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RESEARCH ARTICLE

Comparing the safety awareness of workers on the virtual and real construction site using eye-tracking technology

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Abstract

Because the construction industry inherently contains dangerous practices, safety training has a critical role in preventing accidents and mitigating hazardous outcomes. However, due to the inefficiency of traditional safety training methods and the riskiness of hands-on training, virtual safety practices have great potential to train construction workers. Therefore, this study aims to investigate the effectiveness of virtual safety exercises, comparing the workers' safety awareness on real and virtual construction sites utilizing eye-tracking technology. Eye-tracking data collected from eleven workers during the experiments in the real and virtual construction sites were analyzed using three main eye-tracking metrics, namely total fixation duration, first fixation duration, and time to the first fixation. The result of the study showed that the workers' time to first fixation duration in the real site is significantly lower than in the virtual environment ($Z=-4.18$, $\rho<0.05$), which means that participants noticed risk sources in the actual construction site more quickly compared to the virtual environment. On the other hand, total fixation duration ($Z=-3.99$, $\rho<0.05$) and first fixation duration ($Z=-3.99$, $\rho<0.05$) in the virtual environment were significantly higher than in the actual construction site, indicating that participants had higher attention level and higher risk perception during the virtual tour. The results support the effectiveness of a risk-free virtual environment by showing the participants' high level of attention and increased risk perception. By creating the most appropriate virtual environment for the relevant construction task, workers' safety awareness can be enhanced utilizing non-hazardous and effective Virtual Reality (VR) safety tools.

1. Introduction

The construction sector has always maintained its position as the locomotive sector of the countries with the added value and employment opportunities it provides for the economy. However, the high rate of occupational accidents and fatalities occurring in the sector due to highly hazardous operations is a severe problem for many countries around the world [1]. Fatalities due to dangerous and complex construction operations are the top priority, but this also disrupts the construction process, delays the project schedule, and negatively affects cost, productivity, and reputation. Therefore, safety is a significant concern in the construction industry, as it is a source of substantial direct and indirect expenses [2]. Since the current safety management

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practices fail to mitigate occupational accidents and prevent violations of safety rules, new methods and approaches using virtual simulation technologies are developed to create safe workplaces in the construction industry [3-5]. Among all, experience-based safety training using virtual technologies is an alternate way of providing effective training. Accordingly, trainees can experience quite dangerous scenarios using virtual technologies without compromising their and other participants' safety. However, for virtual applications to be practical and widely adopted in the construction industry, virtual sites should be developed that reflect the workflow, equipment usage, and working environment in a realistic approach. To accurately discuss virtual safety simulations' effectiveness, we need to compare them with the real construction site. In other words, we should bridge the gap between the virtual and real world by ensuring enhanced ecological validity, which is critical to justify using virtual simulations for safety training. Naugle et al. [6] define ecological validity as the degree to which results obtained in a controlled laboratory experiment relate to those obtained in the real world. Accordingly, virtual simulations, despite being computer-generated, can actually be quite effective in achieving ecological validity in safety training as virtual environments provide realistic scenarios mimicking actual work environments, dynamic interactions which might be challenging to sustain in a real site, behavioral observation opportunity, consistent trainings with measurable outcomes and most importantly having cost effective replications. Shortly, the use of virtual simulations in safety training enhances ecological validity by providing realistic, adaptable, and cost-effective environments that closely mirror the challenges individuals may encounter in their actual construction sites. This approach ensures that the skills and knowledge acquired during training are directly applicable to real-world scenarios, ultimately improving overall safety outcomes. Yet, assessing the ecological validity of virtual simulation, in other words developing a proper benchmark for virtual-real world comparison, can be challenging (e.g. [7]). One approach may be assessing the transfer of improvement gained in the virtual environment to the real world by directly comparing experiment subjects' situation awareness in virtual training and real construction site scenarios. Previous studies have investigated the role of ecological validity in human behavior, such as hazard perception and emotional response [7, 8]. For example, Malone and Brünken [8] showed that a high level of ecological validity causes a better hazard recognition ability. Thus, comparing participants' performance in real and virtual worlds provides a better understanding of the effectiveness of VR environments for safety issues. Also, as Cao et al. [9] mentioned, VR-based behavior studies have some challenges in terms of ecological validity because the results cannot be generalized to real life. In this respect, this study aims to show that virtual training tools successfully simulate the real construction site conditions so that the trainees' safety awareness in the virtual and real construction site practices are similar.

