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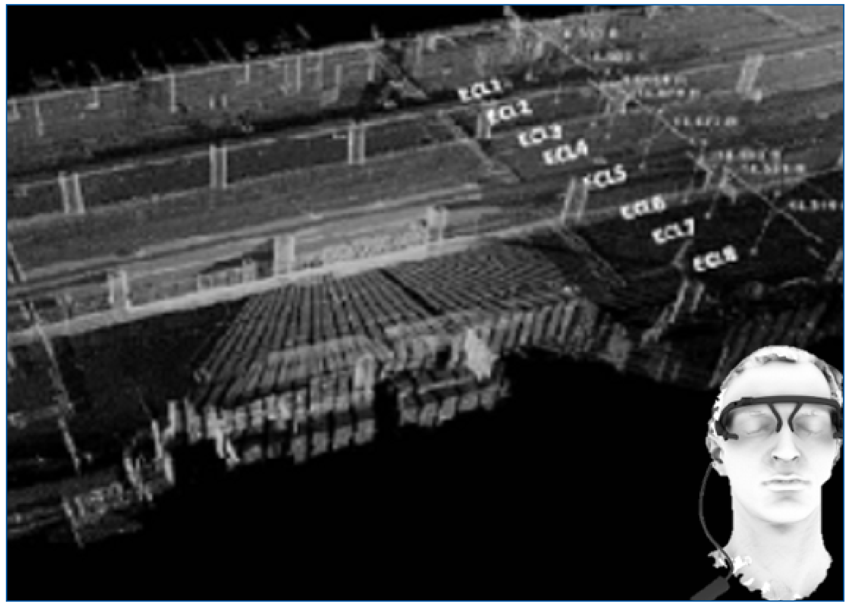
OPTIMIZE WORK ZONE SAFETY WITH SPATIAL INFORMATION TECHNOLOGY AND EYE TRACKER



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16. Abstract

The project aims to using eye-tracking technology to optimize the work zone safety. Firstly, a systematic literature review was conducted to present the background of its application in construction safety. In total, 81 publications were screened from Web of Science (WoS), Scopus, and American Society of Civil Engineers (ASCE) library. A statistical analysis was conducted from time-series, location, publication and co-author analysis. The procedures of the research were summarized, including how to recruit participants, design of experiment and eye-tracking metrics. Opportunities and challenges of the technology on construction safety were also presented. Then, the project revolved around three research aims: (1) test the elements that can influence workers' hazard identification rate (HIR); (2) verify whether the immediate training is efficient in improving workers' HIR; (3) illustrate whether the safety training has an effect on visual search strategy for different groups.The result shows that the field of study can influence workers' HIR but safety training certificates and related jobs work experience cannot. A brief safety training affects the high-HIR rate and low-rate groups differently. It recommends that the organization adopts various safety training methods to improve workers' visual search strategy.

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OPTIMIZE WORK ZONE SAFETY WITH SPATIAL INFORMATION TECHNOLOGY AND EYE TRACKER

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ABSTRACT

This project aims to using eye-tracking technology to optimize work zone safety. First, a systematic literature review was conducted to present the background of its application in construction safety. In total, 81 publications were screened from Web of Science (WoS), Scopus, and American Society of Civil Engineers (ASCE) library. A statistical analysis was conducted from time-series, location, publication, and co-author analysis. The procedures of the research were summarized, including how to recruit participants, experiment design, and eye-tracking metrics. Opportunities and challenges of the technology on construction safety were also presented. The project revolved around three research aims: (1) test the elements that can influence workers' hazard identification rate (HIR); (2) verify whether the immediate training is efficient in improving workers' HIR; (3) illustrate whether the safety training has an effect on visual search strategy for different groups. The result shows that field of study can influence workers' HIR but safety training certificates and related work experience cannot, and safety training has a different effect on high-rate and low-rate groups. It recommends that the organization should adopt various safety training methods to improve its visual search strategy.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

Given the high rate of accidents, the construction industry is regarded as one of the most dangerous industries in the world (Sunindijo & Zou, 2012). Injuries, deaths, and lost time in the construction industry all occur at alarmingly high rates each year (Esmaeili & Hallowell, 2012). According to statistics from the Bureau of Labor, U.S. industry is responsible for 20% of all employee-related deaths even though it only employs less than 6% of the country's total workforce (Bureau of Labor Statistics, 2021). Every year, more than 6,000 deaths occur on construction job sites around the world (Lingard, 2013). Construction safety has aroused wide attention all over the world because of its huge financial and human losses. Researchers and practitioners in construction safety have spent a great deal of time and energy trying to figure out what causes accidents and injuries (Mitropoulos, Abdelhamid, & Howell, 2005; Rajendran & Gambatese, 2009). A major factor affecting an employee's ability to perform safely is the inability to perceive important environmental factors to make accurate predictions or decisions (Ensley, 1995).

Workers on construction sites face a multidimensional cognitive challenge in identifying safety hazards, such as brain activity and visual attention search (P.-C. Liao, Sun, & Zhang, 2021). When an observer is in a dangerous situation, behavioral data on eye movements can provide valuable insight into the observer's attention and the course of their actions (Sogand Hasanzadeh, Esmaeili, & Dodd, 2017b; Huestegge, Skottke, Anders, Müsseler, & Debus, 2010). Eye-tracking technology has also opened up new avenues for the problem as a result of the advancement in digital and computer technology (Ahn et al., 2019). Extensive effort has been made to adopt eye-tracking technology to address construction safety problems. Han, Yin, Zhang, Jin, and Yang (2020) investigated the effect of environmental factors on workers' safety hazard recognition rate, including distinctness of hazards, site brightness, and tidiness. Zhang, Zhang, Liao, and Hu (2021) examined the relationship between the interactions among factors in the search and decision stages and workers' hazard identification performance. Hasanzadeh et al. (2017b) explored the impact of construction safety knowledge on workers' visual distribution and hazard recognition performance. They also investigated into how personality and attentional failure affect fall-hazard identification in the workplace. These studies have adopted eye-tracking technology to record users' eye movement data and use statistical methods to reveal the relationship between the affecting elements and the hazard identification rate.

Additionally, the transportation industry is also actively using eye-tracking technology to solve safety problems. Ma and Yan (2021) examined the impact of improved traffic signs and markings on drivers' driving and sensory abilities. The results showed that optimizing the design of traffic signs and markings is an excellent method to increase traffic safety. Lu, Shang, Wei, and Wu (2021) investigated the relationship between various exit advance guide signs and traffic safety in mountainous highway tunnels. They found the distance sign on the left wall and the plan with a height, width, and spacing of 1.5 m are the best choices for safety and have a significant impact on minimizing traffic accidents.

To improve workers' hazard identification rate, a variety of training has been proposed. The Occupational Safety and Health Administration (OSHA) produced a 10-hour training. Every day, before construction work begins, all workers receive safety training about construction safety hazards. However, researchers and organizations hardly study the effect of this training on hazard recognition performance. It is essential to investigate the efficiency of safety training, which can provide recommendations to further improve workers' identification skills. Therefore, the research focuses on examining the effect of safety training.

In this project, the study revolves around three research directions: (1) To test the factors that can influence workers' hazard recognition performance; (2) To verify whether a safety training is efficient in improving workers' hazard recognition rate; (3) To illustrate whether the safety training has an effect on visual search strategies for different groups from different dimensions, including vector, length, direction, position, and duration and their specific performance in a variety of eye-tracking metrics.

This report is presented in five sections. Section 1 is the introduction. Section 2 is the literature review of eye-tracking technology in construction safety. Section 3 illustrates the procedure and methods of the research, including how to recruit the participants and the process of the experiment. Section 4 shows the results in response to the research objectives. Section 5 summarizes the study, the contributions of the study, presents the limitations, and identifies the future direction of the research.

2. LITERATURE REVIEW OF EYE-TRACKING TECHNOLOGY ON CONSTRUCTION SAFETY

In this project, a systematic review is conducted trying to answer the following research questions: Is eye-tracking technology an emerging research topic in construction safety? What are the typical research methodologies and procedures? What are the opportunities and challenges of using eye-tracking technology in construction safety applications? What are the recommendations? The first step in the review process included searching relevant keywords for eye-tracking on construction safety from several databases and screening them to get the most appropriate literature. Next, a bibliographic analysis was conducted from four aspects: time series analysis, location analysis, publication analysis, and author correlation analysis. This report has illustrated the general research methodology and procedures for using eye-tracking technology in construction safety, including participants, design of experiment, and eye-tracking metrics. The discussion section presented the opportunities and challenges in the application process. Finally, recommendations for future work were presented.

2.1 Methodology

Systematic reviews are the type of research synthesis carried out by review groups with specialized skills to identify and retrieve evidence that is relevant to a specific question, as well as evaluate and synthesize the results of the research to convey readers what is known about one topic and what is unknown and make recommendations for the future research direction (Munn et al., 2018). Systematic reviews have two main advantages: transparency and comprehensive characteristics, which allow other researchers to identify, evaluate, and synthesize current research on a specific issue (Schuldt, Jagoda, Hoisington, & Delorit, 2021). Systematic reviews generally focus on searching for relevant literature, analyzing and summarizing previous research, and offering guidelines for future research (Schirmer, 2018).

This research adopts a literature-based approach-bibliometric analysis. It is the quantitative investigation of literature using mathematical and statistical approaches (Nusair, 2020). Furthermore, bibliometric analysis can produce more objective and scientific conclusions (Donthu, Kumar, Mukherjee, Pandey, & Lim, 2021). As a result, bibliometric analysis was used in this study, and bibliometric research stages were carried out based on various studies (Clarke et al., 2007; Nobanee et al., 2021; Pizzi, Caputo, Corvino, & Venturelli, 2020; Yari, Lankut, Alon, & Richter, 2020). The research flowchart is shown in Figure 2.1.

