Less Experienced	0,24	1,19	2,93	20,52%	13
	More Experienced			2,7	15,40%	14
True Miss	Less Experienced	0,04	-3,19	1,78	11,71%	13
	More Experienced			2,49	22,10%	14

To further analyze the effect of education both groups are again divided into two according to level of experience. The resulting four groups are named from least experienced to the most as Q1, Q2, Q3, and Q4 as seen in the Figure 4.10. The mean of the level of the experience of the groups are respectively; 3.3 years, 9.7 years, 15.3 years, and 32.7 years. Mean TMR of the groups can be seen in Figure 4.10 and mean their mean MRT can be seen in Table 4.3. Positive Effect of formal education on hazard recognition performance is visible in both figures.

Table 4.3. *Four groups according to the level of experience*

Group name	*Mean Experience*	*Number of Subjects*
Q1	3.3 years	7
Q2	9.7 years	6
Q3	15.3 years	7
Q4	32.7 years	7

There are seven subjects in Q1, six in Q2, seven in Q3, and again seven in Q4. Mean TMR for Q1 is 25.4%, for W2 is 40%, for Tertiary is 34.6%, and for Q4 is 40.1%. Mean MRT for Q1 is 2.8 seconds, for Q2 is 2.4 seconds, for Q3 is 2.2 seconds, and for Q4 is 2.7 seconds.

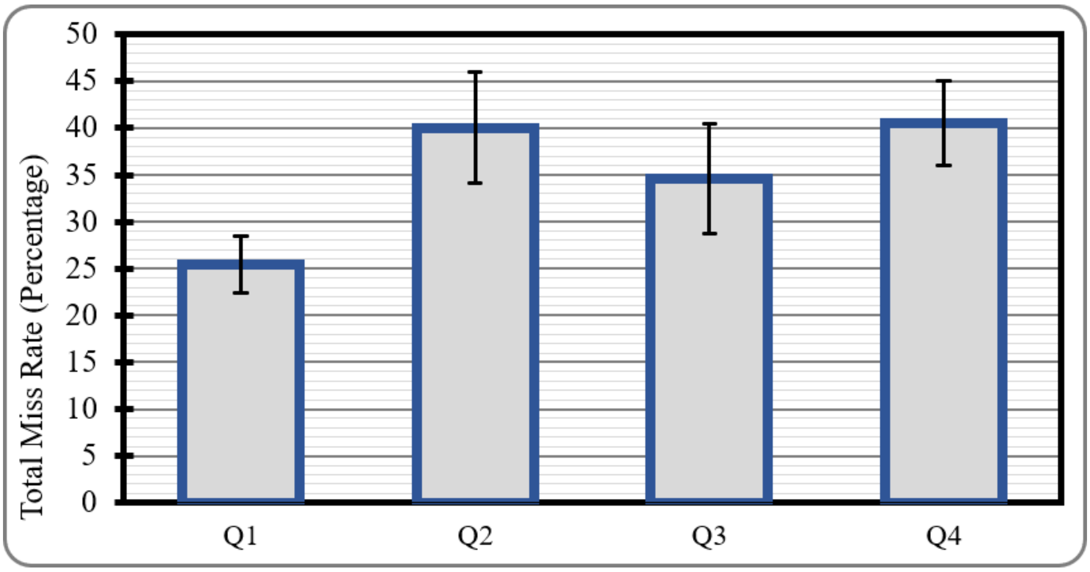

Figure 4.10. Mean TMR of Q1, Q2, Q3, and Q4 groups

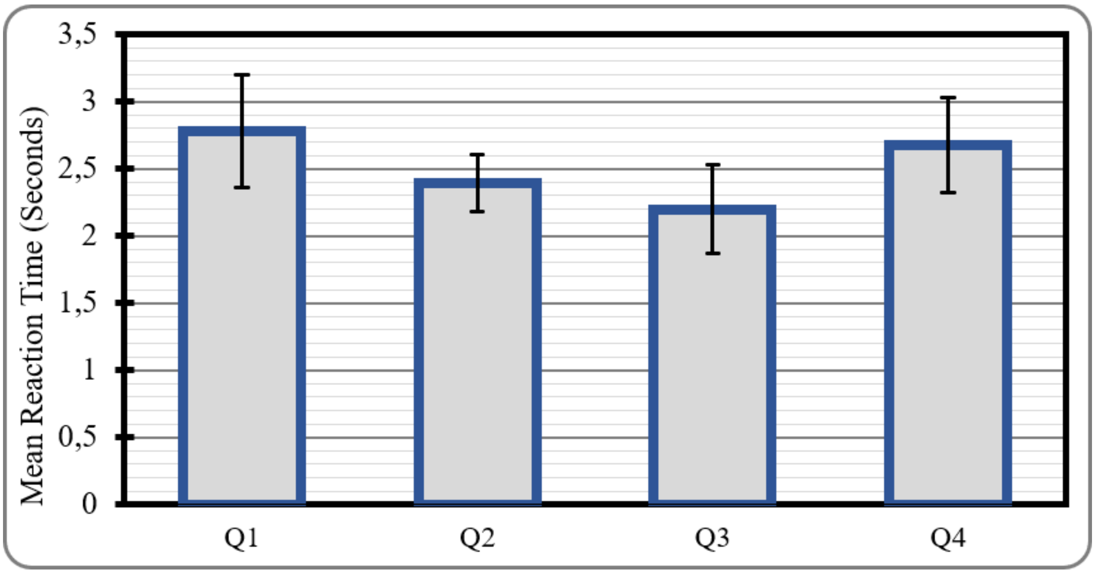

Figure 4.11. Mean MRT of Q1, Q2, Q3, and Q4 groups

4.4.1. True Miss or Seen&Missed According to Experience

The results of groups based on level of experience is also analyzed in terms fixating on the missed hazards. The rate of True Miss and the rate of Seen&Missed are given below in Figure 4.12 for Less Experienced and More Experienced groups. Two tailed T-test was applied to the results of the groups to understand if the differences are statistically significant.

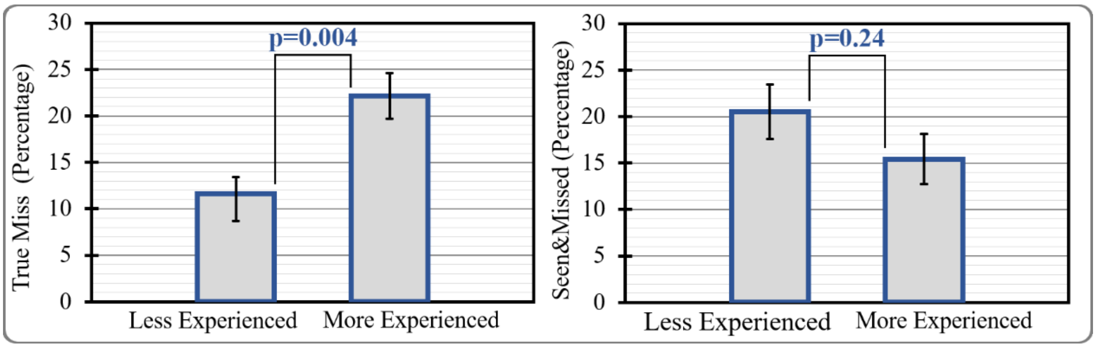

Figure 4.12. Rate of True Miss and Seen&Missed for More Experienced and Less Experienced groups

Mean rate of True Miss of the Less Experienced Group is 11.7% and of the More Experienced Group is 22.1%. The difference is statistically significant with p value of 0.004.

Mean rate of Seen&Missed of the Less Experienced Group is 20.5% and of the More Experienced Group is 15.4%. The difference is statistically non-significant with p value of 0.24.

The results were also analyzed according the groups Q1, Q2, Q3, and Q4. Rates of True Miss can be seen in Figure 4.13 and rates of Seen&Missed can be seen in Figure 4.14.

Mean rate of True Miss of the group Q1 is 8.2%, Q2 is 15.7%, Q3 is 21.8%, and Q4 is 18.9%. Mean rate of Seen&Missed of the group Q1 is 17.2%, Q2 is 24.3%, Q3 is 12.7%, and Q4 is 18.1%.