2. Background

2.1. Safety training tools in the construction industry

The high number of fatal accidents in the construction industry indicates the current inadequacies in safety management practices [10]. Previous literature shows that the low level of hazard identification [11, 12], the unsafe behavior of workers [13], poor safety attitudes [14], and lack of collaboration [15] are the main causes of accidents on the construction site. As highlighted in the literature, human-oriented factors need to be eliminated to avoid accidents on the construction site. Accordingly, all stakeholders in the construction industry need to expand their safety awareness to maintain a healthy working environment. In this regard, safety training plays an impactful role in preventing occupational accidents caused by human factors [16]. Many studies in the literature introduce novel training tools to enhance traditional safety training methods (e.g. [17-19]). For example, Zhao and Lucas [19] examined the US construction industry's electrical safety-related instructions to reveal the existing state of construction safety training. As the authors state, the most common safety training types are classroom training, on-the-job training, and on-site safety meetings. These conventional methods are mainly based on verbal lectures and visual presentations. Also, except for on-the-job training, they do not require direct participation or responsibility. However, considering the occupational accident statistics, standard training practices in the construction industry do not prevent accidents [19]. Therefore, a training program that focuses on risk recognition, a valuable feature for safety practices, is essential for workers to be aware of the hazards and take measures without getting injured. Accordingly, the visualization and gamification approach enhances trainees' participation, and risk identification becomes crucial for construction safety training practices. Hence, a growing number of studies develop and propose VR-based training tools for construction workers and professionals (e.g. [16, 18, 20-22]). VR technology is a computer-based method that enables users to engage and visualize their surroundings from an immersive and interactive standpoint. This simulation technology created through several software and hardware technologies to realistically represent all types of environments (e.g. [22]). By leveraging a combination of cutting-edge hardware and software technologies, VR has the capacity to convincingly replicate diverse environments. The synthesis of technology leads to the creation of a potent instrument for training, teaching, and simulation. Moreover, as Pereira et al. [16] suggested, VR environments can be improved using different approaches, such as integrating panoramic real construction site displays. In a nutshell, VR technologies provide safe and realistic training environments that may help construction workers and professionals train more efficiently.

2.2. Effectiveness of safety training

The traditional safety teaching methods are a question of debate regarding their inefficiency in preventing construction site accidents. Moreover, the hybrid survey of Wilkins [23] revealed the opinions of workers on construction safety training. The results showed that the participants were not satisfied with the existing safety programs because of the inefficient training approaches. In this regard, discussing the training methods from a broader perspective is critical to evaluating construction safety applications' efficiency. Several teaching methods and their performance have been analyzed for decades in the education literature (e.g. [24-26]). Dale [24], who published one of the earliest studies on this topic, evaluated the effectiveness of teaching modes and presented them as parts of a cone named Dale's Cone of Experience. As the cone indicates, doing the real thing and simulating the real experience are the most effective ways to learn, and they constitute the bottom of the cone.

On the other hand, Burke et al. [27] assessed the effectiveness of teaching methods in health and safety training. The authors grouped the training methods into three categories, including least engaging, moderately engaging, and most engaging training. The least engaging training includes only information transfer through videos and lectures. However, most engaging training methods support hands-on practices and behavioral modeling besides ensuring information transfer. According to Burke et al. [27], the effectiveness of the most engaging approaches, including hands-on training, is more prominent than other practices to prevent accidents. In a semantic study, Flick [28] defines the term hands-on practice as "a specific instructional strategy where trainees are actively engaged in manipulating materials." He stated that due to hands-on learning's main characteristics, such as encouragement to think about responsibilities, the students are expected to learn far more than their observations. Accordingly, hands-on training has a crucial role in experiential learning. Moreover, providing suitable training similar to on-site applications becomes essential for effective hands-on practices. In other words, as Sisson [29] mentioned, the trainees complete the procedure under realistic working conditions and do the same training they are required to do every day. However, in high-risk cases, providing hands-on practice could be highly dangerous, and a potential error of a trainee could result in a hazardous situation [29]. In this sense, simulations are suitable for risky processes; thus, the trainee pretends to do the daily activities. When the instructor finds the trainees' performance satisfying, they may move on to the real job [29]. Klahr et al. [30] argued that virtual technologies have a high potential to provide risk-free hands-on training and avoid the disadvantages of physical hands-on training. In a nutshell, we can say that a similar application to the actual work may provide the most effective training experience for trainees. However, although various studies emphasize the advantages of VR tools, none directly compares VR tools' eligibility from a situational awareness perspective. In other words, the cognitive process of workers, whether or not they are paying attention to risk sources in the virtual environment, needs to be examined.

2.3. Eye-tracking for construction safety

A person's cognitive process can be evaluated through visual attention. In their "eye-mind" hypothesis, Just and Carpenter [31] state that whenever participants look at a virtual item such as an object or a word, at the same time, they start to think about it. In this regard, Poole and Ball [32] define eye-tracking as "a technique whereby an individual's eye movements are measured so that the researcher knows both where a person is looking at any given time and the sequence in which their eyes are shifting from one location to another." Accordingly, the use of eye-tracking technology is appropriate for providing an objective analysis of the cognitive processes of construction workers in the virtual environment compared to the real construction site. Given that eye tracking technology offers an unbiased evaluation of visual search behavior, it is not unexpected that the application of this technology in construction safety studies has grown recently (e.g. [33-37]). For example, Li et al. [35] aimed to identify the mental fatigue level of the operators by using eye-tracking technology through a virtual excavation simulation. As a result, the study revealed the reliability of eye-tracking technology use in mental fatigue identification. On the other hand, Han et al. [36] investigated the factors affecting construction workers' cognitive load and hazard recognition by evaluating participants' eye movement patterns. The study results showed the influence of site conditions on the participants' eye-tracking metrics and revealed the relationship with hazard identification. Moreover, Jeelani et al. [33] identified various quantitative visual search patterns predictive of superior hazard recognition performance: i) Search duration shows that the more time the site is examined, the more risks are noticed. ii) Higher concentration degrees are obtained through higher fixation count and fixation time. iii) The higher fixation spatial density means that a broader area is involved in workers' visual attention.

