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Eye-Tracking Technology for Construction Safety: A Feasibility Study

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Abstract

A construction site is a harsh environment demanding entire human senses and attention, even for regular scheduled tasks. Many accidents occur on construction sites because of inability of workers to identify hazards and make timely decisions. To understand why some hazards go unseen, it is crucial to study how workers perceive the site. The objective of this research is to leverage eye-tracking technology to study workers' gazing pattern in a construction environment. A real picture from an active construction site is modified to introduce hazards and a desktop experiment is conducted, in which, subjects are asked to identify the hazards. A different group of subjects are made to make similar observations on a 2D sketch-representation of the same construction scenario. Eye-tracking data gathered from their observations is analyzed to understand when, how, and which hazards do they recognize and the pattern of recognition is studied. The results of this study will enhance our understanding on the visual factors that govern attention and help workers recognize potential hazards in a construction site. The comparison between the observation pattern in real and sketch-representation is done to assess how subjects respond to artificial images compared to real images. This comparison will test the feasibility of using virtual reality for safety training and simulations.

Keywords –

Construction Safety; Eye-tracking; Virtual Reality; Site Perception; Hazard Recognition

1 Introduction

Despite safety regulation efforts to reduce numbers of injuries and deaths in construction industry, it remains responsible for most of the work-related injuries and deaths consistently [1, 2]. There is still no adequate investment and research in developing new methods and technologies to effectively improve safety within the construction industry.

It is crucial that construction workers are able to identify possible hazards in work sites in order to take preventive actions to reduce or eliminate the risk of injuries and illnesses. Therefore, it is important to understand their perception of the construction environment and what kind of hazards they are able to recognize when exposed to different circumstances [3]. By evaluating which aspects need improvement it is possible to develop more efficient approaches, increasing worker and student assimilation of site hazards and construction safety practices. This study aims to explore how eye tracking can best contribute in analyzing the perception of hazards in construction sites and utilize it as a potential educational/training tool.

2 Literature review

2.1 Construction Safety Scenario

Even with the rapid advance of new technologies, methods and materials in construction industry, safety tends to receive insufficient attention. According to the Occupational Safety and Health Administration (OSHA) [1], in the United States, five work-related deaths in private industry, one was in construction, which represents 20.5% of work-related accidents occurred in 2014. The Census of Fatal Occupational Injuries, conducted by the U.S. Bureau of Labor Statistics [2], shows that this scenario has hardly improved from the past years. In 2014, construction industry presented the highest rate of fatal work injuries since 2008, rising from 828 in 2013 to 874 in 2014. Heavy civil engineering was the only segment that showed some improvement, decreasing from 165 fatal injuries in 2013 to 138 in 2014.

Different factors are responsible for these high accident and fatalities rates, such as non-use of Personal Protective equipment (PPE), lack of supervised working environment, lack of a site safety plan and insufficient training. A study conducted by Hinze and Teizer [3], analyzed 659 fatality accidents investigated by OSHA. It was observed that blind spots, obstructions and lighting conditions were the most common factors contributing to vision-related fatalities. Equipment or vehicles, especially heavy equipment were involved in most of the identified accidents. Struck-by, collisions, rollovers and other equipment incidents represented one-fourth of construction workers deaths. The lack of visibility or a worker being present in the blind spot of equipment was the main cause of struck-by accidents, which represents 22% of all construction fatalities. It was also noted that 72.6% of the incidents occurred when the equipment were traveling in reverse.

The increasing cost of injuries has a direct financial impact on medical, legal and insurance expenses [3]. Therefore, the implementation of an efficient construction safety plan can reduce costs in construction industry besides improving employee health.

2.2 Safety Training

Planning and design of construction projects has seen revolutionary changes in recent years while safety training still follows traditional methods. New methods and technology applications are being considered and studies are being performed to encourage the use of more dynamic and precise methods, such as 3D training environments or personnel tracking and monitoring. Global Positioning System (GPS) and radio frequency technology, for instance, can be used to monitor workers distance from risky areas, fall prevention from height and collision avoidance [4]. Studies have shown sensing devices as a useful tool for safety managers identify, monitor and assist risky situations involving workers and equipment in construction sites [5].