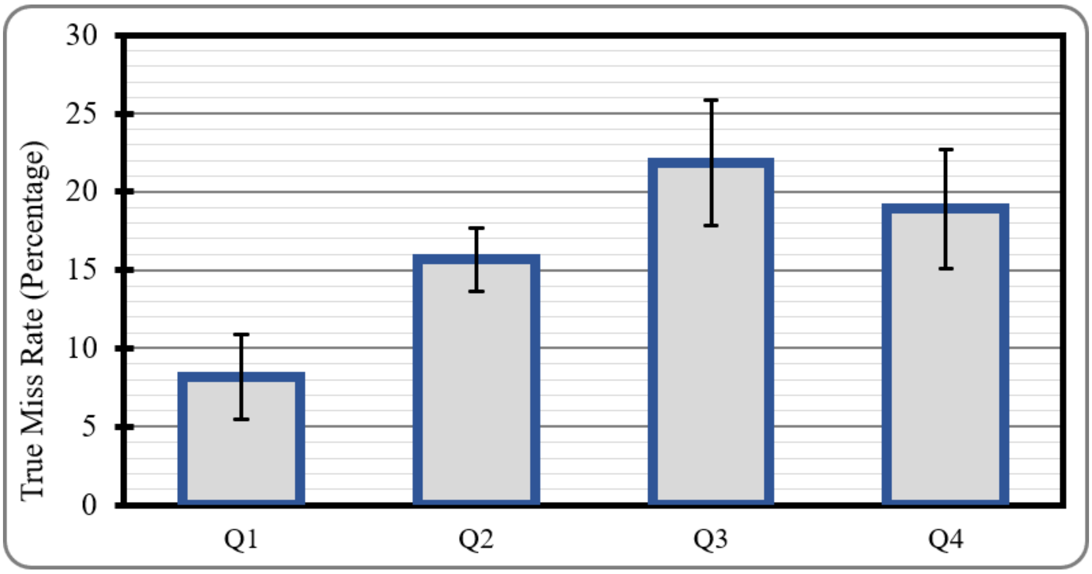

Figure 4.13. Rates of True Miss for groups Q1, Q2, Q3, and Q4

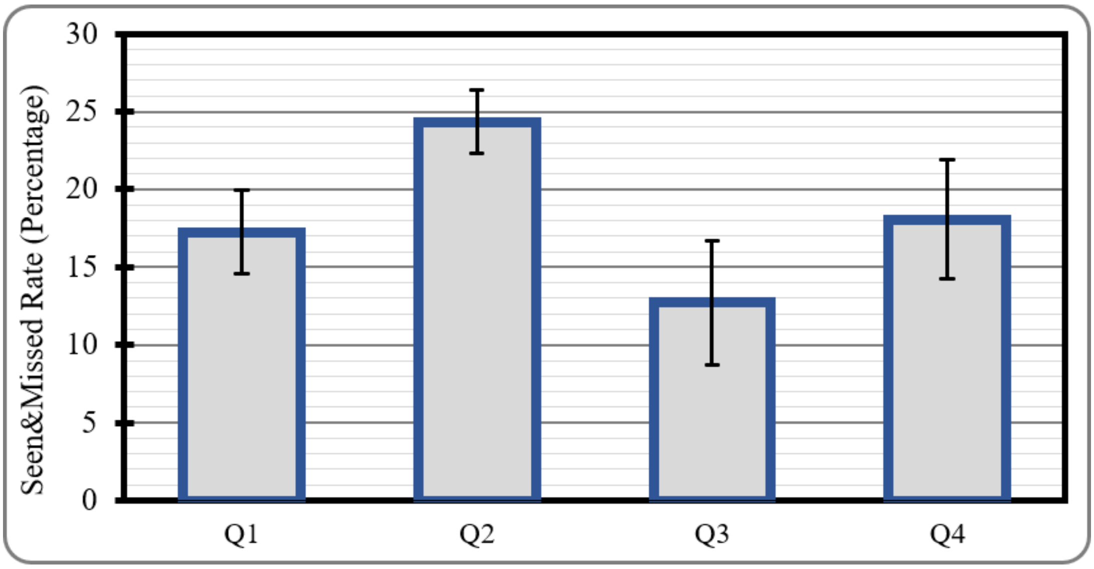

Figure 4.14. Rates of Seen&Missed for groups Q1, Q2, Q3, and Q4

4.5. Analyses by Hazard

Although it is not the in main the main scope of this research, analyses were conducted on individual hazards too. Reaction times and miss rates were analyzed for all hazards individually for level of experience and level of education groups. Two tailed t-test was conducted for reaction times to check statistical significance of differences.

4.5.1. Hazards and Education

Miss rates of Less Educated and More Educated groups can be seen in Table 4.4 and Figure 4.15. Mean of the reaction times of the subjects who did not miss the hazards can be seen in the same table and Figure 4.16, divided according the level of education. P values for the latter are also presented. It was not possible to run a t-test for the *Damaged Power Cord* because only one subject in the Less Educated Group had recognized the hazard.

Table 4.4. *Miss Rates and Reaction Times of Less Educated and More Educated groups*

Hazard	*Miss Rate*		*Reaction Time*		
	Less Edu. (%)	*More Edu. (%)*	*Less Edu (sec)*	*More Edu (sec)*	*p*
Harmful Substance Tanks	69	0	2,24	2,20	0.96
Unsecured Chainsaw on the Ground	62	57	1,86	1,08	0.26
Wooden Planks on the Ground	77	21	1,29	1,50	0.58
Unsecured Tools on Mobile Scaffolding	23	28	2,70	2,08	0.36
Ladder Propped on the Wall	46	14	3,20	3,72	0.55
Bucket on Windowsill	38	14	2,05	1,53	0.4
Stacked Wooden Crates	15	7	3,47	1,99	**0.01**
Unsecured Shaft Opening	31	36	3,90	2,05	0.07
Broken Safety Railing	23	0	1,98	1,54	0.27
Gas Tanks	8	7	4,80	4,06	0.54
Stacked Bricks	23	43	3,40	2,84	0.62
Hoist (Lifting Brick Stack)	38	14	2,28	2,35	0.93
Unsecured Bent Rebar	46	36	2,40	1,51	**0.02**
Unsecured Edge	38	14	1,60	2.00	0.54
Damaged Power Cord	92	64	0,96	1,60	-
Lifted Power Cord on the Ground	69	57	2,75	1,65	0.4

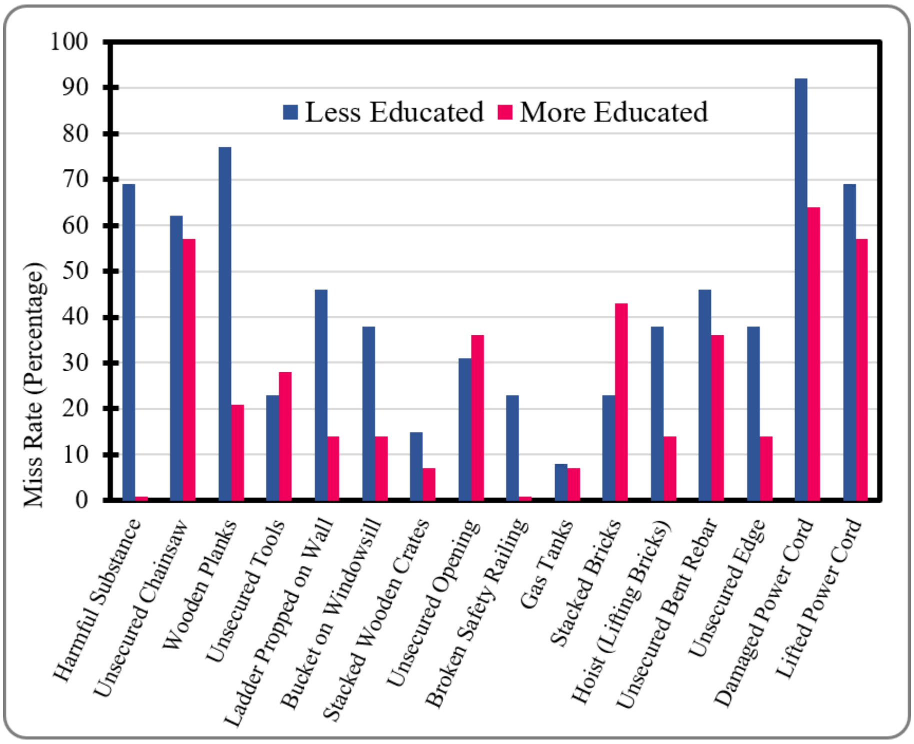

Figure 4.15. Miss Rates of Less Educated and More Educated groups

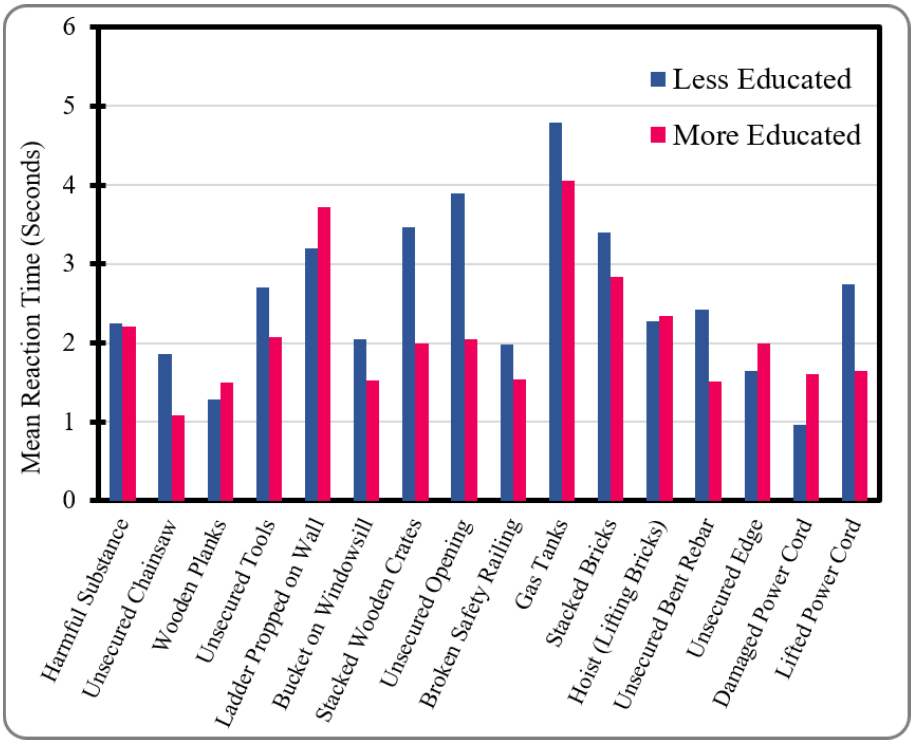

Figure 4.16. Reaction Times of Less Educated and More Educated groups

4.5.2. Hazards and Experience

Miss rates of Less Experienced and More Experienced groups are in Table 4.5 and Figure 4.17. Mean of the reaction times can be seen in the same table and Figure 4.18.

Table 4.5. *Miss Rates and Reaction Times of Less Experienced and More Experienced groups*

Hazard	Miss Rate		Reaction Time		
	Less Exp (%)	*More Exp (%)*	*Less Exp (sec)*	*More Exp (sec)*	*p*
Harmful Substance Tanks	31	36	2,31	2,11	0.72
Unsecured Chainsaw on the Ground	62	57	1,20	1,52	0,55
Wooden Planks on the Ground	40	63,64	1,51	1,35	0,74
Unsecured Tools on Mobile Scaffolding	31	21	2,22	2,52	0,65
Ladder Propped on the Wall	31	29	2,85	4,31	0,11
Bucket on Windowsill	31	21	1,44	1,98	0,40
Stacked Wooden Crates	0	21	2,71	2,75	0,96
Unsecured Shaft Opening	31	43	3,38	2,63	0,47
Broken Safety Railing	8	21	1,47	1,98	0,14
Gas Tanks	0	14	4,98	3,78	0,29
Stacked Bricks	54	14	3,83	2,81	0,52
Hoist (Lifting Brick Stack)	8	43	2,67	1,80	0,27
Unsecured Bent Rebar	46	36	1,84	1,89	0,90
Unsecured Edge	20	15	2,17	1,58	0,36
Damaged Power Cord	77	79	1,79	1,00	0,21
Lifted Power Cord on the Ground	62	64	2,25	2,15	0,94