Existing studies in the literature (e.g. [38-40]) indicate that one of the leading causes of accidents at construction sites is the unrecognized hazards. Namian and colleagues [41] claim that even though safety and hazard recognition training is provided, they are not at the desirable level partly because knowledge acquired through training programs is often not transferred or applied on the construction sites. The researchers [41] also conclude that in order for the occupational safety training to be successful, it is necessary to develop the risk identification skills of the trainees through proper training delivery and the adaptation of high engagement training methods. Knowing that virtual environments have a great potential to provide highly engaging training through behavior modeling and hands-on practice in a risk-free environment [5], we propose that the situation awareness of the trainees in the virtual environment should be similar or superior in terms of eye-tracking metrics. Hauland [42] stated that workers' eye movements falling into a particular area of interest (AOI) could be interpreted as a situation awareness measure. Previous studies have utilized eye-tracking technology to measure the situation awareness of construction workers (e.g.[43-45]). As Hasanzadeh et al. [44] highlighted, the eye-tracking approach provides opportunities to evaluate the situation awareness of workers and enhance the efficiency of safety training. Therefore, considering the potential of eye-tracking technology in the existing literature, this study aims to examine the effectiveness of VR-based techniques compared to on-site safety applications by analyzing trainees' attention, hazard recognition, and risk perception using eye-tracking technology.

3. Methodology

3.1. Hypothesis development

Given the hazardous environment of construction sites, virtual training offers a realistic risk-free practice for construction workers [46]. However, in order to determine the effectiveness of training provided in the virtual environment, it is necessary to compare the safety awareness of the trainees in the actual construction site and the virtual environment. Construction workers should be aware of surrounding actions and items to enhance occupational safety [47], and Endsley defines this condition as "situation awareness" [48]. Accordingly, situation awareness means perceiving the elements in the environment in a time and space volume, comprehending their meanings, and finally estimating their situation in the near future. As Hasanzadeh et al. [45] state, "to form situation awareness, one needs to pay attention to perceive and process the environment". Therefore, trainees should perceive the sources of risk in the virtual environment, comprehend their precariousness, and anticipate the possible consequences these sources of risk may cause. In short, situation awareness of trainees becomes a critical issue to evaluate and compare their safety awareness, such as hazard recognition, level of attention, and risk perception in virtual versus real construction sites. Numerous studies attempted to improve the performance of safety training to enhance workers' awareness of their surroundings and possible hazards (e.g. [41, 49]). For example, in their study, Namian et al. [49] examined several experimental data and revealed that high engagement training is far more efficient for hazard recognition. In this training method, trainees take active roles and interact with other workers and experts. According to Albert et al. [3], enhancing on-site hazard recognition can be achieved through monitoring field workers' activities, identifying risky status arising from these activities, and developing effective strategies to improve the hazard recognition skills of workers.

In their seminal study, Wang et al. [50] defined the factors that may influence safety risk tolerance. The authors state that one of the most critical elements to provide on-site safety is sensitivity to the potential risks, which focuses on the capability of the workers to make quick responses and judgments to potential threats. Thus, workers could take immediate and correct safety action by being more sensitive to potential threats. For instance, when a worker detects a retaining wall's possible collapse, this person will leave the area very quickly. As a result, a potentially fatal accident could be avoided. From this simple example, one could conclude that the duration to make decisions is very significant to prevent a potential crash accident. Furthermore, Han et al. [36] stated that this cognitive load, which shows a person's mental effort, shapes workers' safety behaviors. Besides, as the eye-mind hypothesis indicates, a person's cognitive processes are relevant to their eye movements, such as fixations. In this regard, many studies in the literature utilized eye-tracking technologies to evaluate the trainees' risk recognition performance. In this context, time to the first fixation refers to the "amount of time that passes following the scenario's first appearance until the participant first fixates on an AOI" [51]. AOIs are the specific locations or objects in a scene specified by researchers. In light of this research, lower time to the first fixation could be considered a more effective safety awareness in the construction safety management context, since the lower amount of time to look at a trigger visual allows trainees to take quicker action. Therefore, the following hypothesis is developed:

Hypothesis 1: The time to first fixation durations of participants in the virtual environment is significantly shorter than the time to first fixation durations of the same participants on the real construction site.

Another critical indicator to provide on-site safety is the workers' level of attention. Previous literature [52, 53] states that one of the main human-related factors that lead to on-site accidents is the lack of workers' awareness when detecting potential hazards. Consequently, the workers could not react correctly and make the appropriate decision. Furthermore, in the eye-tracking context, total fixation duration (also known as time spent) "often indexes motivation and top-down attention, since respondents have to blend out other stimuli in the visual periphery that could be equally interesting" [54]. In this sense, the higher total fixation duration indicates greater attention of the trainees. Therefore, higher total fixation duration is preferred in the construction safety training context. Thus, the following hypothesis is developed:

Hypothesis 2: The total fixation durations of participants in the virtual environment are significantly longer than the total fixation durations of the same participants on the real construction site.

Several researchers have frequently highlighted the importance of risk perception (e.g. [55-57]). Risk perception is a nominative assessment of a person regarding the frequency and severity of risk [56]. This personal assessment is critical for construction safety in preventing workers' failure to recognize occupational hazards [58]. In the eye-tracking context, first fixation duration refers to "information about how long the first fixation at a certain region lasted for, which can be compared to other regions" [51]. In their comparative analysis, Habibnezhad et al. [58] evaluated the impact of workers' risk perception on their visual search behaviors when identifying hazards. As the analysis results of Habibnezhad et al. [58] indicate, the trainees with higher risk perception have higher first fixation duration. In this sense, the following hypothesis is developed:

Hypothesis 3: The first fixation durations of participants in the virtual environment are significantly longer than the first fixation durations of the same participants on the real construction site.