As stated by Rosch and Vogel-Walcutt [6], the applications of eye tracking devices in safety training are wide. Physical reactions, such as gaze and pupil response measurements provided by the eye tracker can help to evaluate the effectiveness of training, measuring attentional focus and reading comprehension users, towards given image stimuli or tasks. By customizing e-learning environment based on eye tracking data, the content is adapted to the needs of each user, according with individual learning levels. By analyzing cognitive load, distraction and attention levels and user's perceptions and comprehension towards instructional materials it is possible to improve the user interface of courseware, resulting in a more interactive and efficient learning method.

2.3 Applications of Eye Tracking Technology

Murray et al. [7] defines eye-tracking as the process of measuring the point of gaze, and an eye tracker as a portable device that measures eye movement and eye positions. This technology can assess the user's mental state, exploring visual pattern and allowing the access to information that, otherwise, could not be accessible through any different approach. Through eye movement recording, it is possible to understand the behavior and cognitive processing of users and interpret their response to different image stimuli.

Eye tracking has become a multifunctional technology that can be implemented in many different fields of study. Human-computer interaction, virtual and augmented reality, usability tests, e-learning, assistive technology, pilot training assistance are some of the many eye-tracking applications [8]. Medicine, psychology and neuroscience can also benefit from this technology in studies, accessing cognitive abilities, attention and recognition memory in patients [9]. Assistive technology has been helping individuals with disabilities to improve their functional capabilities, enabling them to perform activities conducted by eye movements. A computer controlled by an eye tracker makes communication possible and also entertainment activities, which significantly improving patient quality of life [10].

Published studies relating eye tracking and construction are very limited so far. Driver Safety System (DSS) is one of the very few examples found regarding tracking applications used in construction industry. Developed by Caterpillar, this system can be used in construction and mining equipment in order to reduce the risk of drowsy driving-related accidents involving heavy machinery. The equipment consists a console-mounted camera to track the driver's head and eye movement, monitoring the driver's behavior in real time. When signs of sleepy or distraction occurs, the system sounds an alarm and produces a loud vibration in the driver's seat, alerting the driver to a possible risk situation. It also helps the company to track and monitor driving practices.

Eye tracking can also be used as a tool for education. In the 3D game "Safety Inspector", students act as a controlling contractor's safety inspector on the job site, identifying on-site hazards during a virtual walk-thru [11]. There are different levels of challenge, according with the player safety background. For every point obtained, the game provides the player with valuable information such as corrective actions, rules and regulations. This game can be used as a supplemental educational resource in the classroom and as an alternative to walk-throughs. Even though this project does not support eye tracking, it could work as an excellent future application for this technology, since the use of eye tracking in a 3D construction environment would provide a more accurate study of the student's perception of a jobsite. Besides, for students, it can be used with construction workers such as heavy equipment operators, laborers, electricians, foremen, drivers or inspectors. In this case, the challenges would be related with the occupation and activities performed by each worker. This approach can also be used for training, helping to facilitate the comprehension of the workers perception of construction sites, potential risks and its relationship with their visual attention [12]. Games in a virtual environment also increase the learning interest of the participant and potentially lead to a more critical awareness of safety hazards [4].

2.4 Eye Tracking Data

Eye tracking experiments can provide a wide variety of data. The results can be displayed according to the study requirements. The principal measurements obtained through eye-tracking applications are fixations, saccade and gaze. Yousefi et al, [12] provide the following definitions for these metrics:

- Fixations: Eye movements with a series of short stops pauses in specific positions
- Saccade: Eye movement from one position to the other
- Gaze: The eye gaze pauses in a certain position

In function of these data, heat maps or gaze plots are generated, allowing the measurement of attention allocation, the number and duration of eye fixations, as well the amount of re-fixations, establishing patterns of the user's attention.