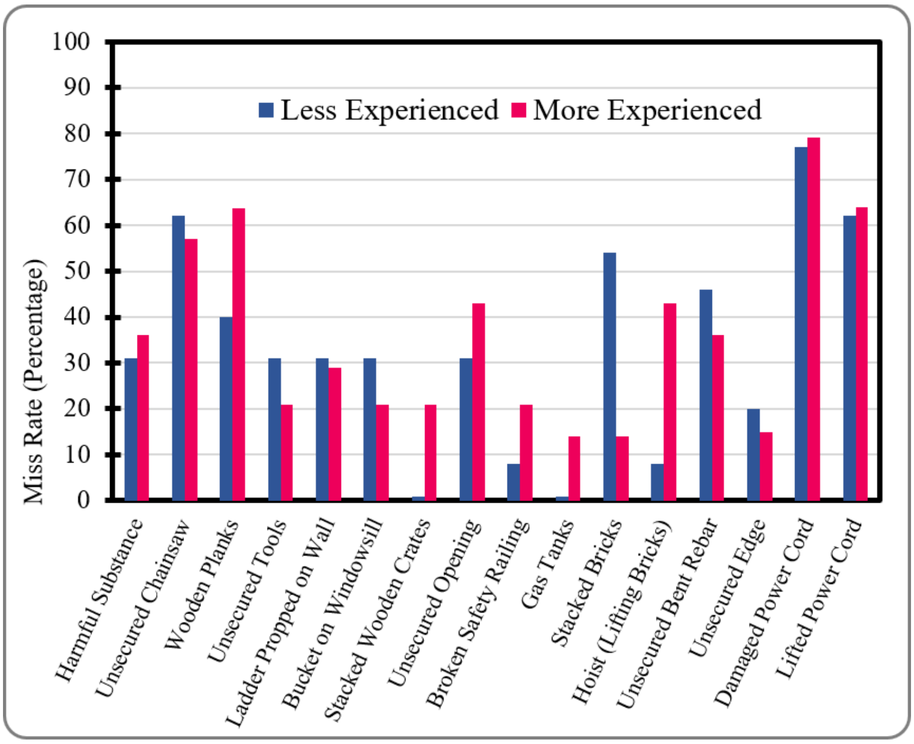

Figure 4.17. Miss Rates of Less Experienced and More Experienced groups

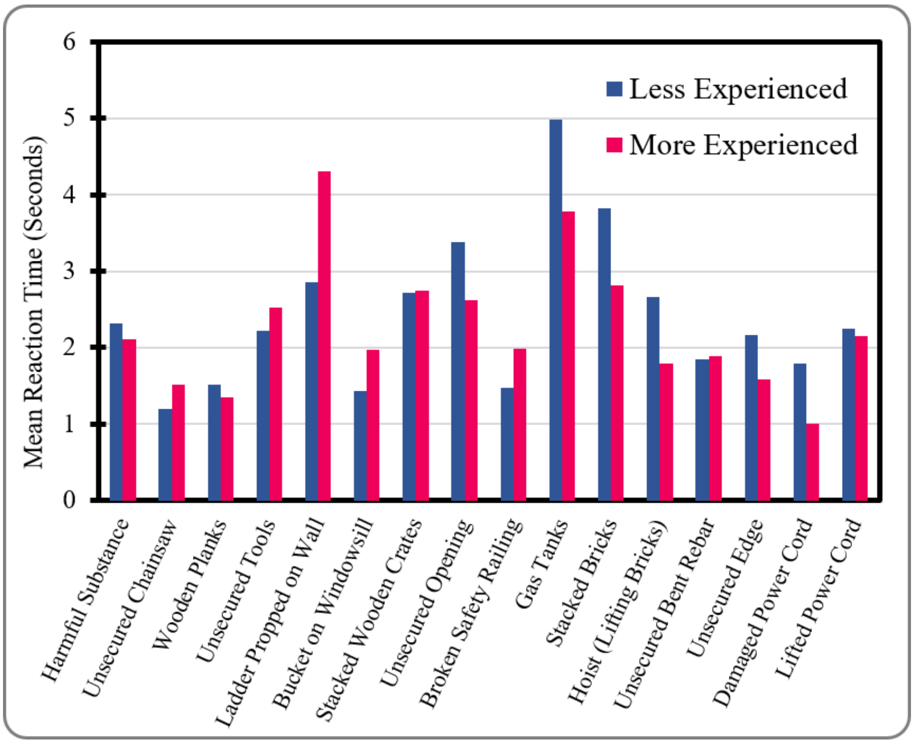

Figure 4.18. Reaction Times of Less Experienced and More Experienced groups

4.6. Questionnaire Results

The pre-experiment questionnaire has demographical questions. Information from it was used for categorizing the data. The post-experiment questionnaire is for evaluation of the experiment setup. The subjects were asked to rate the realism of the virtual construction site in a scale from 1 to 10, 1 being the least and 10 being the most realistic. Also, they were asked if they feel uncomfortable because of anything in the virtual environment. Third and the last question asks for any suggestions to improve the experiment setup.

The arithmetic mean of the answers given to the reality question is 8.81 out of 10. To the second question; four subjects answered they felt mild nausea, four subjects answered the higher resolution is needed, and two subjects answered the navigation system was hard to control.

CHAPTER 5

DISCUSSIONS

5.1. Chapter Disposition

This chapter of the thesis includes discussions on the results of the experiments and their analyses according to the framework drawn in the Introduction Chapter and in touch with the background provided in the Literature Review Chapter. Moreover, experiment setup is evaluated in this chapter. The first three topic namely "5.2. Discussion on the Effect of Education", " 5.3. Discussion on the Effect of Experience", and "5.4. Discussion on the Individual Hazards" are the discussions of the experiment results. The last topic is "5.5. Evaluation of the Experiment Setup". It is the discussion of the Virtual Construction Site that is developed for this study and the SMI Mobile Eye Tracking HMD which is used in the experiments.

5.2. Discussion on the Effect of Education

The null and alternative hypotheses related to the education are as follows:

- $H_0$1: Rate of recognition of hazards is not affected by level of education.
- $H_0$3: Hazard recognition speed is not affected by level of education.
- H_a1: Rate of recognition of hazards increases as level of education increase.
- H_a3: Hazard recognition speed increases as level of education increase.

Results of the experiments show that workers with higher level of formal education recognized significantly more ($p=0.000058$) hazards than those with lower level of education as it can be seen in Figure 4.1. This effect is visible also when the sample is divided into four groups according the level of education as seen in Figure 4.3. Based on this results $H_0$1 is refuted and H_a1 supported.

Analyses on the effect of education on recognition speed are also similar. More Educated Group recognized hazards significantly faster (p=0.021) than the Less Educated Group. These results can be examined in Figure 4.2. The trend is also visible when the sample is divided into four according to their level of education as Figure 4.4 shows. Therefore, $H_0 3$ is refuted and $H_a 3$ supported.

True Miss rates and Seen&Missed rates also support $H_a 1$. Both rates are higher for Less Educated group. The difference is significant (p=0.0005) only for Seen&Missed rates and non-significant (p=0.28) for True Miss rate though. The trend is also visible for both rates when the sample is divided into four.

It is apparent that the main reason for this difference is the hazards they saw but did not recognized as hazards. True Miss rates also increase as the level of education decrease but the difference is non-significant. Seen&Missed rates, however, is significantly more in Less Educated Group.

One possible explanation for the difference of hazards recognition speed and recognition rate between Less Educated and More Educated groups is the effectiveness of safety training. Ineffectiveness of traditional safety training methods has been declared by different researchers (Albert et al., 2017; Sacks et al., 2013). Considering safety training material is prepared and presented by the people with higher education, it is possible that safety training is even less efficient on people with lower level of education. This also explains the lower recognition speed of Less Educated Group. Because that their knowledge in hazards is inadequate, those with lower level of education struggles to recognize a situation as hazardous. Furthermore, the fact that effect of level of education is predominantly on Seen&Missed rate also supports this reasoning. Of course, all these explanations are in need of further research.

Another explanation is the safety culture of the Less Educated group. Swuste et al. (2012) address in Hong Kong, construction workers consider themselves as *tough guys* and caring about safety is considered cowardness. This *tough guy* culture might be more prominent among workers with lower level of education and it could explain the higher miss rates of Less Educated Group. However, if this was the case, True Miss rate should have been the main reason of the difference not the Seen&Missed rate. Less Educated Group would scan the scenes carelessly and do not even fixate on hazards. Moreover, longer reaction times is also hard to explain with safety culture. The difference in True Miss rate might be explained with this kind of a safety culture though. It is plausible that the effect of the *tough guy* culture gets more prominent as the level of education decrease, and cause a less careful scan of the environment.

Nonetheless, the difference in the True Miss rates still worth further studying even though the difference in not statistically significant. Because visual examination of the Figure 4.5 and 4.6 suggests level of education also has an effect on True Miss rates too.

5.3. Discussion on the Effect of Experience

The null and alternative hypotheses related to the education are as follows:

- $H_0 2$: Rate of recognition of hazards is not affected by level of experience.
- $H_0 4$: Hazard recognition speed is not affected by level of experience.
- $H_a 2$: Rate of recognition of hazards increases as level of experience increase.
- $H_a 4$: Hazard recognition speed increases as level of experience increase.

Results of the experiments show that workers with higher level of experience recognized slightly less hazards than those with lower level of experience and the difference is statistically insignificant ($p=0.15$) as it can be seen in Figure 4.8. Moreover, a relationship between level of experience and hazard recognition rate cannot be seen when the sample is divided into four groups according the level of experience as seen in Figure 4.10. Based on these results $H_0 2$ is supported.

Analyses on the effect of experience on recognition speed are also similar. More Experienced Group recognized hazards slightly faster than the Less Educated Group and the effect is statistically non-significant ($p=0.48$) as seen in Figure 4.9. Analyses made of four group divided according to the level of experience also does not indicate a relationship between level of experience and hazard recognition speed as seen in 4.11. Results support $H_0$4.

Analyses indicate that recognition performance, neither recognition rate nor recognition speed, is not affected by the level of experience. These results are in line with the results from previous studies which suggest experienced workers do not recognize significantly more hazards than inexperienced workers (Dzeng et al., 2016; Perlman et al., 2014).

On the other hand, Seen&Missed and True Miss rates show differences in different levels of experience. These differences can be seen in Figure 4.12 for Less Experienced and More Experienced groups. True Miss rate of More Experienced Groups is significantly higher (p=0.004) then the Less Experienced Group. On contrary, Seen&Missed rate is higher of Less Experienced Group is higher, but the difference is not statistically significant (p=0.24).