3.2. Experimental settings

A three-staged experiment is prepared to test whether the 3D virtual environment provides effective hands-on practice. Eleven male construction workers participated in the experiment, and their demographic information is presented in Table 1. Each participant initially toured the real construction site, then entered the 3D virtual environment. The experiment took place in a high-rise reinforced concrete residential project under construction in Turkey, against which the virtual environment was developed. The risk sources in the real site are also included in the virtual environment.

Table 1. Participant demographic information

Participant	Age	Field Experience	Job Title	3D Game Experience
Worker 1	59	31	Foreman	No
Worker 2	41	17	Foreman	No
Worker 3	40	15	Insulation Worker	Yes
Worker 4	43	20	Foreman	No
Worker 5	35	10	Plumber	No
Worker 6	48	28	Site Worker	No
Worker 7	27	5	Insulation Worker	Yes
Worker 8	24	3	Insulation Worker	No
Worker 9	37	19	Crane Operator	Yes
Worker 10	60	40	Plumber	No
Worker 11	26	4	Safety Inspector	Yes

The experimental and analysis steps of the study are shown in Fig. 1. After calibrating the mobile eye-tracker device in the first stage, each worker is asked to identify potential hazards in the actual construction site. During the experiment, the total fixation duration, first fixation duration, and time to the first fixation data are collected using Tobii ProGlasses 2 eye-tracker. Each worker interacts with the instructor and identifies the potential hazards by their verbal statements, and the instructor interviews the workers following the experiment. In the second stage, the participants watch a lecture-based video-recorded presentation explaining 3D virtual construction environment software usage. Also, an infographic presenting the necessary information required to use simulation, such as controller configuration, simulation settings, etc., is provided for the participants. Then, participants enter the virtual environment in the third stage after calibrating the Tobii X2-30 on-screen eye-tracker. Subsequently, the participants commence the experiment by inspecting the virtual construction site to identify potential hazards without any time limit. Again, workers identify the risks by verbal notice.

3.3. Virtual environment

In order to test the hypotheses, a virtual environment was developed, which provides a specific VR tour for the tower crane tasks. The tool, developed using Unreal Engine 4, simulates a construction site, including a tower crane lifting operation in a 3D environment. The virtual environment provides a realistic construction workspace in a 3D view. The potential hazards of tower crane tasks were defined utilizing the study of Shepherd et al. [59] to design the virtual environment. Major accident precursors during the crane operations, such as blind lifts, load types, the wind, weather conditions, etc., are integrated into the virtual environment. On the other hand, considering several articles [60-62], other risks faced in the simulation are defined, and potential hazards are embedded into the virtual objects existing in the simulation. Fig. 2 shows the virtual visuals of risk sources that commonly lead to accidents on construction sites.

Users enter the environment by creating their avatars on the server (Fig. 3) and randomly select one of the roles in the crane operation simulation; (i) crane operator, (ii) pointer, and (iii) bricklayer. The tour starts after entering the warehouse and choosing the correct personal protective equipment (PPE) for the selected role (Fig. 4). During their virtual time, the participants are allowed to interact with the models (e.g., crane, lift, rope, etc.) and other workers in the virtual environment.

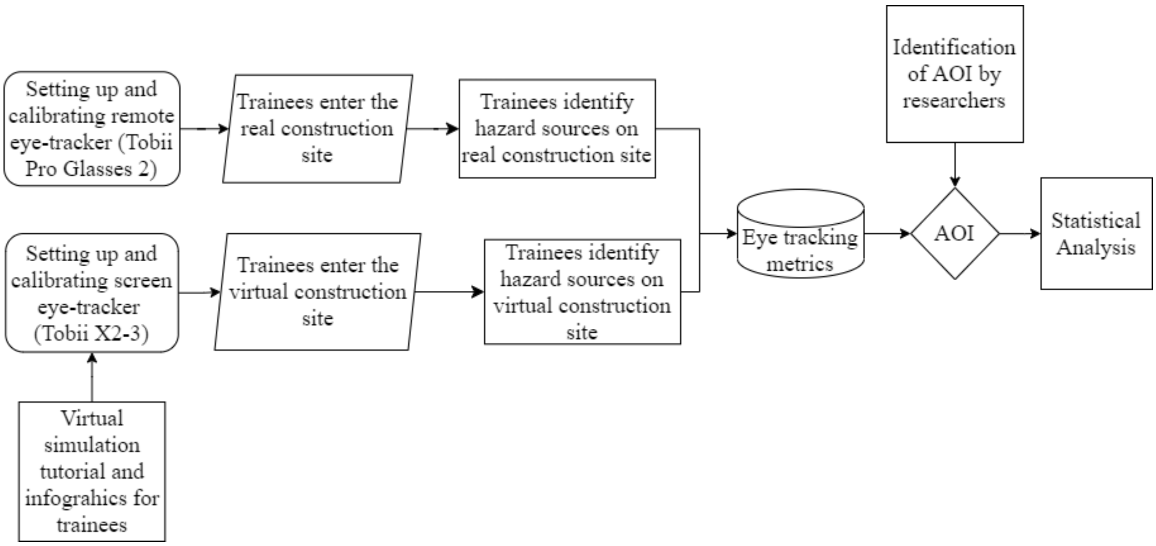

Fig. 1. Experimental and analysis steps

Fig. 2. Visual risk sources integrated into simulation

Fig. 3. An avatar with PPE

Fig. 4. PPE selection

3.4. Data collection

Several eye-metric data were collected using eye-tracking devices to analyze the trainee's safety awareness in both virtual and real construction sites. The definition of some eye-tracking terms and metrics are presented in Table 2.