3 Objectives and Methodology

The main objectives of this research are as follows

- to test the feasibility of using eye-tracking technology for construction safety training
- to assess the difference in gazing pattern on a real image and a virtual scene in regards to construction hazard identification
- to understand the difference in gazing pattern of individuals based on their knowledge about construction processes and operations

To achieve these objectives, the first step was to get an overview about safety scenarios in the construction industry and what has been done in terms of training to prevent injuries and fatalities on constructions sites. The literature review also consisted of the study of what has been published about eye tracking and what has been marketed about this technology in the last few years.

Then, an experiment was designed to evaluate the perception of subjects towards a construction scene. A picture taken from an active construction site was selected based on the level of activity, areas that require attention and potential of making adjustments. Two groups were defined and the selected image of a construction site was adjusted to contain a variety of hazards, what will be explained in detail in the next section. Beside the results generated by the eye tracker, a checklist was designed to be completed by the subjects to reinforce the data obtained from this study.

This research isolates visual gazing pattern and ignores the effects of prior training, cognitive and learning capabilities and other potential factors.

4 Experiment

The initial purpose of this experiment is to analyze the visual perception of an image of a construction site based on recorded eye tracking data. For this test, a picture of a construction site is displayed at the monitor to volunteers. The goal is to identify patterns of visual fixation, visual hierarchy, and perception of the displayed picture.

4.1 Eye-Tracking System Selection Process

The required level of data precision and relevant metrics must be considered in order to select the more appropriate eye tracking system for each type of experiment. There are two types of eye tracker: static or head-mounted (mobile). The static eye tracker consists of a portable device that can be mounted on computer monitors, laptops, iPads or other equipment. A head-mounted eye tracker is a more flexible alternative that consists of a helmet or glasses with a built-in eye tracker and a video camera. This option is recommended when the participant needs freedom of movement or in outdoor environments. For the purpose of this study, an indoor experiment using laptop monitors, the more suitable option is the use of a static eye-tracker. The equipment used in the present study was a Tobii EyeX eye tracker for data collection and a 15" computer monitor.

4.2 Participants

Sixteen student participants were recruited for this experiment. The subjects, undergraduate and graduate students, were divided in two groups: construction students and students of a different major (no construction background). No prior training was given to the participants. They went through a pre-written briefing.

4.3 Image Stimuli

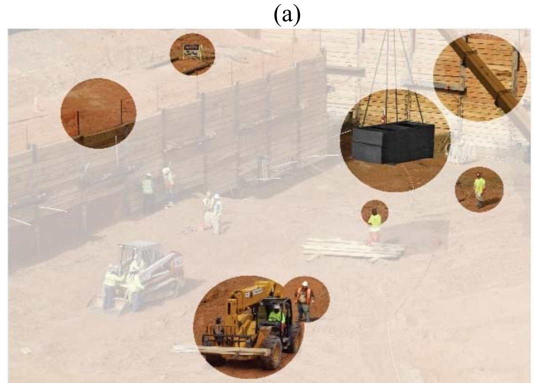
Two different images were used on the experiment. A picture taken of a construction site and a 2D representation of the same picture. The photograph used was manipulated in Photoshop to simulate different situations of hazards in the same image. The hazard selection for the scene was based on the major causes of injuries and fatalities that occurred in construction sites for the past few years.

Figure 1. Original image from a construction site

Figure 2. Photoshopped image based on Figure 1

Some elements were modified or added to the scene, such as a bulldozer and part of a crane and a loader, representing lifting and hoisting operations and an operator, moved to right behind an equipment, representing a struck-by hazard. Two workers were positioned in the area within the crane's swing radius, representing the risk of being struck by an overhead load. Two other pieces of equipment were removed from the scene. The perimeter protection was edited and part of the safety net was removed, representing a possible risk of fall. In the same area, a construction safety sign was added. Some operators had their positions changed. The worker with the orange vest was positioned behind the equipment, which might be a blind spot for the driver that could lead to a struck-by accident. In addition, the helmet of one of the workers was removed.