Research questions and work scope were defined in the study design, as mentioned in the previous section. This research identified the related literature published between 2001 and 2021 in the Web of Science (WoS), the Scopus, and the American Society of Civil Engineers (ASCE) library. WoS and Scopus are great resources when conducting multidisciplinary and international bibliometric analysis (Mongeon & Paul-Hus, 2016). The ASCE library has a significant impact on and a prominent position in the construction engineering research community (Pariafsai & Behzadan, 2021).

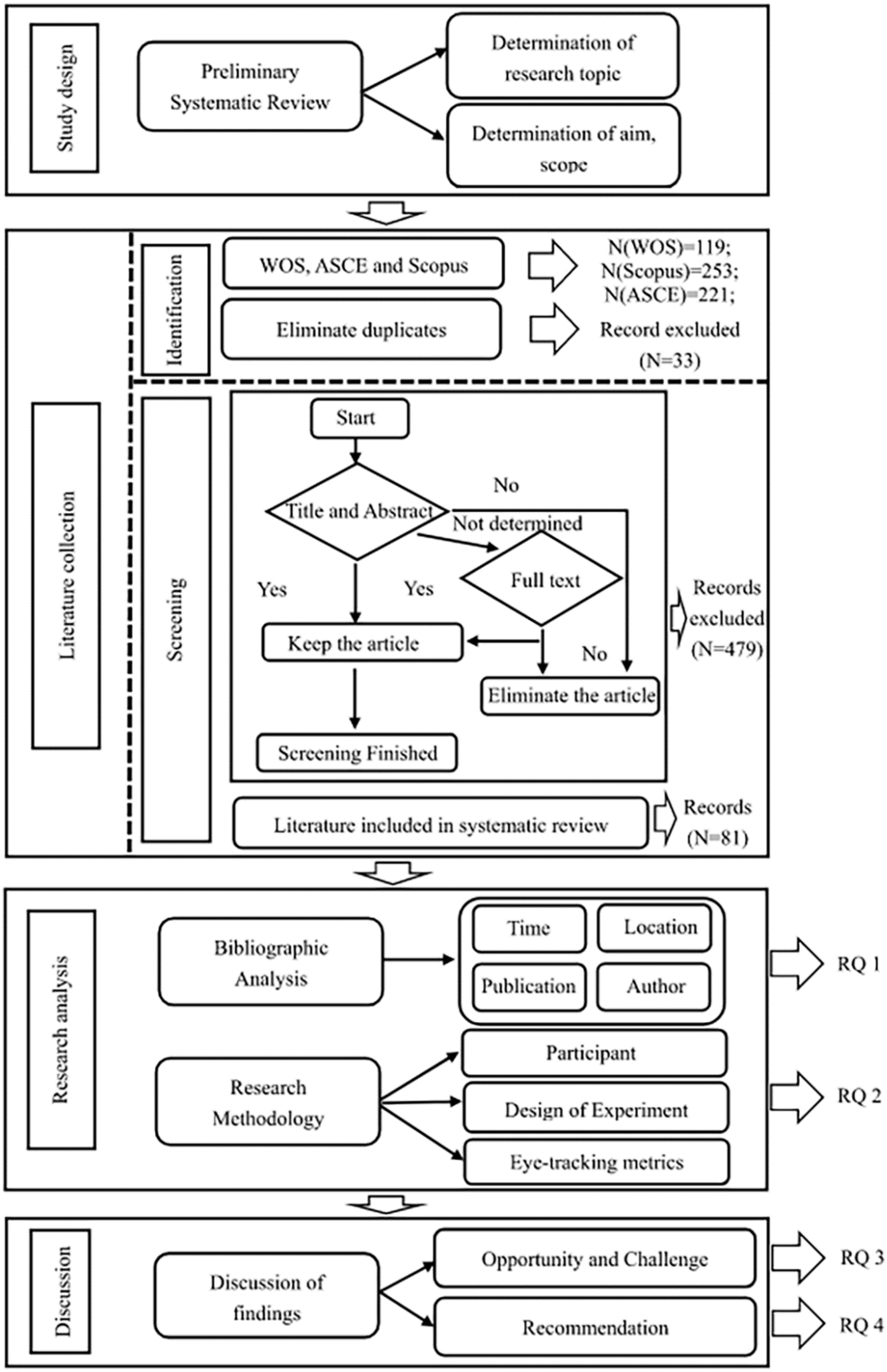

Figure 2.1 Flow chart of literature

The following keywords were used to search the conference papers and journal articles: (construction OR work zone OR work area OR job site) and (eye track OR eye-track) and (safety OR hazard). Non-English published literature was excluded from this study. The duplicates extracted from the database were eliminated. Criteria were set aside from the literature screening process; these include: (1) non-construction applications, (2) records where eye-tracking technology was not the tool of the research, and (3) non-safety and non-hazard subjects. The co-author conducted the screening process independently, and the corresponding author made the final decision for any inconsistencies. The screening first reviews titles and abstracts based on the predefined exclusion criteria. Then if researchers cannot determine the scope of the manuscripts based on the title and abstract, a full-text screening was done. In the end, 81 publications were kept in the literature review for statistical analysis.

The research analysis sections, based on the 81 related literature findings, analyzed time, location, publication, and author correlations to determine if eye-tracking technology is an emerging research topic in construction safety. Then, the general research methodology and procedures of applying eye-tracking technology were defined in this section. In the findings section, the opportunities and challenges of using eye-tracking technology in construction safety were discussed and recommendations for future research areas were made.

2.2 Bibliographic Analysis

This chapter uses descriptive analyses, such as time-series, location, journal, and author correlation, to identify the research trends from 2001 to 2021, publication distribution, preferred journal and conference proceedings, and the author relationship (Schuldt et al., 2021; Soltanmohammadlou, Sadeghi, Hon, & Mokhtarpour-Khanghah, 2019). From these aspects, the section answers research question 1, namely whether eye-tracking technology is an emerging research topic or not.

2.2.1 Time-series Analysis

Figure 2.2 depicts the eye-tracking technology in construction safety research trends from 2001 to 2021. The first related paper appeared in 2006. Between 2001 and 2015, research in this field developed slowly. Before 2015, no more than two papers were published in any one year. After 2016, there was a clear increasing trend in the research, reaching the highest level in 2021. It can be seen that with the technology advance, eye-tracking technology is more affordable, and more researchers have adopted it.

2.2.2 Location Analysis

Figure 2.3 presents the number of publications across countries and regions that released more than one. Fifteen countries and regions have produced and published related research. The United States and China are the two countries that lead the rest of the world in total publications, and have published 31 and 25 related papers, respectively, which account for more than half of the total. In addition to the U.S. and China, Australia published six research articles, and Germany four.

2.2.3 Publication Analysis

Table 2.1 lists journals and conference proceedings that published more than two papers. The literature review for the eye-tracking technology on construction safety covers many disciplines, such as engineering, computer science, and psychology.

Eleven articles were published in the *Construction Research Congress*, followed by the *Journal of Construction Engineering*, which released eight publications. *Transportation Research Part F: Traffic Psychology and Behavior* had six related publications. Both *Automation in Construction* and *Safety*

Science released four publications. The *Journal of Construction and Management* was the most cited, reaching 297. Although *Safety Science* only published four papers, its average citations per paper was 38, the most among these publishers.

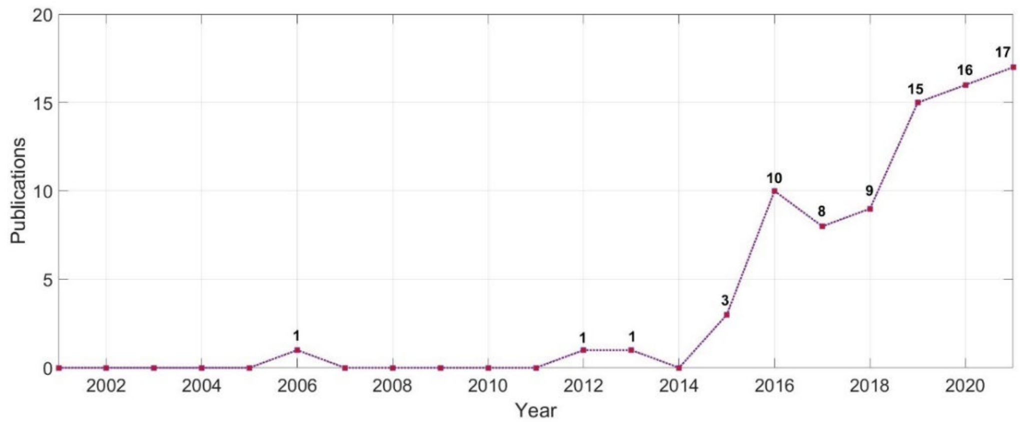

Figure 2.2 Publications from 2001 to 2021

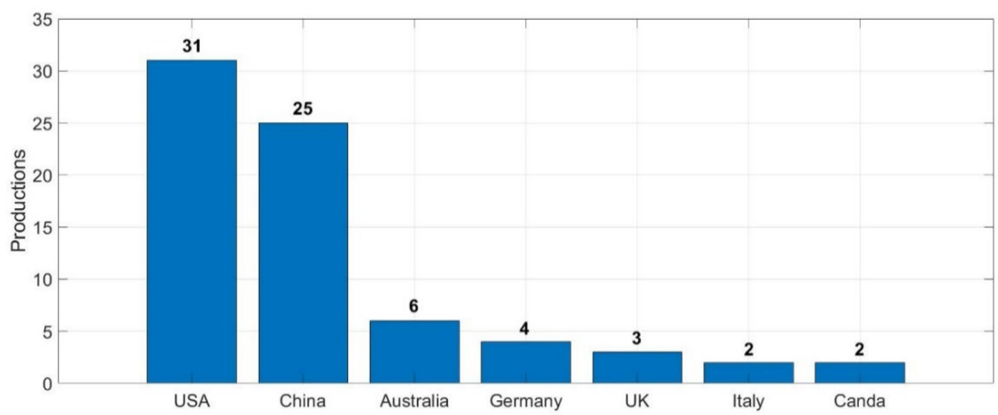

Figure 2.3 Publications distributions across countries

Table 2.1 Distribution of publications

No	Journal or Conference	Document Type	Numbers	Citations
1	*Construction Research Congress*	Conference	11	98
2	*Journal of Construction and Management*	Journal	8	297
3	*Transportation Research Part F: Traffic Psychology and Behavior*	Journal	6	130
4	*Automation in Construction*	Journal	4	120
5	*Safety Science*	Journal	4	152
6	*International Journal of Occupational Safety and Ergonomics*	Journal	3	17