The study's data collection process consists of two parts: i) collecting eye movement data of the workers on a real construction site and ii) collecting eye movement data of the same workers in a virtual environment. Firstly, the on-site experiment is conducted, and eye-tracking data is collected from the participants using Tobii Pro Glasses 2 wearable eye-tracker (Fig. 5). Tobii Pro Glasses 2 device was designed to capture natural viewing behavior in any real-world environment while ensuring outstanding eye-tracking robustness and accuracy [63]. The technical specifications of Tobii Pro Glasses 2 are gaze sampling frequency of 100 hertz, 1 point calibration, and scene camera recording angle of 82 degrees (horizontal) and 52 degrees (vertical). Secondly, the eye-tracking data is collected from the same workers experiencing the virtual environment. Tobii X2-30 compact on-screen eye-tracker was used (Fig. 6) to gather the eye-tracking data of workers. Tobii X2-30 is a screen-based eye tracker capturing gaze data at 30 hertz. The technical specification of the Tobii X2-30 eye-tracker involves the accuracy of 0.4 degrees, the precision of 0.32 degrees, freedom of head movement 50-centimeter (width) x 36-centimeters (height) x 90 centimeters (depth), cm (20 x 14″), system latency of 50 to 70 milliseconds range, 30 hertz of data rate and 9 points calibration [64]. The eye-tracking data collection processes in a real site and virtual environment are presented in Fig. 7 and Fig. 8, respectively.

Table 2. Definition of eye-tracking terms

Term	Definition	Unit
General Eye-Tracking Terms		
Fixations and Gaze Points	"Gaze points show what the eyes are looking at. If a series of gaze points is very close – in time and / or space – this gaze cluster constitutes a fixation, denoting a period where the eyes are locked towards an object." [65].	-
Saccade	"The instantaneous and ballistic changes of the eyes between fixation points." [66].	-
Areas of Interest (AOI)	"A tool to select subregions of the displayed stimuli, and to extract metrics specifically for these regions." [65].	-
Eye-Tracking Metrics		
Time to first fixation	"The duration of time it takes for a person to first focus their gaze on an AOI" [67].	Second
Total fixation duration (also referred to as time spent or dwell time)	"The total amount of time an individual fixated on AOI." [67].	Second
First fixation duration	"The duration of the first fixation on an AOI." [68].	Second

Fig. 5. Tobii Pro Glasses 2

Fig. 6. Tobi X2-30

Fig. 7. Data collection process using Tobii Pro Glasses 2

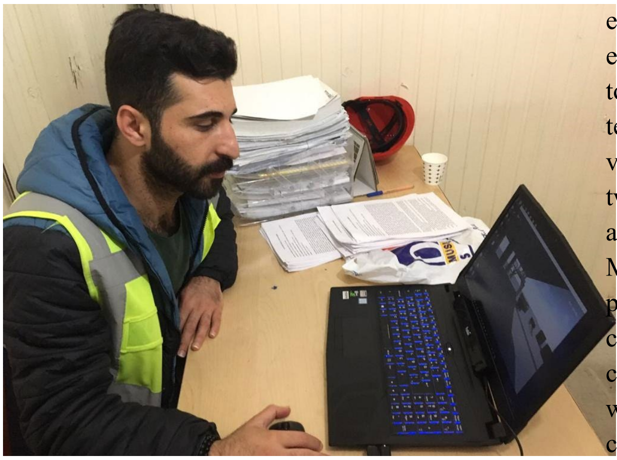

Fig. 8. Data collection process using Tobii X2-30

3.5. Data analysis

After completing the both tours, potential risk sources are defined as the AOI on real and virtual construction sites. For instance, potential risk sources, such as ladders without a railing and nails on the construction site, which are from the workers' viewpoint, are defined on the real and virtual construction sites. Fig. 9 illustrates the sample assignment of the AOIs. Then, considering the eye-tracking metrics that fall into specific AOIs, the safety awareness of the trainees in the actual and virtual sites are analyzed and compared.

We analyzed the eye-tracking data collected in two different settings from the workers. First of all, to select the appropriate statistical analysis method, normality, homogeneity, and randomness tests are conducted. Because the sample size is significantly larger than 50, we utilize the Kolmogorov-Smirnov analysis to test the normality. Regarding the homogeneity analysis, Levene's test is conducted to evaluate whether the variances of the masses were equal. Lastly, the Wald-Wolfowitz runs test is used to test the randomness, a nonparametric statistical test checking the randomness hypothesis for a two-valued data set. Besides, the experiment includes two different groups, the dataset consists of interval and continuous data. Consequently, we use the Mann-Whitney U test to compare the search patterns of the trainees between the virtual and real construction site interaction. On the other hand, calculating the minimum required sample size when planning any study, the effect size must be considered [69]. When the effect size is small, even if the difference of means is viable and statistically significant, the results could be trivial. Therefore, the Cohen's D for the t-test is calculated to analyze the effect size.

4. Analysis Results

Table 3 shows the descriptive statistics analysis of the participants' eye-movement behavior in real and virtual construction sites. 91 and 127 AOIs were defined in the real and virtual construction sites, respectively.

Regarding the normality, Kolmogorov-Smirnov analysis results showed that all eye-tracking metrics are not normally distributed, but the first fixation duration of the trainees. Moreover, Levene's test of homogeneity showed that all eye-tracking metrics do not provide homogeneity. Lastly, according to the test result, randomness is significantly provided in each metric in the dataset. Accordingly, non-parametric analysis methods are utilized in this study.