A probable explanation of this situation is the confidence and a false sense of safety that comes with experience. This is something suggested in some previous studies based on observations (Namian, Zuluaga, & Albert, 2016; Šukys, Čyras, & Šakėnaitė, 2011). Now there is also qualitative analyses to support this explanation. Higher True Miss rate of More Experienced Group implies they search for hazards more carelessly than the Less Experienced Group. This effect does not reflect on the total miss rate because the More Experienced Group is more successful at recognizing the hazards they fixate on, which is apparent in their lower Seen&Missed rate. True Miss rate and Seen&Missed rate neutralize each other. However, the results are not totally conclusive. The difference in Seen&Missed rates is not statistically significant. Moreover, the difference in True Miss and Seen&Missed rates is not very traceable when the sample is divided into four as seen in Figure 4.13 and 4.14. This is especially true for Seen&Missed rates (Figure 4.14).

In terms of effect of experience, the differences on True Miss and Seen&Missed rates between the workers with different levels of experience is promising and worth further studying. The relationship between these differences and the concept of safety complacency gained with experience can be discussed in more detail under the light of additional data.

Several differences between the inherent structure of this study and previous studies may potentially increase the understanding of the impact of work experience on hazard recognition. While the results of the study support the finding of the earlier studies on, we may now have a clearer picture. This is due to several factors that are different from previous studies that has tested the effect of the experience.

Firstly, previously unmeasured variables like reaction time and more importantly, True Miss and Seen&Missed rates of the hazards were measured via eye tracking. As discussed earlier, the results show that based on the experience of the subjects it can be seen that subjects have a tendency to ignore the hazards all together or ponder on objects but not recognize them as hazards.

Secondly, HMD based VR that is used in this thesis provides a higher level of immersion than fish tank (desktop based) VR and CAVE VR settings that were used in the previous studies. Higher immersion means that the visual interaction of the subjects with the virtual environment would be more realistic. This may help the subjects to take the experiment more seriously. Moreover, virtual construction site in this thesis has a higher fidelity than the previous ones. Therefore, overall experiment setting is more realistic than the previous studies.

Finally, the sample of the present study is exclusively composed of professionals. Most of the previous studies had considerable number of students in the sample and it is clear that data from construction professionals would be more valid.

5.4. Discussion on Individual Hazards

Results of the individual hazard analyses are not very conclusive. First of all, since the data set of miss rates for hazards is binary (a hazard is either recognized or not), not quantitative, it is not possible to run statistical significance test on this data. Secondly, as the miss rate increase for a hazard, MRT analyses becomes less valid because reaction time data is only available when the hazard is recognized. Yet still there are some results that are worth discussing.

Parallel to previously mentioned results in "5.3. Discussion on the Effect of Experience", none of the differences between less and more experienced groups in MRT is statistically significant. For nine of the hazards miss rate is higher for the More Experienced Group and for seven of the hazards miss rate is higher for the Less Experienced Group. Moreover, the difference between miss rates is less than 10% for nine of the sixteen hazards. These results support $H_0 2$ and $H_0 4$, and therefore the previously mentioned outcome that experience is not related to hazard recognition performance is supported.

More Experienced Group has more than 20% higher miss rates in "Wooden Planks in the Ground", "Hoist (Lifting Brick Stack)", "Stacked Wooden Crates", and Less Experienced Group has more than 20% higher miss rates in "Stack Bricks". The data on these differences are not enough to reach to any results but they are still worth mentioning.

Results of the education groups are again parallel to the results discussed in "5.2. Discussion on the effect of Education" topic. In thirteen out of sixteen hazards, miss rates are higher for the Less Educated Group. In eleven hazards reaction time is slower for the Less Educated Group; however, the difference is statistically significant only in "Stacked Wooden Crates" ($p=0.01$) and "Unsecured Bent Rebar" ($p=0.02$). These results partially support $H_a 1$ and $H_a 3$ Therefore the previously mention outcome that hazard recognition performance increases as the level of education increases is partially supported.

Lastly, data from individual hazards is meaningful in terms of showing the effectiveness of the tool and the methodology. If the aim was to analyze performance of a single worker, very detailed qualitative analyses and discussions could be made based on this data. An education or safety competency test tool which can give personal and detailed feedback can be designed based on this system.

5.5. Evaluation of the Experiment Setup

Two major materials of this study are the virtual environment and the HMD used for taking people inside this virtual environment. They are discussed in terms of reactions from subjects and considerations of the research team.

5.5.1. The Virtual Construction Site

In the post-experiment questionnaire, the subjects were asked to evaluate the realism of the virtual construction site and indicate the problems they faced in it. The mean of the answer to the reality question is 8.8/10. The lowest answer is six and the highest one is ten. This result shows at least a satisfactory level of fidelity had been achieved for all subjects. Moreover, some of the subjects gave positive feedback about how they liked the virtual construction site, without being asked. The virtual construction site also has been inspected by three occupational health and safety specialists and has been approved by them.

A major advantage of using a digital model is the practicality and flexibility that it provides. The assets created for this study can be used for modelling new scenes in the virtual construction site effortlessly. It is also possible to create new assets, add them to the virtual construction site and enlarge the scenes. Furthermore, the model can be modified to test different variables, collect different data, or improve the mechanics of the system easily.

Hazards in the virtual construction site are determined regarding to several researches as pointed out in “3.2.2. Experiment Design”. That means they are derived from hundreds of hours of observations, researches, and discussions collectively. Even if it was not asked, some of the subjects noted after the experiment that hazardous situations were really close to real hazardous situations they face in construction sites.

There are some limitations about the virtual constructions site. First of all, the scenes include only a single space. After switching into a scene, the subjects do not require to walk into another room. There are two reasons for this. The HMD used in the experiments does not have a body tracking feature. Therefore, movement inside the virtual environment has to be done by a controller instead of walking in the real world. Subjects could have been distracted in case of complex movement requirements. Even at current state, two of the subject reported movement in the VR was challenging. The second reason is that SMI Mobile Eye Tracking HMD has a limited processing power and the more complex the virtual environment is the heavier the load on the HMD would be. On the other hand, abovementioned digital practicality of the model enables quick and feasible solutions to these limitations when the hardware limitations can be tackled.

Even though the subjects rated realism of the virtual construction site, it is far from being photorealistic. It can be discussed whether it has to be photorealistic or not for his kind of an experiment. However, considering the current state of computer graphics, it is clear that there are a lot of room for improvement in its graphical quality.

5.5.2. SMI Mobile Eye Tracking HMD

General impression of the research team about the SMI Mobile Eye Tracking HMD and reactions of the people to it were very positive throughout the research. The research team did not face any unsolvable problems and the comments from the subjects did not indicate any serious flaw.

Being mobile is one of the most important features of the HMD. Bringing workers to a fixed location was reported to be one of the major problems of VR studies (Sacks et al., 2013). SMI Mobile Eye Tracking HMD can be carried in a backpack and its setup takes only one minute. It was possible to bring it to the workplaces of the subjects so that they could attend to the experiments easily. It would be much harder, if not impossible, to conduct this kind of an experiment in a fixed location. Moreover, it does not have any spatial needs, a regular office room is sufficient for it to be used. More number of mobile HMDs like Oculus Quest or HTC Cosmos has become available recently. They are more capable devices than SMI Mobile Eye Tracking HMD with higher processing power and 6 degree of freedom tracking. It is reasonable to expect they will also receive eye tracking enabling retrofits like some other HMDs. In this case, conducting VR experiments, either in construction safety or other topics, would be much more feasible. Data gathered with possible new methods that would be enabled with these new devices could give us new perspectives in many areas.

However, there are also downsides of using a mobile HMD. There is a tradeoff between mobility and processing power. Most of the time mobile devices have weaker processors than their less mobile or stationary counterparts. As explained in the "3.2.2. Experiment Design", an extensive effort had to be spent on creating a less demanding virtual environment.

Another possible problem of using a mobile device for extended periods is overheating. The HMD used in the experiments is a slightly modified version for better cooling performance and overheating problems did not occur during experiments. But the heat level of the device increased perceivably during successive experiments.

There were no problems caused by eye tracking capabilities of SMI Mobile Eye Tracking HMD. The frequency and precision of it is enough for hazard recognition studies. However, it should be noted that area of interests in this study were quite large. It wouldn't be nearly enough for more sensitive research areas like reading studies. Eye tracking scripts provided by SMI is working without any major problems in Unity.

One of the biggest setbacks of the SMI Mobile Eye Tracking HMD is its resolution. Screen resolution of the Galaxy S7, which is used in the HMD, is 2560x1440. It is not a problematic resolution when viewed from a distance, but HMDs place the screen a few centimeters away from the user. When viewed from such short distance, pixels become visible to the user. Moreover, the *screen-door effect* which is explained in "2.6. Critical Analysis of the Literature" is more apparent and disruptive in lower resolutions. This situation affected this study too. Four of the subjects named low resolution of the HMD as a problematic part of the experiment setup. One of the subjects noted it was hard to read warning signs from a distance due to low resolution.

As indicated in "3.2.2. Experiment Design", SMI was acquired by Apple in 2017. Therefore, SMI Mobile Eye Tracking HMD is not getting software updates. Most of the interoperability problems caused by this issue is solvable by using older versions of other software; however, this situation seriously harms fluidity of experiment design process. Furthermore, it disables some opportunities. For example, some of the asset packages in Unity Asset Store cannot be used because of an older version of Unity have to be used or importing models from SketchUp becomes a very cumbersome process.

Since the controller used in the experiments is very similar to majority of the controllers used for video gaming, most of the subjects were observed to be familiar with it. Considering VR was a new experience for most of the subjects (%78 of the subjects had never used an HMD before) familiarity of the controller may have had a positive impact on their adaptation to VR.

CHAPTER 6

CONCLUSIONS

6.1. Conclusion of the Thesis

There is no denying of hazardous nature of construction sites, neither among the professionals nor the academia (Swuste et al., 2012). This is a natural call for more research in this area. Hazard recognition is a major element in construction safety management. To be able to mitigate the risk, a hazard should be recognized first. However, workers constantly fail to recognize many of the hazards (Perlman et al., 2014). This problem requires further intervention. As we increase our understanding of hazard recognition and methods of improving it, we could intervene more successfully to this safety problem.

To address this issue; an experiment setup is developed to test hazards recognition skills of construction site workers with different levels of formal education and work experience. The main component of this experiment setup is an immersive VR based hazards recognition test. It comprises a virtual construction site with various hazardous situations placed in it. The virtual construction site is experienced via an eye tracking enabled head mounted display. In the experiments, the subjects were asked to examine the virtual construction site and push a button when they saw a hazardous situation. Meanwhile, their eye movements were recorded.