2.2.4 Author Correlation Analysis

For the authors of the 81 publications that have been screened, the segment highlights the connections among authors in the field of eye-tracking technology on construction safety. VOSviewer software was used to analyze the frequency, relationship, and strength of those authors. The network contains 10 co-author clusters. Every cluster represents a group of authors with more than two co-publications. The representative three clusters are shown in Figure 2.4.

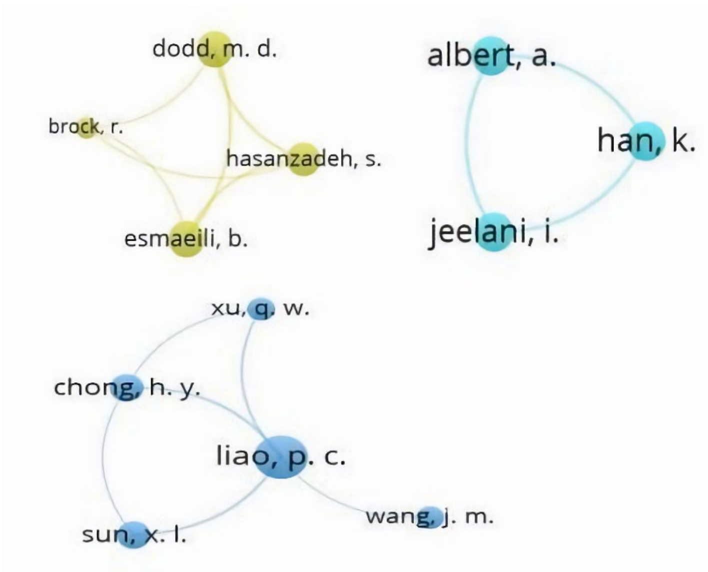

Figure 2.4 Co-author analysis network of author

The cluster, including Behzad Esmaeili, Michael Dodd, and Sogand Hasanzadeh, published eight pieces of related literature, the most among all clusters. Their research covers several different directions, such as the impact of workers' characteristics (including personality and safety knowledge) on visual attention (Hasanzadeh et al., 2017b; Hasanzadeh, Esmaeili, & Dodd, 2018), and the relationship between workers' hazard recognition ability and their visual attention (Hasanzadeh, Esmaeili, & Dodd, 2017a). Liao and his collaborators are also very active in the field and made many contributions. For example, they combined eye-tracking technology and an NIRS device to reassess workers' hazard recognition ability (Sun & Liao, 2019). Jeelani's team contributed to the method to improve construction safety. They developed a personalized hazard-recognition training method to improve and test construction safety (Jeelani, Albert, Azevedo, & Jaselskis, 2017). They also built an automating and scaling safety training method, which is based on eye-tracking data (Jeelani, Han, & Albert, 2018).

2.3 Research Methodology for Eye-tracking Technology on Construction Safety

This section introduces the general research methodology and procedures for using eye-tracking technology in construction safety. It starts with recruiting experiment participants, then discusses experiment design. The last part presents eye-tracking metrics in detail.

2.3.1 Participants

Step one was to recruit the experiment participants. The research teams first identified potential participants depending on the research object. For example, Han et al. (2020) recruited students from construction management or other construction engineering programs as experiment participants instead of local construction workers. Zhang et al. (2021) invited nine undergraduates and 32 postgraduate students to participate in the experiment to study the interaction of elements that influence building hazard detection. Hasanzadeh et al. (2017a) recruited construction workers to investigate the relationship between hazard recognition skills and visual attention. They invited construction workers to participate in one of three ways: (1) an invitation flyer was posted at construction sites; (2) researchers extended invitations by visiting construction companies' main offices and contacting facility managers; and (3) a flyer with a one-page summary of the research project was sent to Associated Builders and Contractors (ABC). J. Li, et al. (2020) invited 12 excavator operators with on-site construction experience from two private construction contractors as experiment participants because the study assessed the influence of mental fatigue on construction equipment operators' ability to detect risks.

Generally, participants were required to have a standard or corrected-to-normal vision (Hasanzadeh, Dao, Esmaeili, & Dodd, 2019). Participants should not have had any neurological or other illnesses affecting the experiment's outcome (P.-C. Liao et al., 2021).

2.3.2 Design of Experiment

An experiment was designed to collect the participants' eye movement data. Participants were informed that no personal information would be stored or saved before signing the consent form. Then, participants needed to wear an eye-tracking device to complete the visual tasks. Their eye movement data were recorded, which were then processed based on the next research purposes.

This part shows two scenarios: presentation styles and related research are summarized and analyzed. It also shows the combination of eye-tracking technology with other wearable sensing technologies for construction safety.

Based on the literature analysis, the study of eye-tracking technology on construction safety can be divided into static and dynamic scenarios. Static scenarios mean the scenes are static and do not change with time or location. A typical static scenario style is pictures displayed on a computer screen. Researchers investigated the relationship between site condition factors and workers' construction safety hazard recognition by computer figures, such as brightness (Han et al., 2020). In dynamic scenarios, the scenes alter with time or location. One common dynamic scenario application is a driving simulator to investigate the effect of drivers' eye gaze on transportation safety (Lu et al., 2021; Ma & Yan, 2021). Figure 2.5 concludes the publication trend for static and dynamic scenarios from 2006 to 2021. It can be seen that researchers are focusing more on dynamic scenarios.

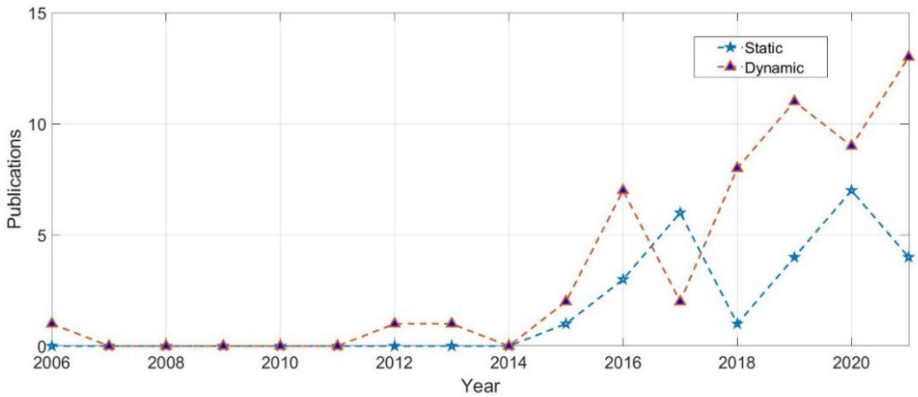

Figure 2.5 Static and dynamic publications distribution

2.3.2.1 Static Scenarios

As physical jobsites are full of various safety hazards that may threaten workers' safety, some researchers replaced real construction sites with static scenarios with construction safety hazards to examine the relationship between users' eye movements and their recognition skills for construction safety hazards. Research emphasis is quite different for factors affecting workers' identification skills. Some scholars emphasized the impact of the environment on that. For example, Han et al. (2020) measured workers' recognition ability under different site condition elements, such as distinctness versus obscurity, brightness versus darkness, and tidiness versus messiness. Alruwaythi and Goodrum (2019) studied how hazard recognition skills are influenced by information format and spatial cognition while involved in complicated spatial work. However, other researchers focused on workers' characteristics, such as work experience, training, personality, and knowledge. For example, Hasanzadeh et al. (2017b) verified the effect of safety knowledge, including training, work experience, and injury exposure, on hazard recognition in construction sites. Zhang et al. (2021) interactively examined the relationship between experience and risk tolerance and their ability to show how visual clutter can influence workers' performance for hazard recognition. Table 2.2 summarizes representative publications based on the static picture.

According to Table 2.2, fixation time, first fixation time, and dwell time are the most used eye-tracking metrics. Although these metrics can be interpreted differently in different research depending on their context, they all can examine the depth of cognitive processing and the distribution of attention (Zhao, Schnotz, Wagner, & Gaschler, 2014).