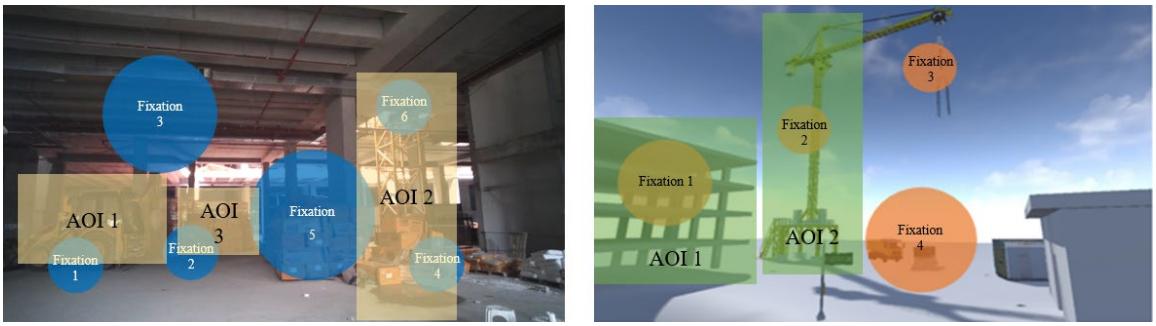

Fig. 9. The sample assignment of the Area of Interests on real construction site and virtual environment

Table 3. Experiment results of eye-movement behavior comparison experiment

	Time to First Fixation	Total Fixation Duration	First Fixation Duration
Real Construction Site - Mean	6.28	1.95	0.15
Real Construction Site - St. Deviation	11.12	3.01	0.13
Real Construction Site - N	91	91	91
Simulation - Mean	19.24	3.35	0.29
Simulation - St. Deviation	25.58	3.79	0.35
Simulation - N	127	127	127

Table 4 shows the results of the Cohen's D for t-test. Cohen (1992) presented the required power level as 80% and classified effect size as small (0.2), medium (0.5), and large (0.8). The first fixation duration, time to the first fixation, and total fixation duration are pretty close to medium effect size. At the same time, a high level of power is achieved in these metrics' analyses. According to the meta-analysis of Chita-Tegmark [70], which includes 38 published papers on eye-tracking use in autism research, the average value of Cohen's d effect size is 0.55. Therefore, we can conclude that the calculated effect size also shows a similar trend to the existing literature besides having a high power value.

To compare the difference in the eye-tracking behavior of the trainees, Mann-Whitney-U Test, non-parametric independent samples t-test analysis, is conducted. Table 5 illustrates the Mann Whitney-U test analysis results.

Table 4. The summary of Cohen's D for t-test analysis results

Eye Tracking Metric	Environment	Mean	St. Dev.	Sample Size	Effect Size	Power
Time to First Fixation	Real Construction Site	6.2765	11.123	91	0.6574	0.9991
	V-SAFE	19.2426	25.576	127		
Total Fixation Duration	Real Construction Site	1.9482	3.0080	91	0.4089	0.9070
	V-SAFE	3.3475	3.7913	127		
First Fixation Duration	Real Construction Site	0.1532	0.1275	91	0.4986	0.9758
	V-SAFE	0.2854	0.3528	127		

Table 5. Mann Whitney-U test analysis results

	Time To First Fixation	Total Fixation Duration	First Fixation Duration
Real Construction Site - Mean	6.28	1.95	0.15
Real Construction Site - St. Deviation	11.12	3.01	0.13
Real Construction Site - N	91	91	91
Simulation - Mean	19.24	3.35	0.29
Simulation - St. Deviation	25.58	3.79	0.35
Simulation - N	127	127	127
Mann-Whitney U	3861.5	3945.5	5031
Z	-4.18	-3.99	-1.64
Asymptote Significance (2-tailed)	0	0	0.097
Exact Significance (2-tailed)	0	0	0.097
Exact Significance (1-tailed)	0	0	0.048

Point probability, significance (1-tailed) values on two metrics, the total fixation duration and the first fixation duration, indicate a statistical difference between the workers' eye-tracking data on the real construction site and the simulation. However, contrary to expectations, the time to first fixation duration in the virtual environment is longer compared to the real construction site. Therefore, the status of the hypotheses is presented in Table 6.

5. Discussion

The number of occupational accidents has been relatively high in the construction industry due to the sector's inherently dangerous nature. Considering the failure of traditional safety training methods in preventing occupational accidents, many researchers focused on different safety practices. They presented risk-free virtual environments to train construction workers efficiently (e.g. [5, 19, 71, 72]). VR-based simulations aim to model a real-time event or a hypothesis to understand how the system works and evaluate the deficiencies of real-world practices [73]. Significantly, virtual simulations might be pretty helpful when the real system is not suitable to access because of the high-risk conditions [74]. In this sense, considering the risky nature of construction sites, virtual environments provide an excellent opportunity for off-site training, enabling the trainees to learn from their mistakes, and correct them without entering the actual construction site. As a result, trainees could improve their behavior-based skills, communication, and cognitive abilities [71]. In short, simulation-based computer technologies can significantly improve the training level and substitute conventional construction safety training methods.