Two types of indicators are determined for the measurement of hazards recognition performance. The first one is the miss rate. It is the ratio of missed hazards to all hazards present in the virtual construction site. For the second indicator, timings of the fixations of the subjects' eyes on the hazards and timings of the button pushes are superimposed on a timeline. The time between a fixation and button push is recorded as hazard recognition speed. Results are analyzed based on these two indicators.

Data from twenty seven construction site workers were analyzed. Among them there were unskilled workers, skilled workers, foremen, architects and engineers from three different companies. Subjects were divided into groups according to their levels of formal education and work experience. Results were analyzed according to these groups.

There are two main contributions of this study. The first one is to provide deeper knowledge about hazard recognition skills of the construction site workers. Miss rates and recognition times of the subjects were analyzed for groups divided according the levels of education and experience. The results show that more educated workers have a better hazard recognition performance according to both indicators. The differences are statistically significant. This result might be explained with ineffectiveness of safety training on the less educated workers and partly effect of difference of safety culture among less educated and more educated workers.

On the other hand, according to the analyses, level of experience has no effect on either miss rate or recognition speed. This result is parallel to similar previous studies (Dzeng et al., 2016; Perlman et al., 2014). Deeper analyses on the data suggest that, even though the hazard recognition performances of less experienced and more experienced groups are almost the same, the reasons behind their limited performances might be different. Less experienced workers usually fixate on the hazards yet still they struggle to recognize it. On the other hand, weight of truly unseen hazards is higher in more experienced workers. This situation might be explained with the effect of increased knowledge and a false sense of safety on the more experienced workers. Increased knowledge makes it easier for experienced workers to recognize hazards, however; it also creates a false sense of safety and makes their search for hazards less careless.

Inefficiency of current construction safety training methods has been pointed out repeatedly (Albert et al., 2017; Sacks et al., 2013) This study can help improving these methods both directly and indirectly. Results summarized above would increase knowledge base in hazard recognition behavior of construction site workers. It could directly help improving the training methods. Furthermore, the system itself could be used as a training tool. Detailed, personalized, and realistic measurement of hazard recognition skill is possible and feasible via the proposed system.

The second contribution is the introduction of a novel methodology for construction safety studies. Three key technologies are used together for this methodology. The first one is mobile immersive VR. It has several benefits. First of all, it solves a very central problem in safety related empirical studies. It is unethical to expose subjects to unsafe situations. Immersive VR is an ethical and feasible solution to this problem. Moreover, since the HMD used in this study is completely mobile, it is possible to bring the experiment setup to the subjects, instead of bringing subjects to a fixed location. Considering the rapid advancement in mobile HMD technology, it can be foreseen they will be more and more effective and affordable for research purposes. Second technology is eye tracking. Eye tracking in HMDs allows collection of honest, unbiased data noninvasively. Moreover, subject can be uninformed about eye tracking during the experiment. An eye tracking enabled HMD provides the same user experience with a regular HMD other than a single very short calibration. Previously unexplored aspects of hazards recognition behavior could be studied with help of eye tracking in an immersive environment. The third one is the game technologies. Game engines and modelling techniques used in games could help designing financially feasible, flexible, repeatable and high-fidelity experiments. Gathering data in game engines is also quite practical. Combination of these three technologies enables a novel research methodology for construction safety methodology which is ethical, practical, financially feasible, and flexible.

At the end of every experiment, Subject were asked to evaluate the virtual construction site designed for this research. Mean score that the virtual construction site has received is 8.8/10. Subjects were also asked if they had experienced anything uncomfortable or disturbing during the experiments. A small number of subjects reported mild nausea and hardship in movement in the VR. Other than these, no problems were reported. These feedbacks indicate that subjects' thoughts about the experiment setup were generally positive.

6.2. Limitations and Future Research

This research has some limitations. First of all, even though the subjects gave very positive feedback about the realism of the VR experience, the VR employed in this study is definitely not undistinguishable from the real world. Secondly, solely trying to find hazards might be different from recognizing a hazard while being focused on a different task. The distraction caused by a task could affect the results.

There are also some minor limitations caused by the HMD used in the experiments. In short, low resolution of the HMD has limited the immersion of the VR, design of the virtual construction site was bounded by the rather low processing power of the HMD, and lack of location tracking caused some movement problems. A comprehensive evaluation of the HMD is present in "5.2.2. SMI Mobile Eye Tracking HMD" including these limitations.

These limitations about the HMD also bring out some potential future works and improvements over the current methodology. There are already some HMDs like Oculus Quest and HTC Vive Focus which are completely mobile as the HMD used in this research and has more advanced processing capabilities. Moreover, they have integrated 6 degrees of freedom tracking which means they can track the location of the subjects without any external trackers. Therefore, more immersive and higher fidelity experiment setups are possible. Furthermore, it is reasonable to expect even more advanced HMDs to be released in the future. One drawback, however, is that these HMDs do not have eye tracking natively. They would require eye tracking retrofits to allow this kind of a research.

It is also worth stating that construction sites are very complicated environments. Thousands of different hazards can be present in a construction site and it is not possible to include all of them in an experiment. Moreover, more complex types of constructions could include more complex hazardous situations. On the other hand, all of the central event groups documented in the literature are represented in the virtual construction site and the virtual construction site has been reviewed by several health and safety professionals and approved by them.

One of the interesting findings that could lead to future research is the difference in the types of unrecognized hazards between more experienced and less experienced groups. The results implicate less experienced workers see the hazards but cannot recognize them, while experienced workers do not see them at all. The data is not solid enough to make a bold statement; however, there is certainly a research potential on this specific aspect of hazard recognition. The root cause of this situation; its relationship with attention, risk perception, worker attitude, or safety culture could be examined. Further and wider studies are recommended.

The above mentioned second contribution of this study is also naturally a call for many types of empirical construction site safety research. Research ideas that are restrained by ethical, practical, or financial issues could be realized with the suggested methodology.

Customized training methods could be developed for groups with different levels of education or experience since their understanding and capabilities of hazard recognition seem to be different from each other. Information gathered could be used for development of more successful training methods with contribution from the construction professionals. Furthermore, validation of the efficiency of the safety training and detection of its shortcoming would also be possible on a personal level.

Workers constantly get killed, become disabled, get seriously injured in construction sites all around the world. This thesis is a tiny step inside a combined effort of prevention of these tragedies. More research that will deepen the knowledge on safety issues, improve safety training and management methods, directly or indirectly affect safety culture on sites and cause improvements on many other aspects of construction site safety is required.

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APPENDICES

A. Hazard Images

This is the first appendix of this thesis. It includes screenshots of hazardous situations in the scene 2 and the scene 3. This appendix is needed because hazards needs to be shown in large images to be correctly understood; however, it would not be feasible to put 18 full page images inside the main text. Hence, smaller versions of the images were put in the main text and full-page images were left to this appendix.

Screenshots were taken in the scene window of Unity. Lighting levels are increased in Unity to be able to show the hazards clearer.

Figure A.1. Scene 2, Bucket on Windowsill

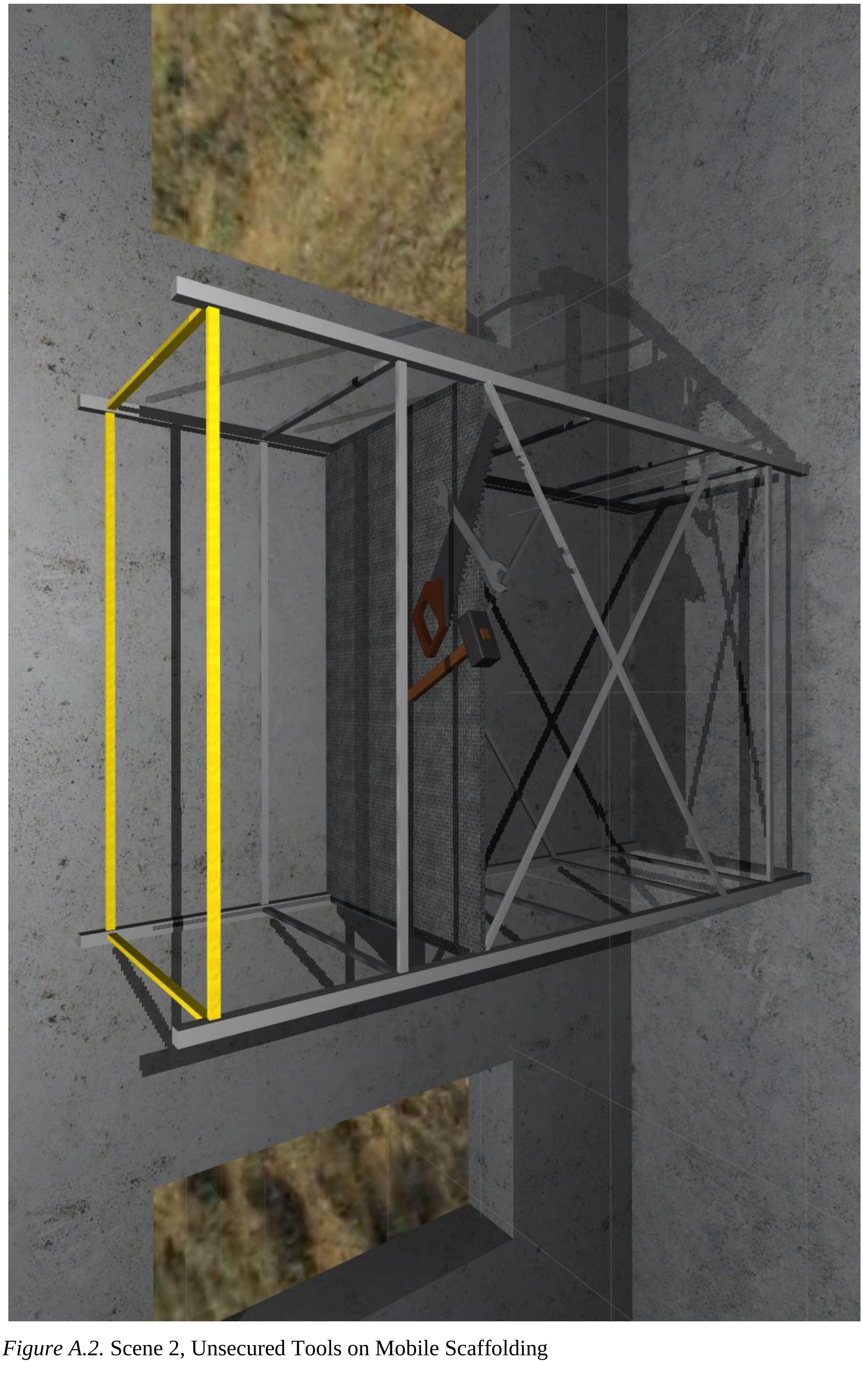

Figure A.2. Scene 2, Unsecured Tools on Mobile Scaffolding

Figure A.3. Scene 2, Unsecured Chainsaw on the Ground

Figure A.4. Scene 2, Harmful Substance Tanks

Figure A.5. Scene 2, Wooden Planks (with nail on one) on the Ground

Figure A.6. Scene 2, Unsecured Shaft Opening

Figure A.7. Scene 2, Ladder Propped on the Wall

Figure A.8. Scene 2, Stacked Wooden Crates

Figure A.9. Scene 3, Flammable Tanks

Figure A.10. Scene 3, Hoist (Lifting Brick Stack)