(a)



(b)

Figures 3: (a) Items removed from Figure 1, (b) Items added to Figure 1

Using the manipulated picture as a base, a 2D drawing was created. The purpose of using a photograph and a 2D image of the same scenario was to compare the perception of the subjects when looking to different types of image stimuli, real and artificial.

Figure 4. Artificial 2D representation of Figure 1

Through this analysis, it is possible to evaluate if the use of 2D images or even 3D non-realistic models on a test, experiment or training have the same effectiveness in regards to gazing pattern.

Before performing the experiment, Areas Of Interest (AOI) were defined by the research team. It is important to define the AOI prior to the tests in order to evaluate gaze data and compute the number of times the subjects visit the AOI and the amount of processing time spent on each area. There were seven AOIs identified in the scene. Figure 5 shows the AOIs in different color. Figure 8 and Figure 9 will use the same color code that is assigned to the AOIs in Figure 5.

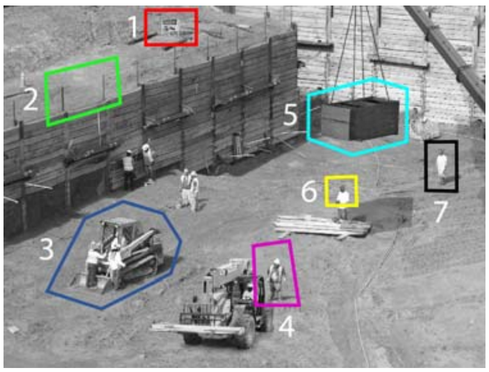


Figure 5. Color-coded Areas of Interests (AOIs)

4.4 Procedure

Each student looked at one image individually. The participants were randomly divided in two groups. Half of them were assigned to observe the photoshopped image (Figure 2), and the other half, the 2D representation (Figure 4). A list with construction hazards, and brief explanation about each item, was provided to the subjects prior to the test. The participants were seated approximately 30 cm from the computer screen.

Calibration of the eye tracker is a crucial procedure toward accurate data collection and analysis. The calibration was performed based on the Tobii's default calibration settings, where the subject is asked to look at specific points on the screen (calibration dots). This process optimizes the eye tracker settings for the current light conditions and the user's eye characteristics. After calibration, the subjects were asked to look to the image and fill out the checklist to identify potential hazards. The identified items should be numbered so it would be possible to observe the sequence of recognition of the items. The list also contained extra items (hazards), not included on the image. The checklist can be found in Figure 9. The subjects were free to take as much time as they want to view and analyze the scene. Figure 6 shows the experimental setup.

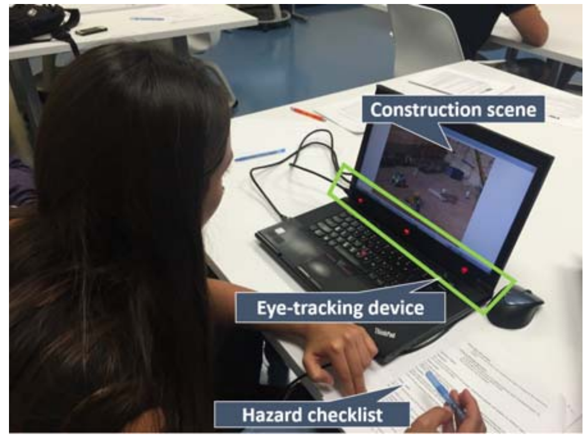


Figure 6. Experimental setup

5 Preliminary Results

Sixteen subjects participated in this experiment, eight construction students and eight non-construction major students. Four subjects from each groups were assigned to view photoshopped image and the other four were supposed to view the 2D representation. This assignment was also made randomly.