Static scenarios have strengths. First, construction safety research using static scenarios is generally conducted in laboratory environments, substantially reducing economic burden and injury (Pinheiro, Pradhananga, Jianu, & Orabi, 2016). In addition, the parameters that can influence workers' eye attention, such as task parameters and environmental elements, are easier to control (Hasanzadeh, Esmaeili, et al., 2017b). Although static scenario styles have many advantages, such as risk reduction, they still has one limitation (Hasanzadeh, Esmaeili, et al., 2017b; Hasanzadeh, Esmaeili, Dodd, & Pellicer, 2017; Jeelani et al., 2017). There is a gap between the static scenarios and the actual jobsites as the construction sites are dynamic and full of uncertain factors that cannot appear on the figures (Han et al., 2020; Hasanzadeh et al., 2019; Hasanzadeh, Esmaeili, et al., 2017b).

Table 2.2 Research with static scenarios

Publications	Influence elements	Environment/ Human	Metrics
Alruwaythi and Goodrum (2019)	Information format	Environment	(1)(2)
Aroke, Esmaeili, Hasanzadeh, Dodd, and Brock (2020)	Work experience	Human	(3)(6)
Comu, Kazar, and Marwa (2021)	Attitudes	Human	(3)(11)
Habibnezhad, Fardhosseini, Vahed, Esmaeili, and Dodd (2016)	Risk perception	Environment	(3)(7)(9)
Han et al. (2020)	Site conditions	Environment	(1)(2)
Hasanzadeh, Dao, Esmaeili, and Dodd (2017)	Working memory load	Human	(3)(6)(8)
Hasanzadeh, Esmaeili, et al. (2017a)	Attention	Human	(3)(6)(8)
Hasanzadeh, Esmaeili, et al. (2017b)	Safety knowledge	Human	(7)(8)
Hasanzadeh, Esmaeili, Dodd, et al. (2017)	Type of hazards	Environment	(3)(6)(8)
Jeelani et al. (2017)	Training	Human	(14)
Jeelani, Albert, Han, and Azevedo (2019)	Personalize training	Human	(1)(2)(9)(10)(11)(12)
Jeelani et al. (2018)	Viewing patterns	Human	(1)(2)(5)(6)
Li, Zhao, Su, and Liao (2020)	Attention areas	Human	(14)
P. C. Liao, Ding, and Wang (2016)	Cognitive control	Human	(1)(2)
P. C. Liao, Sun, Liu, and Shih (2019)	Visual clutter	Environment	(5)(10)
Liko, Esmaeili, Hasanzadeh, Dodd, and Brock (2020)	Working-memory load	Human	(3)(6)(7)
Liu, Liao, Wang, Li, and Rau (2021)	Semantic cues	Environment	(1)(2)(9)(10)
Sun, Chong, and Liao (2020)	Visual clutter	Environment	(11)
Zhang et al. (2021)	Experience, Risk tolerance, Visual clutter	Human	(3)

*Eye-tracking metrics are valuable tools to analyze the participants' eye movement. Researchers adopted different metrics based on their requirement. Listing metrics are beneficial to analyze the research. Therefore, Table 2.1 lists the metrics adopted by different researchers. The numbers in the metrics column represent different metrics: (1) fixation time, (2) fixation count, (3) first fixation time, (4) fixation duration, (5) mean fixation duration, (6) dwell time, (7) dwell time percentage, (8) run count, (9) fixation count ratio, (10) fixation time ratio, (11) search duration, (12) search velocity, (13) scan path, (14) heat map, and (15) pupil size.

2.3.2.2 Dynamic Scenarios

As the limitations of static scenarios may affect the research results, some practitioners adopt dynamic scenarios to present construction safety hazards (Noghabaei, Han, & Albert, 2021). According to the analysis for the related publications, scholars adopted three quite different technical routes to show people the dynamic scenarios: virtual reality (VR) technology, simulator, and real construction sites, as shown in Table 2.3.

VR technology creates immersive environments in which users can gain new perspectives on how the real world operates (M. Kim, Wang, Love, Li, & Kang, 2013; Whyte, 2007). It provides a platform to repeat the real construction sites (Noghabaei et al., 2021). When people wear the VR head-mounted device, the virtual scene appears in their view, and the scene changes with their position (M. Kim et al., 2013). Therefore, some researchers have begun to adopt VR technology as an alternative to real construction jobsites. Ye and König (2019) combined eye-tracking technology with VR to improve cognitive data collection and human-computer interaction of site hazards. The research offers a new method of using eye-tracking technology to gather data. N. Kim, Kim, and Ahn (2021) investigated how to predict workers' inattentiveness to struck-by hazards by eye-tracking technology in scenarios built by VR.

Table 2.3 Research with dynamic scenarios

Publications	Dynamic scenarios	Metrics
N. Kim et al. (2021)	VR	(1)(2)(5)(12)(15)
Noghabaei et al. (2021)	VR	(12)(15)
Ye and König (2019)	VR	(13)(14)
Zimasa, Jamson, and Henson (2019)	Driving simulator	(4)
Yan, Zhang, Zhang, Li, and Yang (2016)	Driving simulator	(2)(5)
Lu et al. (2021)	Driving simulator	(15)
Ma and Yan (2021)	Driving simulator	(3)(4)
Xu, Chong, and Liao (2019); Xu and Liao (2020)	Semi-real scenarios	(13)
Vignali et al. (2019)	Real scenarios	(3)(4)
Hasanzadeh, Esmaeili, and Dodd (2018)	Real scenarios	(2)(3)(6)(8)
Młyńczak, Folęga, and Celiński (2021)	Real scenarios	(12)
Zhang et al. (2021)	Real scenarios	(3)

*Metrics can be found in Table 2.1 with the corresponding number.

The simulator is another method to present dynamic scenarios, and it can be divided into many categories based on their application scenarios, such as driving simulator. The combination of eye-tracking technology and a driving simulator has been widely applied on the study related to the relationship between a driver's visual patterns and transportation safety (Kearney, Li, Yu, & Braithwaite, 2019; Lu et al., 2021; Yuen, Tam, Churchill, Schweizer, & Graham, 2021). For example, Lu et al. (2021) used eye-tracking technology and a driving simulator to evaluate the safety of exit advance guide signs in mountainous high tunnels. Ma and Yan (2021) investigated the efficacy of improving traffic signs and markings at flashing-light-controlled grade crossings. The research used a driving simulator to connect with drivers, and eye-tracking technology recorded drivers' visual patterns.

To make the scenarios closer to the actual construction workplace, some scholars have started to build real environments to emulate complicated jobsite scenarios. For example, Xu et al. (2019) chose the structure laboratory as the experiment site. An important reason is that the structure laboratory has many standard engineering components and equipment, and 10 hazards are distributed across the site. Some researchers directly chose the real site as the experiment site. Młyńczak et al. (2021) investigated the traffic scene recognition problem at level crossings based on train drivers' perspectives. Their research was conducted on a 30-km-long section of a double-track line containing 10-level crossings. Hasanzadeh et al. (2018) chose the workplace near the University of the Nebraska-Lincoln campus as the experimental environment.

2.3.2.3 Combination with Other Wearable Sensing Technology

Wearable sensing technologies have only recently been available and opened up new possibilities for improving construction safety (Ahn et al., 2019). When eye-tracking technology is used alone, it provides only a sliver of insight into the mental processes involved in effective hazard recognition (Noghabaei & Han, 2020; Noghabaei et al., 2021). The advancement of wearable sensing technology leads to more opportunities to combine with eye-tracking technology to investigate construction safety problems (J. Li et al., 2020). Therefore, practitioners have started combining eye-tracking technology with wearable sensing technology to examine the relationship between workers' characteristics and their ability to recognize safety hazards in construction sites.

According to the summary of the previous research, several wearable sensing technologies combine with eye-tracking technology, such as EEG, near-infrared spectroscopy (NIRS), and electrodermal activity (EDA). NIRS can record workers' hemodynamic responses. Zhou, Hu, Liao, and Zhang (2021) used NIRS and eye-tracking technology to investigate the salient activated areas of the brain during construction safety hazard recognition. EDA describes autonomic changes in skin's electrical characteristics in response to sweat production (Benedek & Kaernbach, 2010). In various situations, such as the workplace, EDA has been used to understand an individual's emotional state and stress (Boucsein, 2012). N. Kim et al. (2021) adopted EDA and eye-tracking technology to see if EDA data will help reduce fatalities and injuries on construction sites. Their findings shed light on the link between multimodal brain reactivities and inattentive behaviors. Table 2.3 shows a record related to eye-tracking technology and other wearable sensing technologies.

Table 2.4 Summary of the research with other wearable sensors

Publications	Other wearable sensors	Metrics
Sun and Liao (2019)	NIRS	(3)
N. Kim et al. (2021)	EDA	(12)(15)
P.-C. Liao et al. (2021)	EEG	(15)
Noghabaei et al. (2021)	EGG	(1)(2)(5)(12)(15)

*Metrics can be found in Table 2.2 with the corresponding number.

2.3.3 Eye-tracking Metrics

Eye-tracking technology can measure various behaviors related to eye movement (Mele & Federici, 2012). Eye-tracking metrics are valuable tools that can be used to uncover the visual activity for participant behavior and mindset (Bitkina, Park, & Kim, 2021). Eye fixation and saccades are two basic eye-movement behaviors. Eye fixation recognizes short-duration, quasi-stationary eye movement, which means individuals concentrate their gazes on the specific items, stimulus, and location (Ahn et al., 2019). Eye saccades document fast eye motion across a scene, and it only happens during the process when an individual shifts the eye between the different fixations (Ahn et al., 2019). A number of metrics can be derived from eye fixations and saccades, such as fixation time and count and saccade duration and velocity. Therefore, researchers select eye-tracking metrics as indicators to investigate the relationship between workers and construction safety (Dzeng, Lin, & Fang, 2016; Han et al., 2020; Hasanzadeh, Esmaeili, et al., 2017a). Table 2.5 lists eye-tracking metrics adopted in previous construction safety-related research.