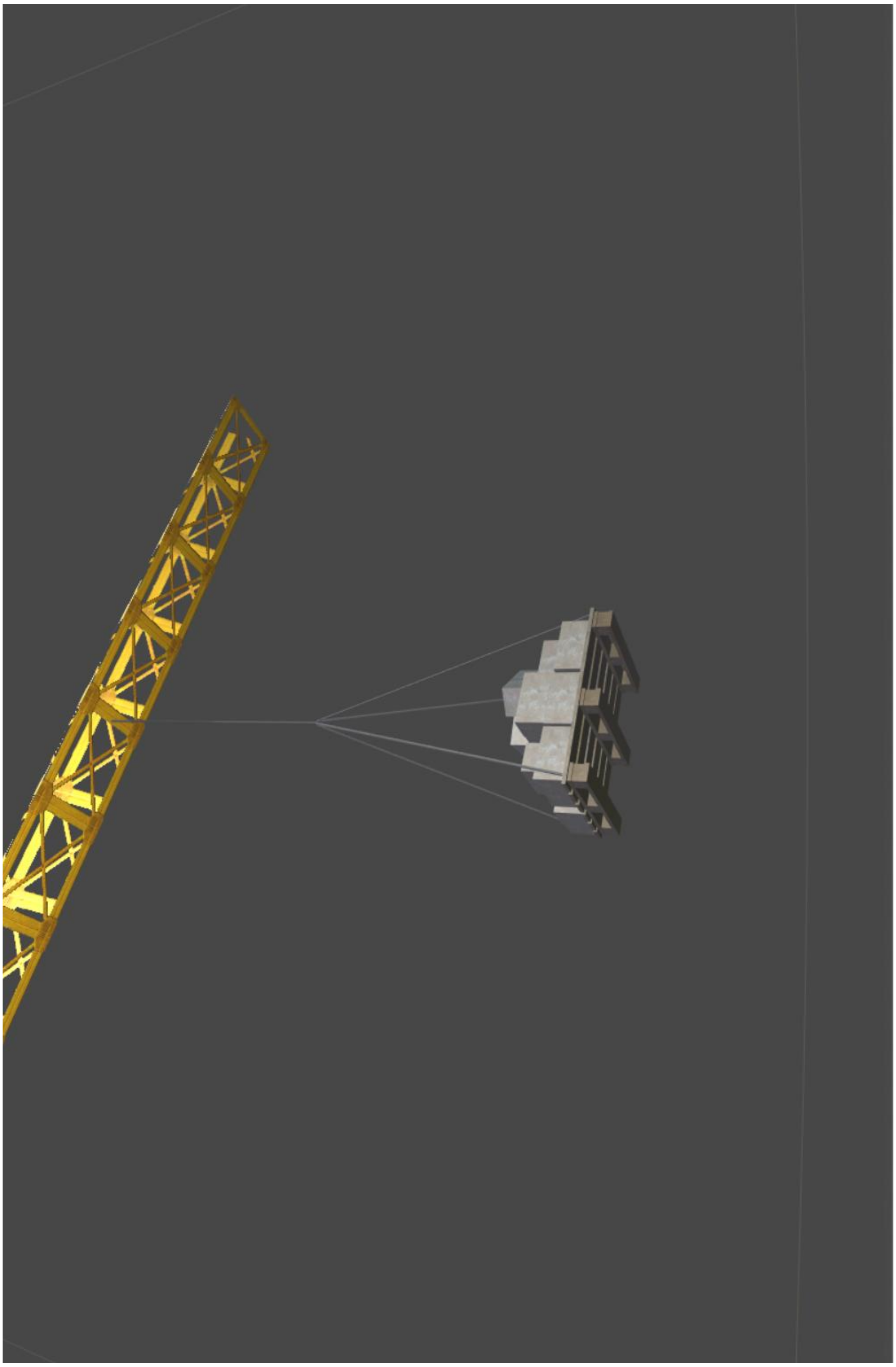

Figure A.10. Scene 3, Hoist (Lifting Brick Stack)