Burke et al. [27] highlight that an adequate safety training method should cover hands-on practice because of its critical role in reinforcing safety knowledge. Several studies simulated different construction tasks utilizing virtual environments to provide hands-on practice opportunities, such as creating plant operator activities in an immersive virtual environment [75] and generating an augmented virtuality-based training platform to improve the trainees' safety awareness for scaffolding activities [76]. In a nutshell, considering these studies, we can state that the virtual safety training simulations have the potential to provide suitable hands-on practice for construction workers. However, the effectiveness of virtual safety training cannot be proven without comparing them with on-site methods. Therefore, to evaluate the effectiveness of the virtual hands-on practices, the safety awareness of trainees in real and virtual construction sites can be compared using eye-tracking metrics. In this respect, the safety awareness of trainees can be evaluated based on their attention level, which indicates the situation awareness of trainees. As Hasanzadeh et al. [44] outlined, the eye-tracking method provides vital benefits for evaluating the situation awareness of construction employees and improving the effectiveness of safety training.

Table 6. The status of the hypotheses in eye-movement behavior comparison

Hypotheses	Abbreviation	Status
The time to first fixation durations of participants in the virtual environment is significantly shorter than the time to first fixation durations of the same participants on the real construction site.	H1	Rejected ($\rho < 0{,}05$)
The total fixation durations of participants in the virtual environment are significantly longer than the total fixation durations of the same participants on the real construction site.	H2	Accepted ($\rho < 0{,}05$)
The first fixation durations of participants in the virtual environment are significantly longer than the first fixation durations of the same participants on the real construction site.	H3	Accepted ($\rho < 0{,}05$)

If related eye-tracking metrics show that the trainees have an equal or higher level of attention, hazard recognition, and risk perception, in the virtual environment than in the real site, we can consider the virtual environment an effective method.

A two-phase experiment was conducted with eleven construction workers to determine whether the virtual environment provides an effective hands-on practice. In each session, one of the workers accessed the construction site and identified potential risk sources. Later on, the same worker enters the virtual environment and is asked to define potential risk sources, just like in the first stage. The eye-mind hypothesis states that eye movements are linked with the cognitive processes of individuals [31]. In other words, this theorem posits that “what persons fixate on closely relates to what they process” [77]. For this reason, we utilized eye-tracking technology to evaluate the interaction of participants with construction environments. During touring the real and virtual construction sites, workers’ pupil movements were tracked and recorded via eye-tracking devices. Subsequently, primary eye-tracking metrics such as total fixation duration, first fixation duration, and time to the first fixation were calculated using software that analyzes raw eye-tracking data. In addition, each worker interacted with the instructor and identified the potential hazards by their verbal statements to validate recognized risk sources. Analysis results showed that the participants’ safety awareness, which indicates their risk perception, is similar in the virtual and real construction sites. Thus, we can argue that virtual reality-based training tools are preferable to provide hands-on training for construction site workers and professionals.

Sensitivity to the potential risks is crucial for taking prompt safety actions to prevent possible accidents [50]. In this sense, analyzing the eye-tracking behavior of trainees in terms of time to first fixation duration is essential to evaluate their risk perception. The results show that the trainees’ time to first fixation duration in the real construction site is significantly lower than in the virtual environment ($Z=-4.18$, $\rho<0.01$). A longer time to first fixation duration may cause adverse circumstances on the construction sites, as the workers cannot take safety actions as quickly as needed. Thus, we can say that the workers have a better visual search attitude on the real construction site compared to the virtual environment. One of the most important reasons that cause this result might be the workers' unfamiliarity with virtual environments.

Additionally, participants experience a different working environment in a virtual environment than in a real construction site. Thus, spending more time focusing on a risk factor is apprehensible. Furthermore, the risk-free nature of the virtual environment might cause the workers to pay less attention as it does not require them to be as vigilant as in the real site. However, a potential error of a worker could lead to catastrophic accidents on real construction sites. Therefore, one can conclude that workers’ awareness and risk sensitivity on the actual construction site are higher than in the virtual environment. Thus, the first hypothesis is rejected. The time to first fixation durations of participants in the virtual environment is not significantly lower than the time to first fixation durations of the same participants on the real construction site. However, by increasing the rendering performance and achieving more realistic virtual environments, the participant can have a quasi-real virtual reality experience. So, the first fixation duration may be reduced. Shortly, solely mimicking the real construction site is not sufficient to achieve ecological validity. While designing virtual safety training tools, enhancing the sense of reality must be ensured.

The previous studies in the literature highlight that trainees’ lack of attention, which leads to failure to recognize risky conditions, is one of the main reasons for on-site accidents [52, 53]. As a result of the unsuccessful hazard identification, trainees may not take correct safety action. Therefore, a high level of attention is critical in the safety management context to identify hazards correctly. We analyzed the total fixation duration of the participants to compare the workers’ attention levels in the virtual simulation environment and the real construction site. The results show that the participants' total fixation duration was significantly higher in the virtual environment than in the real construction site ($Z=-3.99$, $\rho<0.01$). This outcome supports the results of previous studies regarding the eye-tracking methodology. According to Just and Carpenter [31], a longer fixation duration indicates that the object or situation is more engaging for individuals. Several papers [52, 53] state that the higher total fixation duration indicates a higher motivation level. In other words, there is a positive relationship between total fixation duration and attention level. Therefore, we can conclude that workers' attention level was significantly higher in the virtual environment than in the real construction site. Accordingly, the second hypothesis is accepted: the total fixation durations of participants in the virtual environment are significantly longer than the total fixation durations of the same participants on the real construction site. In this regard, many features of the virtual environments can be utilized to increase the ability of trainees to concentrate. For example, the real site distractions can be removed, and various stimuli can be integrated to hold the trainees' attention longer. In this way, the critical risk sources can attract more attention.