Table 2.5 Eye-tracking metrics

No.	Metrics	Definition	Reference
1	Fixation time	Time spent on the particular stimulus	Han et al. (2020)
2	Fixation count	Number of fixations	Han et al. (2020)
3	First fixation time	Time it takes for the observer to focus on an AOI when the image appears on the screen for the first time	S. Hasanzadeh et al. (2017)
4	Fixation duration	Time that all fixations are spent on during the whole visual search process	Zimasa et al. (2019)
5	Mean fixation duration	Average time that all fixations are spent on during the whole visual search process	P. C. Liao et al. (2019)
6	Dwell time	Time that the gaze on the target AOI	Hasanzadeh, Esmaeili, Dodd, et al. (2017)
7	Dwell time percentage	Gaze on the target AOI was divided by the total duration of all gazes.	Liko et al. (2020)
8	Run count	Mean number of times workers return their attention to each AOI	Hasanzadeh, Esmaeili, et al. (2017b)
9	Fixation count ratio	Ratio of number of fixations within defining areas of interest (AOIs) to total number of fixations	Habibnezhad et al. (2016)
10	Fixation time ratio	Rate of amount of time spent in fixations within AOIs to total number of fixations	Jeelani et al. (2019)
11	Search duration	Time that all fixations are spent on during the whole visual search process	Sun et al. (2020)
12	Search velocity	Mean number of pixels per unit time	Noghabaei et al. (2021)
13	Scan path	Reflects the spatial characteristics of fixations	Xu and Liao (2020)
14	Heat map	Visualizes the eye movement data	Jeelani et al. (2017)
15	Pupil size	Pupil diameter variability	Noghabaei et al. (2021)

2.4 Discussion

This section describes the opportunities and challenges of applying eye-tracking technology to construction safety.

2.4.1 Opportunities

2.4.1.1 Providing a New Platform for Construction Safety Research

Eye-tracking technology has brought much attention to construction safety due to the advancement of virtual and computer vision technologies (Shi, Du, Ahn, & Ragan, 2019). Many studies have used eye-tracking technology to measure employees' safety hazard detection or recognition performance (Dzeng & Fang, 2015; Han et al., 2020; Hasanzadeh et al., 2018; Hasanzadeh, Esmaeili, Dodd, et al., 2017; Jeelani, Albert, & Han, 2020). When people gain attention during visual search activities, eye-tracking technology enables objective measurement of attention (Zheng et al., 2016). Therefore, eye-tracking technology provides a research platform to study construction safety.

2.4.1.2 Quantifying Hazard Recognition Ability

To figure out why workers cannot recognize all construction safety hazards, it is crucial to assess their ability to identify them. Previously, the evaluation of hazard skills identification relied heavily on workers' self-reported identification. This method is restricted in representing actual risks of safety hazards as it misses the contextual information, and the worker's self-reported reactions lack objectivity (Ahn et al., 2019).

Eye-tracking technology can fully overcome the weaknesses of the self-reported identification method. Researchers can analyze the worker's eye movement recorded by eye-tracking technology to get information about where they have looked and the duration, and then use these data to determine whether construction safety hazards are identified successfully and how many hazards are recognized, which can be adopted as a metric to assess workers' hazard recognition ability. Therefore, eye-tracking technology provides a method to quantify worker's recognition ability. Hasanzadeh, Esmaeili, et al. (2017a) defined a hazard recognition index as the ratio of the number of hazards recognized by workers in one image to the number of total hazards in the image. He regarded the index as a metric to divide the experiment participants into the low, medium, and high groups to investigate the relationship between workers' hazard identification ability on visual attention.

2.4.1.3 Guidance for Construction Safety

Construction businesses use several hazard-recognition methodologies and training programs to increase hazard-recognition levels. However, the desired levels of hazard recognition have yet to be reached (Jeelani et al., 2017).

Many researchers have used eye-tracking technology to study the factors influencing workers' hazard recognition skills. Their findings can provide useful guidance not only for construction workers but also for construction organizations on how to improve construction safety. Han et al. (2020) found that construction site conditions have a significant effect on workers' safety hazard skills, including the distinctiveness of hazards, site brightness, and tidiness. Based on their conclusions, they proposed three recommendations to enhance construction safety: (1) employing different-colored safety signs to make risks more distinct; (2) correct lighting resource allocation to working zones, especially for night construction or gloomy surroundings; and (3) proper housekeeping to keep sites tidy and well-organized to reduce employees' cognitive burdens. These implications can be used to improve safety education for construction employees.

From the workers' perspective, researchers also investigated how the workers' characteristics affect their visual strategies, such as experience, situation awareness, safety knowledge, and past injury exposure (Dzeng et al., 2016; Han et al., 2020; Jeelani et al., 2017). For example, Zhang et al. (2021) demonstrated that danger identification performance is influenced by both experience and risk tolerance, and that visual clutter and time to the first fixation have significant effects on hazard identification performance. Dzeng et al. (2016) pointed out the difference in workers' visual strategy at hazard recognition between novice and experienced workers. They found that, compared with experienced workers, novice workers were less confident in evaluating whether an attention point represented a hazard, and they had greater fixations on nearly every attention point. These findings could be useful to safety trainers and educators to enhance construction safety.

2.4.2 Challenges

2.4.2.1 Commercial Applications

Although eye-tracking technology is increasingly used in construction safety, the current applications are only limited to research. It is challenging to achieve commercial applications because (1) employees may provide unqualified responses if they believe they are being monitored (Ahn et al., 2019), (2) employees may not follow organizational requirements for how and when to wear the devices as a kind of retaliation for having their privacy invaded (Moussa, 2015), (3) the uncertainty about the return on investment poses a challenge for its commercial application (Ahn et al., 2019). Most construction safety practitioners stated that their investment is hampered by concerns about durability and an unclear cost/benefit ratio.

2.4.2.2 Limitations in Technology

Current research on eye-tracking technology in construction safety still has limitations in technology, including concentrating only on construction presentation styles (Han et al., 2020; Hasanzadeh et al., 2019), lacking of a unified standard of choosing metrics (Jeelani et al., 2019), and unpredictable factors (Han et al., 2020).

Static and virtual technology are two common methods to present the construction scenario. They can lower the risk for participants in the experiment. However, both have one common weakness: they cannot completely duplicate conditions of the real construction sites, such as noise (Han et al., 2020; Hasanzadeh et al., 2019; Hasanzadeh, Esmaeili, et al., 2017b). The weakness may impact workers' judgment of construction safety and further negatively influence the accuracy of the research. A real construction jobsite can be an ideal scenario. However, it has many hazards and uncertainties threatening the workers (Hasanzadeh et al., 2018; Młyńczak et al., 2021).

Another technical challenge is the lack of a unified standard to select eye-tracking metrics. Researchers would choose the metrics based on their understanding of the topic and reference to the related research (Han et al., 2020; S. Hasanzadeh et al., 2018; Jeelani et al., 2019; Jeelani et al., 2018). This limitation may lead to an unconvincing research result.

In addition, there may be unexpected factors, such as the feeling of surroundings, as some experiments are conducted indoors (Han et al., 2020). These unexpected elements may influence participants' ability to recognize construction safety hazards.

3. EFFECT OF SAFETY TRAINING ON SCAN PATH

This report focuses on three hypotheses related to hazard recognition. Hypothesis 1 is to verify whether safety training certificates, field of study, and related work experience can improve hazard recognition rates. Hypothesis 2 is to test the difference in hazard recognition before and after safety training in different dimensions. Hypothesis 3 is to illustrate the difference in visual search strategies before and after safety training between high and low hazard recognition rate groups. An eye-tracking experiment was devised and executed to verify the researchers' hypotheses. The entire process is shown in Figure 3.1.

3.1 Participants and Experimental Environment

Sixty students and faculty members of the University of Wyoming were invited to participate in the experiment. Among those, 49 people (38 males, 11 females) met the requirements of the experiment, and their eye movement data could be applied to the following analysis. All participants had a standard or corrected-to-normal vision.

The experiment was conducted on a series of days between April 13, 2022, and May 4, 2022, in the Construction Research and Innovation Lab located at the University of Wyoming. Each participant took part in a 20-minute session at once. All experimental procedures were authorized by an institutional review board before the start of the study.