Figure A.11. Scene 3, Broken Safety Railing

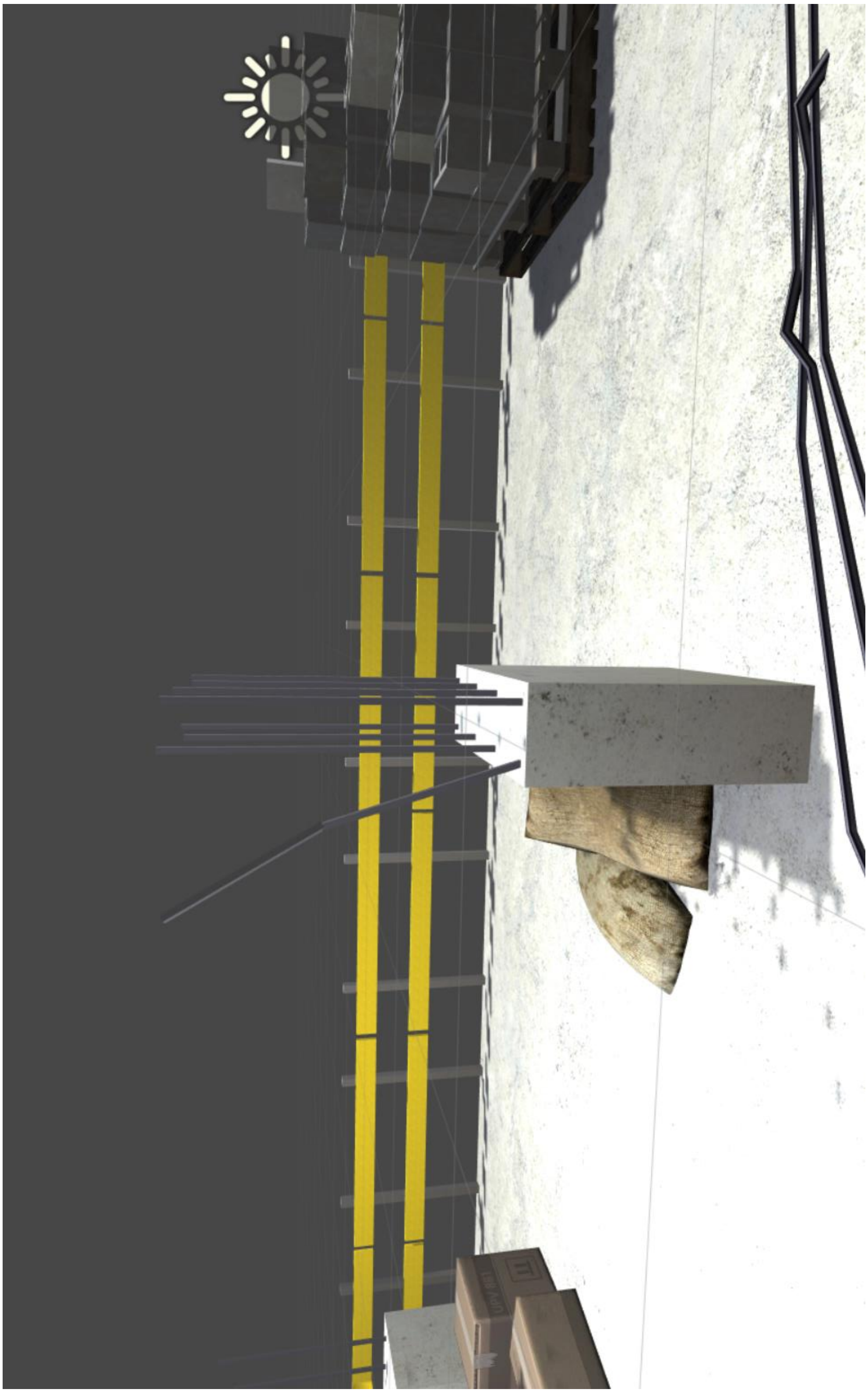

Figure A.12. Scene 3, Bent Rebar

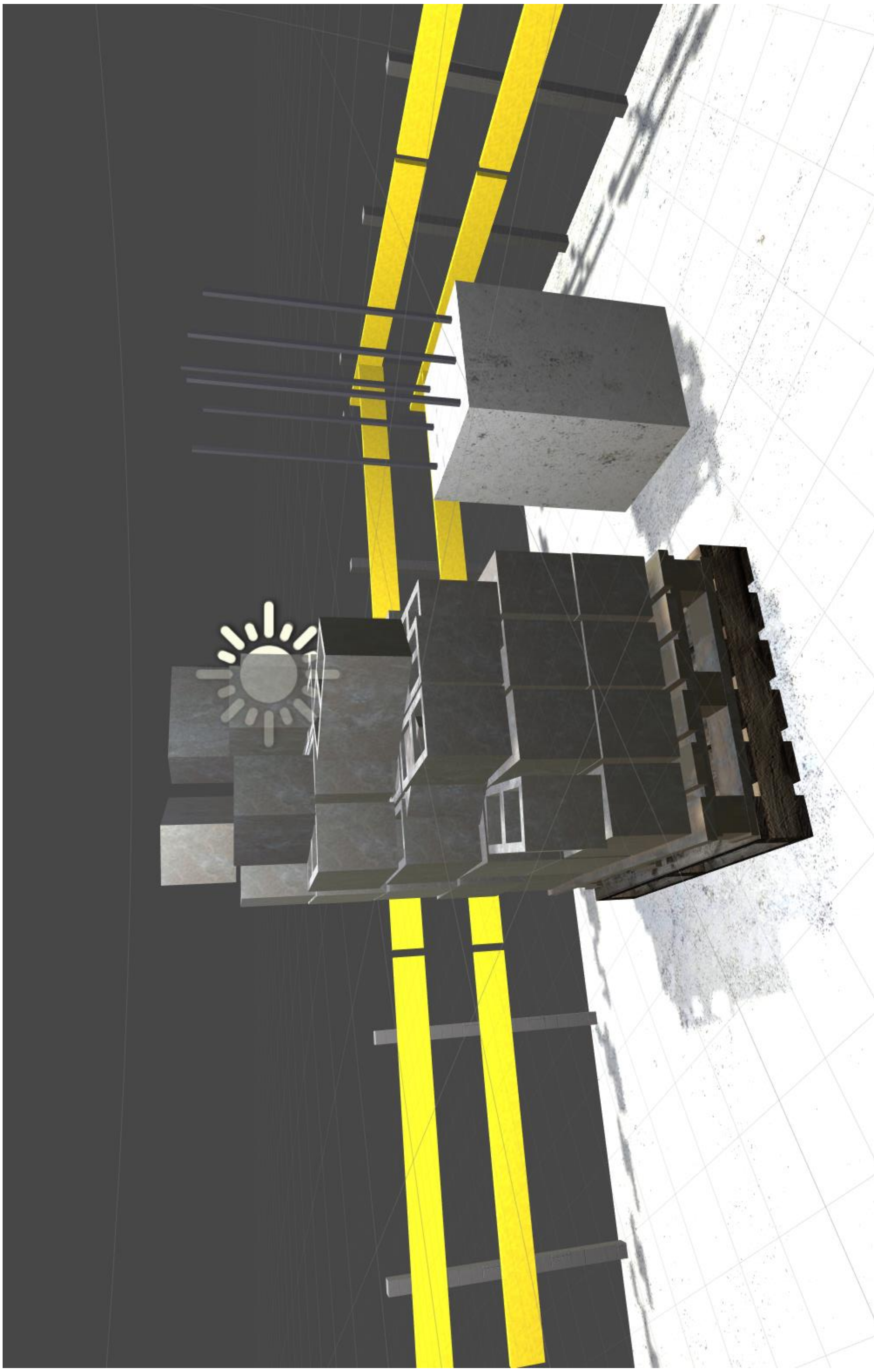

Figure A.13. Scene 3, Stacked Bricks

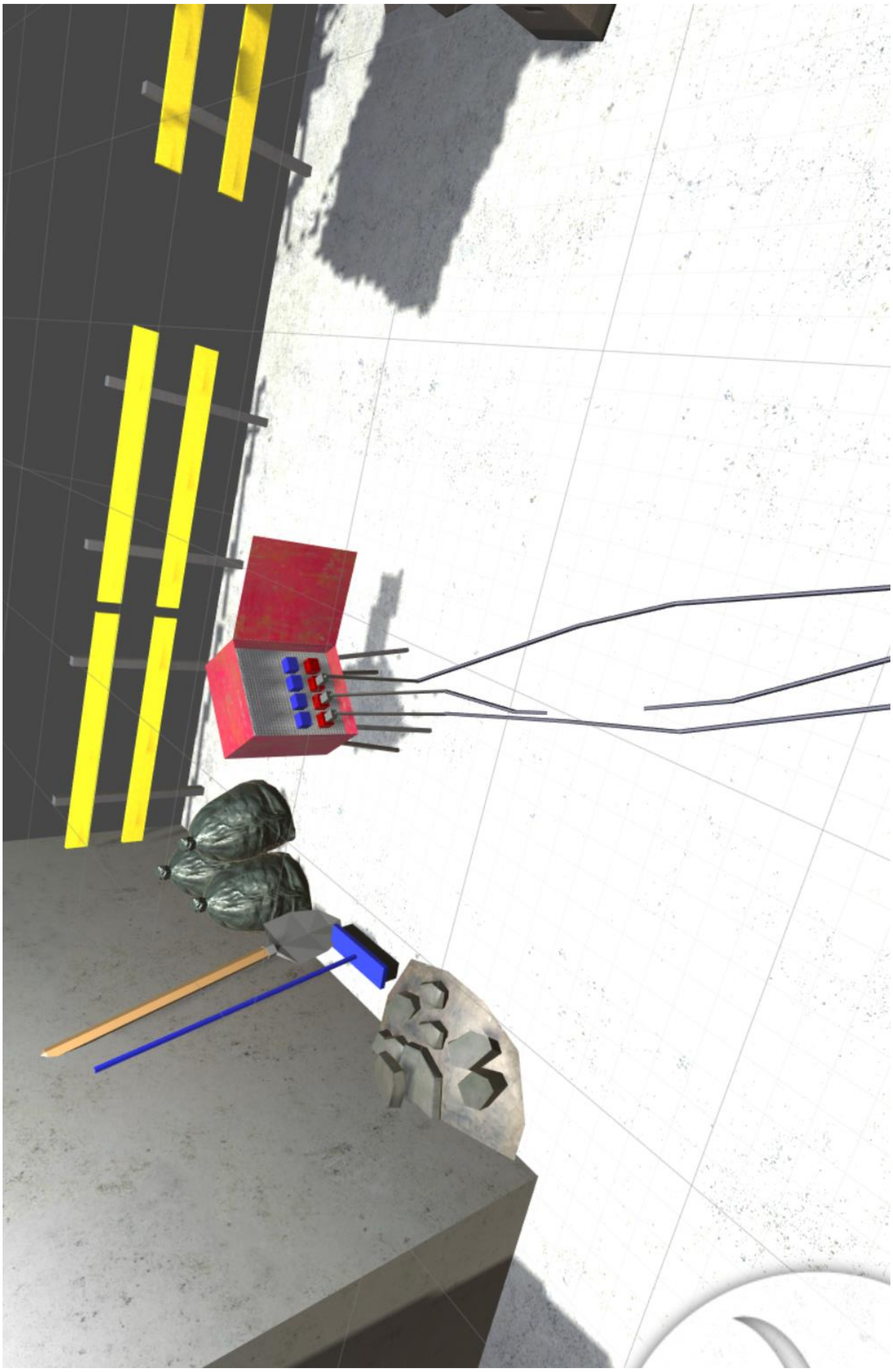

Figure A.14. Scene 3, Damaged Power Cord

Figure A.15. Scene 3, Lifted Power Cord on the Ground

Figure A.16. Scene 3, Unsecured Edge

B. Questionnaires & Forms

This is the second appendix of this thesis. It includes pre-experiment questionnaire, post-experiment questionnaire, voluntary participation form, and post-experiment briefing form. Both Turkish and English versions of the mentioned documents are present.

Deney Öncesi Formu

Deneyimize katıldığınız için teşekkür ederiz. Aşağıdaki soruları cevaplamanızın ardından bir sanal gerçeklik gözlüğü yardımı ile sanal bir şantiyenin içine gireceksiniz. Yapmanız gereken, sizin için veya bir başkası için tehlike oluşturabilecek bir durum gördüğünüzde size verilecek olan kumanda kolundaki düğmeye basmaktır. Deneyde kullanılan cihazların insan sağlığına herhangi bir zararı bulunmamaktadır. Deneyin ilerleyişi ile ilgili talimatlar görevli tarafından verilecektir. Tahmini deney süresi toplam 10 dakikadır.

Lütfen aşağıdaki soruları cevaplayınız. **Cevaplarınız ve deney sonuçlarınız hiçbir şekilde kişisel bilgilerinizle eşleştirilmeyecektir.**

1. **Yaşınız**

2. **Şantiyede toplam çalışma yılınız**

…… yıl şantiyede çalışma tecrübem var.

3. **En son mezun olduğunuz okul**

A.) Yok
B.) İlkokul
C.) Ortaokul
D.) Lise
E.) Ön Lisans
F.) Lisans
G.) Yüksek Lisans/Doktora

4. Aldığınız güvenlik eğitimlerinin toplam saati

…… saat güvenlik eğitimi aldım.

5. Şantiyedeki yaptığınız iş

………………………………………………….. olarak çalışıyorum.

6. Daha önce hiçbir sanal gerçeklik gözlüğü kullandınız mı?

☐ Evet, kullandım ☐ Hayır, kullanmadım

Pre-Experiment Questionnaire

Thank you for participating our experiment. After you answer the questions below, you are going to enter a virtual construction site via a virtual reality headset. You are asked to do is to push a button on the controller when you see a hazardous situation. The equipment used in the experiment does not have effect on any health. Further instructions will be given by the attendant. Expected experiment duration is 10 minutes.

Please answer the questions below. **Your answers and you experiment results will not be matched with your personal information.**

1. Your age

2. Your total working years in construction sites

I have …… years of construction site experiment.

3. Your last graduation is from

A.) None
B.) Primary School
C.) Middle School
D.) High School
E.) Vocational Collage
F.) University
G.) Post-Graduate

4. **Total safety training received**

I have received …… hours of safety training.

5. **Your duty in construction site**

I work as ……………………………………………… in construction sites.

6. **Have you ever used a virtual reality headset?**

☐ Yes, I have ☐ No, I have not

Deney Sonrası Formu

Lütfen sanal şantiyeyi gerçeklik açısından 1 ile 10 arasında puanlayınız.

1 2 3 4 5 6 7 8 9 10

Sanal şantiyede sizi rahatsız eden bir durum olduysa lütfen belirtiniz.

…………………………………………………………………………………………

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Deney sisteminin geliştirilmesi için bir öneriniz varsa lütfen belirtiniz.

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Post-Experiment Questionnaire

Please rate the virtual construction site 1 to 10.

1 2 3 4 5 6 7 8 9 10

Please note if there was anything uncomfortable for you in the virtual construction site.

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Please note if you have any suggestions for us to improve the experiment setup.

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Araştırma Sonrası Bilgilendirme Formu

Öncelikle araştırmamıza katıldığınız için teşekkür ederiz.

Bu çalışmanın amacı, eğitim seviyesi/iş tecrübesi ile riskli durum fark etme hızı arasındaki ilişkiyi incelemektir. Toplanan veriler bu yönde analiz edilecektir.

Bu amaçla, sizden kısa bir sanal şantiye deneyine katılmanız ve riskli bir durum fark ettiğinizde bir butona basmanız istenmiştir. Aynı zamanda göz hareketleriniz sanal gerçeklik gözlüğü tarafından kaydedilmiştir. Verecekleri tepkileri etkileyebileceğinden, katılımcılara deneyden araştırmada göz takibi yapıldığı bilgisi verilmemiştir.

Eğer araştırmayla ilgili sorularınız varsa araştırmacıya sorabilir veya enes.ozel@metu.edu.tr adresinden Bekir Enes Özel'e ulaşabilirsiniz.

Post-Experiment Briefing Form

Thank you for participating to the experiment!