Risk perception is another crucial parameter for hands-on practice effectiveness. According to Paek and Hove [78], risk perception refers to "people's subjective judgments about the likelihood of negative occurrences such as injury, illness, disease, and death". In this sense, it is vital to investigate the risk perception of employees, determine which dangers individuals pay attention to at construction sites, and how they manage them to ensure construction safety. Habibnezhad et al. [58] analyzed the impact of workers' risk perception on their visual search strategies in their seminal study. The results show that the trainees with higher risk perception have higher first-fixation duration. In other words, the first fixation duration indicates the risk perception of trainees, and they are directly proportional. In this sense, a higher first fixation duration is preferable in the virtual environment since a higher first fixation duration proves that the virtual training improves the risk perception level of trainees. Therefore, we compared the first fixation duration of the participants to verify whether workers' risk perception levels were higher in the virtual environment than in the real construction site. The analysis results indicate that the workers' first fixation duration was significantly higher in the virtual environment compared to the real construction site ($Z=-3.99$, $\rho<0.01$). Therefore, the third hypothesis is accepted: the first fixation durations of participants in the virtual environment are significantly longer than the first fixation durations of the same participants on the real construction site. Accordingly, participants first look at the visually salient objects in the virtual environment and look longer. As visual salience captures attention more readily, we suggest that the risk sources on the virtual construction site should be designed to catch the trainees' eye. Thus, it becomes possible to realize the risk sources that are difficult to be detected in the real area or take time to be noticed.

Consequently, this study shows that the virtual safety training concept has a great potential to improve the risk perception level of trainees efficiently without being exposed to construction risks that may cause accidents. Moreover, considering the participants' higher level of attention in the virtual environment, we can conclude that the virtual safety training tools effectively improve trainees' safety awareness. This study proves that virtual safety simulations provide safer and more efficient hands-on training for construction workers and professionals than real on-site safety practices. In light of the study's findings, not only the construction industry but also other sectors might benefit from virtual safety training by developing an appropriate tool that addresses the need of their work. In terms of theoretical contribution, this current study fills the gap in the literature regarding the effectiveness of VR tools for construction safety training. Many studies suggest VR-based safety applications without addressing ecological validity, even though it is the most critical limitation of studies focusing on the VR method [9]. Therefore, it is crucial to evaluate how generalizable the behavior and perceptions of participants can be in real life [79]. Based on this empirical comparison which proves the effectiveness of a virtual environment, researchers may develop a risk-free training environment for several circumstances. In a nutshell, this study provides promising findings that contribute to a novel safety training development for the construction safety literature.

This research has some limitations as well. Trainees' lack of experience in video games or even primary computer usage directly impacts their behavior during the experiment. Moreover, using a computer for VR training might not provide the perfect reality. Other technologies such as VR headsets and Augmented Virtuality would be integrated to present a more realistic training environment. Also, we concluded that the time to first fixation durations of participants in the virtual environment is longer than the time to first fixation durations of the same participants on the real construction site. This conclusion might be due to the unfamiliarity of the workers with virtual environments. A pilot or repetitive training session might be held for workers to practice and get used to the environment to overcome this problem. Lastly, increasing the sample size and improving the diversity of participants will be beneficial for future studies. Comparative analyses can be conducted by including participants of different ages, experiences, and roles. Accordingly, more appropriate tools can be developed for the needs of specific groups.

6. Conclusion

The construction industry inherently contains risky applications. Therefore, providing adequate training to the construction workers is critical to overcoming occupational accidents that frequently create severe consequences on construction sites. However, because the applied safety practices are mostly regarded as inefficient, several researchers suggest using virtual environments to provide risk-free hands-on training to train workers. In this study, the effectiveness of virtual safety exercises, comparing the workers' safety awareness on real and virtual construction sites utilizing eye-tracking technology is investigated. Integrating eye-tracking technology into the evaluation process yields both quantitative data and qualitative insights into users' vital behaviors within virtual worlds. This comprehensive technique enhances the evaluation of ecological validity, guaranteeing that the virtual simulations accurately replicate real-life situations and interactions. Accordingly, an example for evaluating the ecological validity of virtual environments by utilizing eye-tracking technology is provided. The results of the study confirm that the trainees exhibit a higher level of attention and risk perception in the virtual simulation environment according to their total fixation duration and first fixation duration. However, considering the trainees' time to first fixation duration, we might conclude that the participants cannot react as quickly as in the virtual simulation compared to the real construction site. This result might be predictable when considering the trainees' unfamiliarity with computer-based games or due to the awareness of actual hazards present at the construction site, workers may exhibit quicker response times compared to a virtual setting. Consequently, this study supports the effectiveness of virtual safety training tools in providing a risk-free environment for construction workers and professionals.

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Author Contributions

S. Çomu: Conceptualization, Methodology, Writing-Review & Editing, Supervision, Project Administration; B. Yücel: Formal Analysis, Data Curation, Writing-Review & Editing; I. A. Kıral: Formal Analysis, Investigation, Resources, Writing – Original Draft, Visualization.

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Data Availability Statement

The data presented in this study are available on request from the corresponding author.

Ethics Committee Permission

The authors acquired ethics committee permission for surveys implemented in this paper from the Science and Engineering Fields Human Subjects Ethics Committee of Boğaziçi University (Date. 27.02.2016 No: 2017/14).

Conflict of Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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