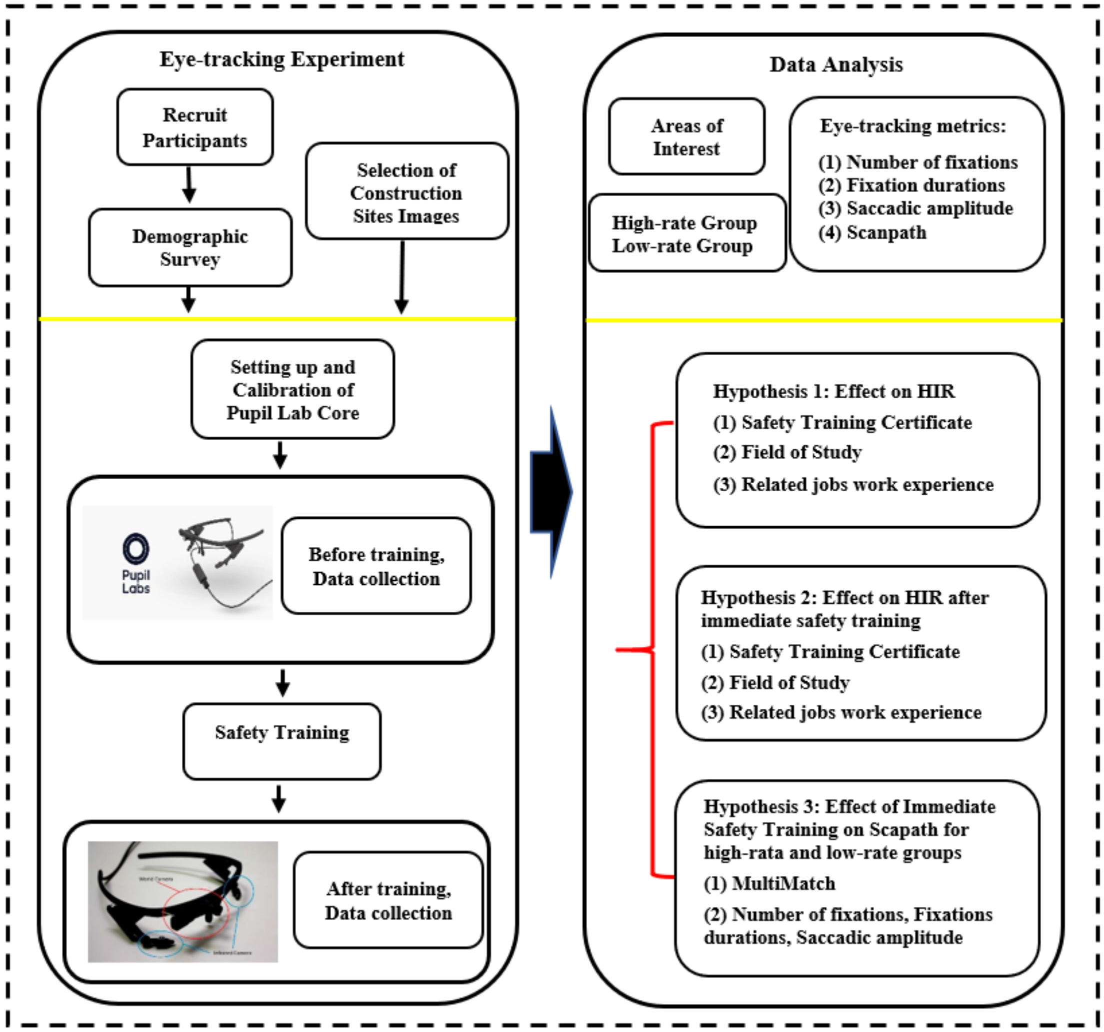

Figure 3.1 Entire process of the research

3.2 Apparatus

With a 23-inch-wide screen with 1920x1080 resolution for large stimuli display, a Pupil Lab core eye-tracker (Berlin, Germany) was used to monitor and record eye movement data of users to judge where they pay attention. It has a sampling of 120 Hz and a high spatial resolution. The eye-tracker manufacturer's (Pupil Lab, 2019) instruction manual defines a fixation as when eye pupils focus on a fixed location for at least 0.08 seconds.

Researchers can directly and clearly evaluate the gazes of humans over any points or areas of an image displayed on the computer screen by the device. It has been applied to a wide range of research fields, such as psychological studies, visual search strategies, and eye-based computer intersections (Han et al., 2020). Yi, Lee, Yum, and Lee (2022) looked into the impact of visitors' social context on their perceptions of their time spent in a museum by a Pupil Lab core eye tracker. Edewaard, Tyrrell, Duchowski, Szubski, and King (2020) made use of a Pupil Lab core eye tracker to examine how motorists perceive bicyclists in broad daylight.

3.3 Stimulus: Area of Interests

To collect eye-tracking metrics, which reflect participants' visual strategy, the first step was to define areas of interest (AOIs) in the scene. AOIs are characterized by the study group as visual environments of interest (Jacob & Karn, 2003). The experiment aims to enable participants to recognize safety hazards in the construction picture. Consequently, AOIs are safety hazards and unsafe working conditions that can cause injury, illness, and death.

Identifying safety hazards in the scene is a complex task and it heavily depends on individual perspectives and safety knowledge. It is essential to organize a safety group to help the study group recognize all safety hazards in all pictures. First, the research team members tried their best to find all AOIs. Then, the safety group would finally determine whether each construction picture contains many safety hazards and where they are. The safety group includes two safety professionals with 10 years' experience in the construction safety field. After the careful screening process, the three images have 12 AOIs in total, including fall hazards from height, tripping hazards, unguarded machinery and moving machine parts (no protection), and improper or no use of personal protective equipment (PPE).

Pupil Capture 3.5.1 can monitor and record the eye movement of participants and Pupil Player 3.5.1 can mark the safety hazard area and export which fixations are on the area, which is beneficial to help researchers distinguish the safety hazards that are successfully identified and those that are not.

3.4 Design and Procedure of the Experiment

Members of the study team directed each participant to complete the experiment. The procedure of the experiment was as follows:

1. The experimental process was introduced to the participants.

2. The approved University of Wyoming consent form was signed.

3. Study team members applied the eye-tracking device to the participant, adjusted the position of the device based on the participants' face shape, and calibrated the device.

4. In the first round, the participant was instructed to search for the construction hazards in construction scenarios shown in the computer.

5. After the first round, the participant would receive a 10-minute safety training, which included reading the construction safety manual and FAQ. The construction safety manual presents some representative construction safety examples, such as falls, electrical and tripping hazards, and unprotected equipment hazards.

6. After the safety training, the participant would search for the construction safety hazard again as in the first round. The experiment was completed.

During the experiment, participants' eye movement data would be recorded, which would be used for the analysis. The University of Wyoming Institutional Review Board approved all procedures.

3.5 Hazard Identification Rate

Hazard identification rate (HIR) is the most direct way to reflect a worker's safety hazard recognition ability. As hazard recognition is a crucial part of the section, it is essential to calculate each worker's HIR. The calculation formula for HIR is as follows:

$$HIR_{i,j,k} = \frac{H_{i,j}}{H_j} \times 100\%$$

$H_{i,j}$ presents the number of safety hazards that are recognized by work *i* in image *j*; H*j* indicates the total number of safety hazards that are identified by the safety group in image j. *k* represents whether the worker receives safety training. 0 means "No", 1 means "Yes". For example, $H_{10,3,1}$ means the HIR of worker 10 recognizes image 3 after receiving safety training. In hypothesis 3, the study would focus on the effect of safety training on scan paths in different groups.

Based on the average performance of workers to identify safety hazards, participants can be divided into groups, namely the high group (HIR>0.5) and the low group (HIR≤0.5).

4. STATISTICAL ANALYSIS AND RESULT

4.1 Hypothesis 1

Hypothesis 1 tests whether elements (such as a safety training certificate [OSHA], field of study, and related job work experience) can improve workers' safety hazard recognition rate. A t-test is an inferential statistic used to determine if there is a significant difference between the means of two groups, which may be related to certain features. For the effect of the safety training certificate, the null hypothesis is that safety training certificate can improve workers' safety hazard recognition rate at the 5% significance level. For the effect of the field of study, the null hypothesis is that AEC (architectural engineering, civil engineering, and construction management) can improve workers' hazard identification performance at the 5% level of significance. For the effect of relevant work experience, the null hypothesis is that related job experience (project manager, project engineer, skilled trade workers, construction manager, inspector, superintendent, and abatement supervisor) can improve workers' hazard identification performance at the 5% level of significance. These statistical results are shown in Table 4.1.

Table 4.1 Statistical results for hypothesis 1

(a) Effect of safety training certificate

Safety Training Certificate	N	Mean	Std. Deviation	Std. Error Mean
Yes	28	0.592046	0.2726251	0.0515213
No	21	0.492048	0.2646440	0.0577501

Safety Training Certificate t-test result	t	df	p-value	Mean Difference	Std. Error Difference
	1.287	47	0.102	0.0999988	0.0777280

(b) Effect of field of study

AEC	N	Mean	Std. Deviation	Std. Error Mean
Yes	32	0.603978	0.2895381	0.0511836
No	17	0.446059	0.2018376	0.0489528

AEC t-test result	t	df	p-value	Mean Difference	Std. Error Difference
	2.001	47	0.026	0.1579193	0.0789283

(c) Effect of related job work experience

Related Jobs Work Experience	N	Mean	Std. Deviation	Std. Error Mean
Yes	17	0.592841	0.2871995	0.0696581
No	32	0.526000	0.2638516	0.0466428

AEC t-test result	t	df	p-value	Mean Difference	Std. Error Difference
	0.819	47	0.209	0.0668412	0.0816408

According to the statistical rest, there is insufficient evidence at the 5% significance level to support the claim that a safety training certificate can improve workers' hazard recognition skills. A safety training certificate cannot improve workers' hazard recognition skills. However, AEC can improve workers' hazard recognition performance. Finally, related work experience cannot improve workers' performance in hazard recognition.

4.2 Hypothesis 2

Hypothesis 2 is to verify the impact of safety training on workers' hazard identification performance for people with different backgrounds. The background includes a safety training certificate, the field of study, and related work experience.

4.2.1 Safety Training Certificate

This hypothesis tests whether there is a difference in hazard identification rate after the safety training for people with safety training certificate and those without. The null hypothesis is that safety training can improve HIR for people with and without safety training certificate. The result is shown in Table 4.2.