The research aims to explore the relation between level of education/work experience and hazard recognition. Data gathered would be analyzed for this purpose.

For this purpose, you were asked to participate a virtual construction site experiment and push a button when you recognize a hazard. Meantime, you eye movements were record via the head mounted display. To avoid any bias, participants were not told about the eye tracking before the experiment.

If you have any further questions you can ask now to the attendant or contact to Bekir Enes Özel via email from enes.ozel@metu.edu.tr.

ARAŞTIRMAYA GÖNÜLLÜ KATILIM FORMU

Bu araştırma, ODTÜ Mimarlık Bölümü öğretim elemanlarından Dr. Öğr. Üyesi Mehmet Koray Pekeriçli tarafından yürütülmektedir. Bu form sizi araştırma koşulları hakkında bilgilendirmek için hazırlanmıştır.

Çalışmanın Amacı Nedir?

Araştırmanın amacı, katılımcıların iş güvenliği riski tanıma süreçlerini incelemektir.

Bize Nasıl Yardımcı Olmanızı İsteyeceğiz?

Araştırmaya katılmayı kabul ederseniz, sizden beklenen, bir sanal gerçeklik ortamındaki riskli durumları bulmaya çalışmanızdır. Ayrıca iki adet anket doldurmanız istenecektir. Bu çalışmaya katılım ortalama olarak 10 dakika sürmektedir.

Sizden Topladığımız Bilgileri Nasıl Kullanacağız?

Araştırmaya katılımınız tamamen gönüllülük temelinde olmalıdır. Anketlerde, sizden kimlik veya kurum belirleyici hiçbir bilgi istenmemektedir. Cevaplarınız tamamıyla gizli tutulacak, sadece araştırmacılar tarafından değerlendirilecektir. Katılımcılardan elde edilecek bilgiler toplu halde değerlendirilecek ve bilimsel yayımlarda kullanılacaktır. Sağladığınız veriler kimlik bilgileriniz ile eşleştirilmeyecektir.

Katılımınızla ilgili bilmeniz gerekenler:

Deney, genel olarak kişisel rahatsızlık verecek durumlar içermez. Ancak, katılım sırasında sanal gerçeklik ortamından ya da herhangi başka bir nedenden ötürü kendinizi rahatsız hissederseniz deneyi yarıda bırakıp çıkmakta serbestsiniz. Böyle bir durumda görevli kişiye deneyi sonlandırmak istediğinizi belirtmeniz yeterli olacaktır. Deneyde kullanılan ekipmanların bilinen uzun vadeli bir zararı yoktur. Sanal gerçeklik gözlüğünü taktığınız sırada hafif bir baş dönmesi hissedebilirsiniz.

Araştırmayla ilgili daha fazla bilgi almak isterseniz:

Deney sonunda, bu çalışmayla ilgili sorularınız cevaplanacaktır. Bu çalışmaya katıldığınız için şimdiden teşekkür ederiz.

Yukarıdaki bilgileri okudum ve bu çalışmaya tamamen gönüllü olarak katılıyorum.

(Formu doldurup imzaladıktan sonra görevliye geri veriniz).

İsim Soyad	Tarih	İmza
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VOLUNTARY PARTICIPATION FORM

This research is being conducted by Assist. Prof. Dr. Mehmet Koray Pekeriçli from METU Department of Architecture. This form is prepared to inform you about the research terms.

What is the purpose of the research?

The purpose of the research is to explore hazard recognition process of the participants.

What will we ask from you?

If you agree to participate, what is asked from you is to recognize hazards in a virtual construction site. Moreover, you will be asked to fill two questionnaires. Average time of experiment is 10 minutes.

How will to use the data we gathered?

Your participation to the experiment is voluntary. The questionnaires do not include any question to determine your identification or associations. Your answers will be kept hidden and only will be visible to researchers. The data gathered will be analyzed and will be used for scientific publishment. Data gathered from you will not be matched with your identification information.

Things you need to know:

The experiment does not contain any disturbing situations. However, if you feel uncomfortable during the experiment due to the virtual environment or any other reason you are free to leave the experiment any time you want. In this case you only need to tell the attendant that you want to end the experiment. The equipment used in the experiment does not have any known permanent unhealthy effects. You may experience a mild dizziness during the time you wear the head mounted display.

For further information about the experiment:

After the experiment, your questions will be answered or directed. Thank you for participating to the experiment!

I have read the information above and I participate to the experiment voluntarily.

(Please hand the form back to the attendant after you have signed).

Name Surname	Date	Sign
	---/----/-----	

C. Example Data

This is the third appendix of this thesis. It includes an example of the data used in the study. Data from subject number 9 was selected because it is the shortest one.

HFT	**PBT Sync**
Fixation Data	
Subject 9	
--	
Cube STARTED 2.063255	
Cube Fixation Duration 0.7297075	2,381977
Cube ENDED 2.792962	
RedSphere STARTED 2.933857	
RedSphere Fixation Duration 0.4780755	3,172065
RedSphere ENDED 3.411933	
BlueCube STARTED 3.749138	
BlueCube Fixation Duration 0.2868607	4,012514
BlueCube ENDED 4.035999	
Fixation Data	
Subject 9.2	
--	
Stackedboxes STARTED 35.96236	
Stackedboxes Fixation Duration 0.322113	
Stackedboxes ENDED 36.28448	
Stackedboxes STARTED 38.79397	
Stackedboxes Fixation Duration 1.67749	

Stackedboxes ENDED 40.47146

Stackedboxes STARTED 42.13561
Stackedboxes Fixation Duration 0.2549438
Stackedboxes ENDED 42.39056

Stackedboxes STARTED 42.48458
Stackedboxes Fixation Duration 0.05371094
Stackedboxes ENDED 42.53829

Ladder STARTED 43.12875
Ladder Fixation Duration 2.200836
Ladder ENDED 45.32958

Ladder STARTED 45.51748
Ladder Fixation Duration 0.6172485 45,76241
Ladder ENDED 46.13473

Tools STARTED 46.93984
Tools Fixation Duration 0.348938
Tools ENDED 47.28878

Planks STARTED 49.00637
Planks Fixation Duration 0.5368042
Planks ENDED 49.54317

Tools STARTED 52.09274
Tools Fixation Duration 0.05368042
Tools ENDED 52.14642

Tools STARTED 52.20007
Tools Fixation Duration 0.5635071
Tools ENDED 52.76357

Tools STARTED 53.19292
Tools Fixation Duration 0.2414551
Tools ENDED 53.43438

Tools STARTED 53.4612
Tools Fixation Duration 0.5635376
Tools ENDED 54.02474

ShaftOpenning STARTED 54.42736
ShaftOpenning Fixation Duration 0.1878357
ShaftOpenning ENDED 54.6152

ShaftOpenning STARTED 54.76275
ShaftOpenning Fixation Duration 1.180817
ShaftOpenning ENDED 55.94357

Chainsaw STARTED 55.94357
Chainsaw Fixation Duration 0.4025269
Chainsaw ENDED 56.34609

ShaftOpenning STARTED 56.37292
ShaftOpenning Fixation Duration 0.4025269 56,72515
ShaftOpenning ENDED 56.77544

Chainsaw STARTED 57.2853
Chainsaw Fixation Duration 0.5635681
Chainsaw ENDED 57.84887

Chainsaw STARTED 57.90252
Chainsaw Fixation Duration 0.02682495
Chainsaw ENDED 57.92934

Bucket STARTED 59.11004

Bucket Fixation Duration 0.05361938
Bucket ENDED 59.16366

HarmfulSubstances STARTED 60.30431
HarmfulSubstances Fixation Duration 0.02682495
HarmfulSubstances ENDED 60.33114

HarmfulSubstances STARTED 60.49215
HarmfulSubstances Fixation Duration 0.02682495
HarmfulSubstances ENDED 60.51897

Bucket STARTED 61.99502
Bucket Fixation Duration 0.2683411
Bucket ENDED 62.26336

HarmfulSubstances STARTED 62.71957
HarmfulSubstances Fixation Duration 0.02682495
HarmfulSubstances ENDED 62.74639

Stackedboxes STARTED 63.91369
Stackedboxes Fixation Duration 3.019615 65,43367
Stackedboxes ENDED 66.9333

Ladder STARTED 68.07405
Ladder Fixation Duration 0.4831543
Ladder ENDED 68.55721

Ladder STARTED 68.58412
Ladder Fixation Duration 0.2147217
Ladder ENDED 68.79884

Ladder STARTED 68.85249
Ladder Fixation Duration 0.06713867
Ladder ENDED 68.91963

Ladder STARTED 70.1006
Ladder Fixation Duration 1.180847
Ladder ENDED 71.28145

Stackedboxes STARTED 73.05324
Stackedboxes Fixation Duration 0.2416992
Stackedboxes ENDED 73.29494

Stackedboxes STARTED 75.2007
Stackedboxes Fixation Duration 0.5235596
Stackedboxes ENDED 75.72426

Fixation Data
Subject 9.3

ElectricBox STARTED 80.5276
ElectricBox Fixation Duration 1.28389
ElectricBox ENDED 81.81149

Cables2 STARTED 81.81149
Cables2 Fixation Duration 0.4379425
Cables2 ENDED 82.24943

Cables2 STARTED 82.52113
Cables2 Fixation Duration 0.09063721
Cables2 ENDED 82.61177

82,76605

HoistedBrickstack STARTED 83.9407
HoistedBrickstack Fixation Duration 0.800354
HoistedBrickstack ENDED 84.74106

HoistedBrickstack STARTED 86.13028
HoistedBrickstack Fixation Duration 0.875679 86,40541
HoistedBrickstack ENDED 87.00596

BentRebar STARTED 87.09666
BentRebar Fixation Duration 0.3321304
BentRebar ENDED 87.42879

CableBump STARTED 88.03277
CableBump Fixation Duration 0.0604248
CableBump ENDED 88.09319

CableBump STARTED 88.15348
CableBump Fixation Duration 0.1509933
CableBump ENDED 88.30447
89,30415

GroundedBrickstack STARTED 90.11626
GroundedBrickstack Fixation Duration 0.6643295
GroundedBrickstack ENDED 90.78059

SafRailBroken STARTED 91.23363
SafRailBroken Fixation Duration 1.751564 92,58089
SafRailBroken ENDED 92.9852

XtremeHeat STARTED 93.03052
XtremeHeat Fixation Duration 4.031639
XtremeHeat ENDED 97.06216

XtremeHeat STARTED 97.15279
XtremeHeat Fixation Duration 0.3321991 97,33568
XtremeHeat ENDED 97.48499