Table 4.2 Statistical result for people with or without safety training certificates before and after safety training

(a) comparison for people with safety training certificates before and after safety training

Safety Training Certificate	Mean	N	Std. Deviation	Std. Error Mean
Before	0.592046	28	0.2726251	0.0515213
After	0.63986	28	0.234687	0.011352

Safety Training Certificate	Mean	Std. Deviation	Std. Error Mean	t	df	p-value
Pair Before-After	0.0478107	0.2084528	0.011352	-1.214	27	0.118

(b) comparison for people without safety training certificates before and after safety training

Without Safety Training Certificate	Mean	N	Std. Deviation	Std. Error Mean
Before	0.49205	21	0.264644	0.057750
After	0.54752	21	0.216889	0.047329

Without Safety Training Certificate	Mean	Std. Deviation	Std. Error Mean	t	df	p-value
Pair Before-After	-0.055476	0.266548	0.058166	-0.954	20	0.176

According to the statistical result, the safety training cannot improve workers' HRR whether they have safety training certificate or not.

4.2.2 Field of Study

This hypothesis tests whether there is a difference in hazard identification rate after the safety training for people with different fields of study. The null hypothesis is that safety training can improve HIR. The result is shown in Table 4.3.

Table 4.3 Statistical result for people who study AEC and not AEC before and after safety training

(a) comparison for people who study AEC before and after safety training

AEC	Mean	N	Std. Deviation	Std. Error Mean
Before	0.603978	32	0.2895381	0.0511836
After	0.62506	32	0.233848	0.041339

AEC	Mean	Std. Deviation	Std. Error Mean	t	df	p-value
Pair Before-After	-0.0210844	0.2404007	0.424972	-0.496	31	0.312

(b) comparison for people who do not study AEC before and after safety training

Not AEC	Mean	N	Std. Deviation	Std. Error Mean
Before	0.44606	17	0.201838	0.048953
After	0.55365	17	0.220562	0.053494

Not AEC	Mean	Std. Deviation	Std. Error Mean	t	df	p-value
Pair Before-After	-0.107588	0.212167	0.051458	-2.091	16	0.026

According to the statistical result, safety training cannot improve workers' HRR if they study AEC. However, it can improve workers' HIR if they do not study AEC.

4.2.3 Related Jobs Work Experience

This hypothesis tests whether there is a difference in hazard identification rate after the safety training for people who do have relevant work experience or do not. The null hypothesis is that safety training can improve HIR for people who have relevant work experience or not. The result is shown in Table 4.4.

Table 4.4 Statistical result for people who have related work experience or do not have before and after safety training

(a) comparison for people who have relevant work experience before and after safety training

Related Jobs Work Experience	Mean	N	Std. Deviation	Std. Error Mean
Before	0.592841	17	0.2871995	0.0696561
After	0.63241	17	0.224482	0.05445

Related Jobs Work Experience	Mean	Std. Deviation	Std. Error Mean	t	df	p-value
Pair Before-After	-0.0395706	0.2604407	0.0631662	-0.626	16	0.270

(b) comparison for people who do not have related work experience before and after safety training

No Related Jobs Work Experience	Mean	N	Std. Deviation	Std. Error Mean
Before	0.52600	32	0.263852	0.046643
After	0.58322	32	0.233975	0.041361

No Related Jobs Work Experience	Mean	Std. Deviation	Std. Error Mean	t	df	p-value
Pair Before-After	-0.057219	0.22041	0.038965	-1.468	31	0.076

According to the statistical result, safety training cannot improve workers' HIR whether they have related work experience or not.

4.3 Hypothesis 3

This hypothesis tests the difference in the effect of safety training on workers' visual scan path between high-rate and low-rate groups. First, the difference in visual search strategy between the high-rate and low-rate groups was presented. The MultiMatch algorithm was then adopted to calculate the scan path similarity before and after safety training. Finally, the difference in the effect of safety training on workers' visual scan path between high-rate and low-rate groups was illustrated.

4.3.1 Difference Between High-rate and Low-rate Groups

The number of fixations indicates the number of attention shifts necessary to complete the task. Fixation duration largely reflects the difficulty of processing stimuli at the fixated location. The above oculomotor statistics are bound together by the third eye movement measure: saccadic amplitude or length. These eye-tracking metrics comprise the scan path. Importantly, contrasting outcomes between these conditions in terms of number and duration of fixations, as well as saccadic amplitudes, would produce quite different effects on each of MultiMatch's dimensions. If the HRR is higher than 0.5, the individual belongs to a high-rate group. If the HIR is lower than or equal to 0.5, the person belongs to the low-rate group. The difference of the three eye-tracking metrics between high-rate and low-rate groups is shown in Table 4.5. The one-way ANOVA method is used to analyze the difference at the 5% level of significance.

Table 4.5 Difference of workers' visual scan path between high-rate and low-rate groups in number of fixations, fixation duration, and saccadic amplitude

(a) Number of fixations

Number of Fixations	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1304.068	1	1304.068	7.248	0.01
Within Groups	8456.276	47	179.921		
Total	9760.345	48			

(b) Fixation duration

Fixation Duration	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	6403.625	1	6403.625	24.625	<0.01
Within Groups	12370.648	47	263.205		
Total	1877.273	48			

(c) Saccadic amplitude

Saccadic Amplitude	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	18534.740	1	18534.740	7.762	0.008
Within Groups	112230.507	47	2387.883		
Total	130765.247	48			

According to the comparison, there is a significant difference between high-rate and low-rate groups in number of fixations, fixation duration, and saccadic amplitude.

4.3.2 Difference of Visual Scan Path Between High-rate and Low-rate Groups

MultiMatch was adopted to calculate the scan path similarity before and after safety training. The vector difference between aligned saccade pairs is used to compute vector similarity. Both the amplitude difference between aligned saccade vectors and the Euclidean distances between aligned fixations are used to calculate length similarity. All three measurements are averaged over scan paths and normalized to the screen diagonally. The angular difference between aligned saccades, normalized by and averaged over scan paths, is used to calculate the direction similarity. This is then averaged across scan paths to determine the degree of similarity between fixation times for two aligned fixations. Figure 4.1 shows the scan path similarity before and after safety training of high-rate and low-rate groups in different dimensions.

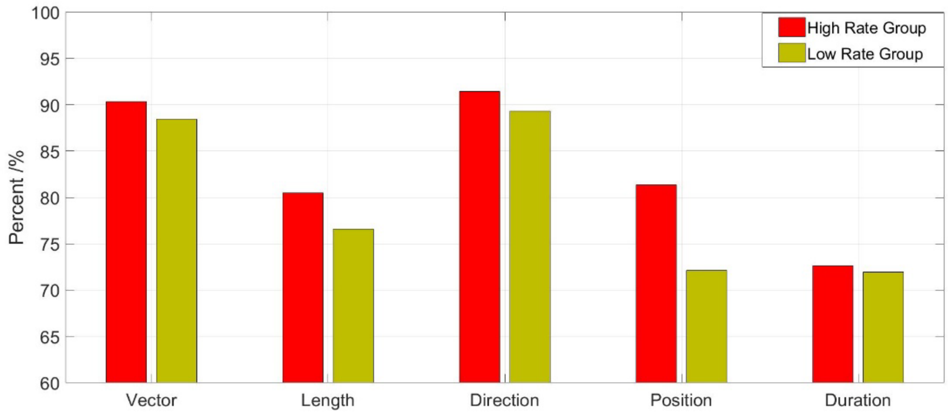

Figure 4.1 Scan path similarity before and after safety training of high-rate and low-rate groups in different dimensions

According to the bar diagram, the scan path similarity of the high-rate group is higher than that of the low-rate groups in the five dimensions. It means the safety training affects low-rate groups more, and the visual search strategy of high-rate groups is more stable. Table 4.6 shows the difference between high-rate and low-rate groups in the number of fixations, fixation duration, and saccadic amplitude before and after safety training.

Table 4.6 Difference before and after safety training of high-rate and low-rate groups in number of fixations, fixations durations, and saccadic amplitude

Group	Number of fixations	Fixations durations	Saccadic Amplitude
High-rate group	+1.1	+2.4	-11
Low-rate groups	+6.9	+6.2	-29.6

Based on the table shown above, we can conclude that the safety training affects low-rate groups more and the visual search strategy of high-rate groups is more stable.

5. CONCLUSION AND FUTURE WORK

This paper conducted a systematic literature review for the application of eye-tracking technology on construction safety. Statistical analysis for 81 literature selections was presented from four different aspects: time-series, location, journal, and co-author analysis. Then, the research procedure of eye-tracking technology on construction was summarized, including participants, design of the experiment, and eye-tracking metrics analysis. The discussion section presented the opportunities and challenges of the application of eye-tracking technology to construction safety. This section presents the future work and the main contribution of the systematic review.

In addition to the systematic literature review, the paper performed the following three tasks: (1) test the elements that can influence workers' hazard recognition performance; (2) verify whether training is efficient in improving workers' hazard recognition rate; (3) illustrate whether the safety training has an effect on visual search strategy for different groups from different dimensions, including vector, length, direction, position, and duration, and their specific performance in a variety of eye-tracking metrics. For the research, the study group designed a series of experiments to illustrate these research questions.

According to the data analysis, the results give the following conclusions:

(1) The industry experience can improve workers' safety hazard recognition rate, but safety training certificates (such as OSHA-10 safety training) and relevant jobs (such as project manager, project engineer, skilled trade workers, construction manager, inspector, superintendent, and abatement supervisor) work experience cannot.

(2) After safety training, workers' hazard recognition rate does not significantly improve. AEC can improve workers' safety hazard recognition rate after safety training, but certificates and relevant job experience cannot.

(3) There is a significant difference between the high-rate and low-rate groups in some eye-tracking metrics, namely the number of fixations, fixation durations, and saccadic amplitude. MultiMatch was adopted to calculate participants' scan path similarity in these various dimensions: vector, length, direction, position, and duration. The scan path similarity of low-rate groups is lower than that of high-rate groups in all dimensions. The difference between the high-rate groups before and after safety training in the number of fixations, fixation durations, and saccadic amplitude is less than that of the low-rate groups. It verified that the visual strategy of people with a high-rate recognition rate is more stable and is hard to affect by safety training.

Consequently, it is essential to adopt different safety training methods to improve workers' hazard recognition performance for different workers.

5.1 Future Work

This study serves as an early stage of eye-tracking technology to evaluate the influence of safety training on construction workers' visual search strategy in detecting site hazards. It still has some limitations. First, the research selected static construction images with safety hazards to present the construction sites. As the real construction sites are dynamic and full of uncertainties, such as noise and moving machines, the construction images cannot duplicate a real construction environment. This may influence the research result to some extent. Experiment participants are other limitations of the research. Most of the experiment participants are students and some are teachers. Although some participants have related work experience, they are not frontline workers, which may also affect the research.

For limitations, future work can be conducted from the following aspects. First, a more real construction environment should be used to replace static photos, such as virtual reality (VR) and real construction sites. Additionally, eye-tracking technology only can record users' eye movement data. To comprehensively analyze users' behaviors, it can combine with other wearable sensing technologies, such as an electroencephalogram (EEG), a tool to monitor and record users' brain activities.

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APPENDIX A: IRB CONSENT FROM

University of Wyoming Consent Form

I. General purpose of the study:

The purpose of this study is to investigate whether construction safety hazards would influence workers' visual search strategy. We hope to figure out the reason why some workers can't recognize the safety hazards provide guidelines for construction safety training. In the research, subjects are required to see the construction safety hazards pictures to collect the data to analyze.

II. Procedure:

First, participants will be introduced to the eye tracker. Detailed information of research purpose and methodology will be introduced. Second, students will be asked to voluntarily participate in this study. Then, participants will be asked to fill out a questionnaire on Qualtrics about their background, including age, gender, working experience, etc. Lastly, they will wear a Pupil Lab eye tracker to recognize all safety hazards by scanning some construction scenarios pictures in front of a computer. This study will be taken at the Construction Research and Innovation Lab at EN 1042. It will take about 20-30 minutes for each participant to complete. Participant will seat in front of the computer screen. No direct contact with the participants.

The following pictures demonstrates the hypothetical setup of the Pupil Lab eye-tracking system.

III. Disclosure of risks

COVID-19

The University has put in place reasonable physical safeguards relative to the COVID-19 virus. However, an inherent risk of exposure to COVID-19 exists in any public place where people are present. While on University property, you agree to follow all posted rules and verbal instructions from staff members, and you voluntarily assume all risks related to exposure to COVID-19.

In this study, the survey could potentially cause boredom or a feeling of lost time for participants, and there is a potential that the eye tracker may cause mild discomfort for participants. In order to relieve boredom, we will try our best to reduce the experiment time. And we would select some interesting pictures.

IV. Description of benefits:

The research attempts to apply eye-tracking technology in order to gain a better understanding of workplace safety from an average employee's perception. In response to the importance of tracking, automatic and real-time systems have been introduced to collect tracking data effectively.

V. Confidentiality:

All subjects' information would be protected. We promise that all information you provide will be kept strictly confidential and used for academic research only. Those data are not allowed to copy to others and only store in one computer.

VI. Freedom of consent:

Participation is voluntary, refusal to participate will involve no penalty or loss of benefits to which you are otherwise entitled, and you may discontinue participation at any time. Participants can withdraw from study by exiting the room.

VII. Questions about the research:

Name： Chengyi Zhang

Address: EN3099

Phone number: 307-766-4232

If you have questions about your rights as a research subject, please contact the University of Wyoming IRB Administrator at 307-766-5322

VIII. Consent to participate:

____
Printed name of participant

__________________________________ ____________________________
Participant signature Date

APPENDIX B: QUESTIONNAIRE

Construction Safety Research Questionnaire

Thank you for taking time to answer these questions. The questionnaire is divided into two parts. Section 1 is related to your personal information. Section 2 is choice question.

Section 1

NO：

Gender: ☐ Female ☐ Male

Age: ☐ Under 18 ☐18-25 ☐ 26-30 ☐ 31-40 ☐ Over 40

Section 2

1. Your past ocular history?
   ☐Glaucoma ☐Glaucoma Suspect ☐Cataract ☐Age-related Macular Degeneration
   ☐Patching☐ Inflammatory Disorder ☐Strabismus ☐Amblyopia ☐Retinal Degeneration
   ☐Retinal Detachment ☐ Keratoconus ☐ Others, please specify
   ☐No
2. If the answer for question 1 is not no, has your vision returned to normal through the treatment?
   ☐ Yes ☐ No
3. Your field of study is:
   ☐ Construction Engineering Management ☐ Civil Engineering ☐ Business
   ☐ Architectural Engineering ☐Others, please specify
4. Your work experience (years):
   ☐ 0 ☐ 1-3 ☐4-6 ☐7-9 ☐over 10
5. Choose the closet job title related to your work experience
   ☐ Project Engineer ☐ Superintendent ☐Construction Manager ☐ Inspector ☐Intern
   ☐ Skilled Trade worker ☐ Student ☐ Others, please specify
6. Have you ever received any safety trainings, such as OSHA Training?
   ☐ Yes
   ☐ No

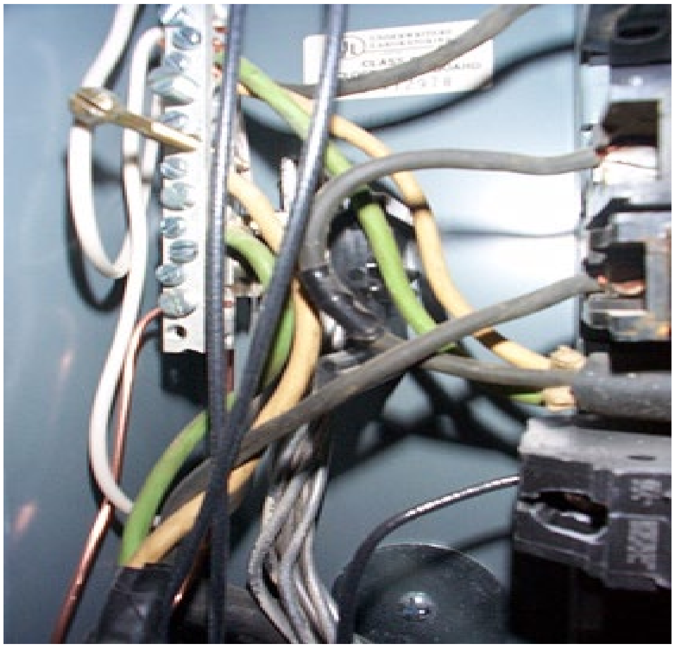
APPENDIX C: CONSTRUCTION SAFETY HAZARD TRAINING MANUAL

As defined by the Occupational Safety and Health Administration (OSHA), safety hazards are unsafe working condition that cause injury, illness, and death. Every year, construction industry occurs a large quantity of accidents, which can lead to huge financial and human loss. The reason behind this phenomenon is construction work zones contain a number of safety hazards. It’s necessary to improve construction workers’ safety hazards identification skills. This safety training manual lists 4 common safety hazards in construction sites to help people better understand construction hazards, including falls, electrocution, being struck by falling objectives and trapped during excavation.

1. Fall Hazard: Falls are the leading cause of fatalities in the construction industry. Conditions that required use of fall protection includes Walkways & ramps, Open sides & edges, Holes, Concrete forms & rebar, Excavations, Roofs, Wall openings, Bricklaying, and Residential Construction. A fall from as little as 4-6 feet can cause loss of work and some cases death. The following picture is one representative example of falls.

Example of falls

2. Electrical Hazard: Electricity is the flow of energy from one place to another and requires a source of power (generating station, power station or portable generator). Travels in a close circuit. The most frequent causes for electrical accidents comprise of contact with power lines, lack of ground fault protector, missing ground on electric cords, improper use of equipment and improper use of electric cords. Electrical accidents are caused by a combination of three factors: Unsafe equipment and/or installation, Workplaces made unsafe by the environment, and Unsafe work practices. Here are some examples of electrical hazards and their reasons.



(1) Isolate electrical parts
(2) Use guard or barriers
(3) Replace covers

(1) Shall be protected from abrasion
(2) All openings shall be closed to prevent access

(1) Usually not insulated
(2) Carry extremely high voltage
(3) 80% of all lineman deaths were caused by contacting a live wire with a bare hand

3. Tripping hazard: A trip occurs when your foot or leg comes in contact with a hazard while walking. The momentum from the upper body continues to move while the tripped leg stays stationary for a moment, causing your body to fall. Trips can also occur when a person steps up or down and the surface is uneven or not at the height they expected. Some examples of tripping hazards are shown below.

4. Unguarded machinery and moving machinery parts guards removed or moving parts that a worker can accidentally touch. The following picture shows one representative example. The construction workers stay under the working arm of the carne.

5. Scaffolding hazard: Scaffolding safety is critical as working on scaffolds results in workers working at heights. When working at heights, there are many dangers that workers may face. Working on scaffolding requires workers to work at heights. As a result, there are many opportunities for workers to fall off a scaffolding. Workers can fall off a scaffold due to many reasons, from lack of guardrails to slipping or tripping on slippery substances, wearing inappropriate footwear, or even due to tools or other debris lying on scaffolding surfaces. Workers can also fall from scaffolding when they are entering or getting off scaffolding if the access being used is not according to OSHA specifications. The image presents some examples of scaffolding hazards.