The results are, hence, presented and categorized by

- Non-construction students / Construction students
- Photoshopped image (PS) / 2D image (2D)

Based on horizontal and vertical coordinates for each sample, it was possible to compare the time spent on each AOI or something other than the marked AOIs. The device measured 137,256 gaze samples during the experiment, with a frequency of 60Hz, which means that 60 gazes were recorded each second. The total gaze samples was equivalent to 2,287.60 seconds, or 38.13 minutes of eye-tracking data.

Gaze plots indicate the eye movement sequence through lines and the fixations illustrated with dots. The size of the dots indicates the fixation duration and shows which elements of the picture holds user attention. A gaze plot was generated in order to observe the sequence of visualization of each subject. However, since we had many AOIs and the time the subjects were exposed to the pictures was considerably long for this type of experiment, the gaze plots will need further in-depth analysis to provide any meaningful information. Figure 7 shows a sample gaze plot for a subject.

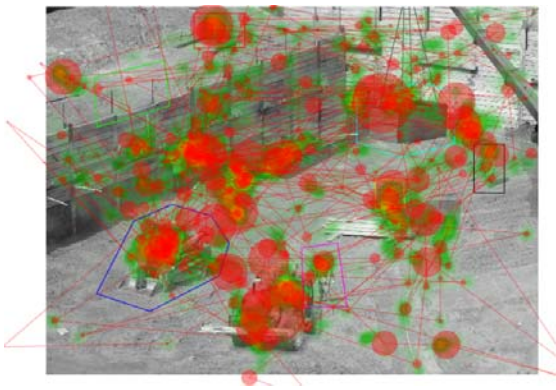


Figure 7. Gaze Plot of a subject

5.1 AOI Analysis

By measuring the two-dimensional eye movement pattern (x,y) the eye tracker software provided the percentage of gaze for each AOI, numbered as one to seven and identified by colors. The scarf plot in Figure 8 shows the gazing pattern of all the subjects as they move from one AOI to another. The colors in vertical bars represent the time spent in the AOIs coded by color shown in Figure 5. Grey part on the bars represent the times spent outside the AOIs. Figure 8 only shows the data pertaining to initial part of the experiment and the vertical bars (time) continues in a similar manner throughout the experiment. Entire scarf plot is not presented in the paper because the colors becomes indistinct as the vertical bars get longer.

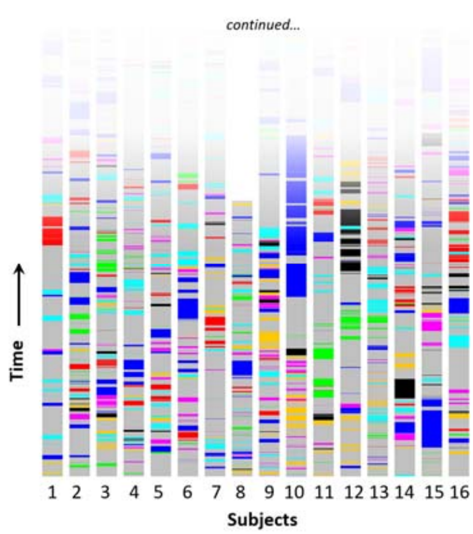


Figure 8: Scarf plot of subjects' gazing pattern color-coded by AOI

During the experiment, the subjects looked outside the AOIs 74% of the time and 26% inside AOI's. All the grey region in Figure 8 contribute to time outside AOI while time inside AOI is the summation of all the colored part of the scarf plot. AOIs only occupied a small portion of the entire picture so it is understandable that the subjects spend more time outside AOI.

Among all seven pre-defined AOIs, AOI 3 was the most viewed, with 32% of total visualizations inside AOIs. The least viewed was AOI 2, with 7% of gaze samples. The position of the AOI in the image and its size must influence the order of visualization, since elements exposed in foreground are usually bigger so they can be noticed first, rather than a background element. The two most visualized elements, the crane and the loader, for example, are considerably bigger compared to the other elements in the image.

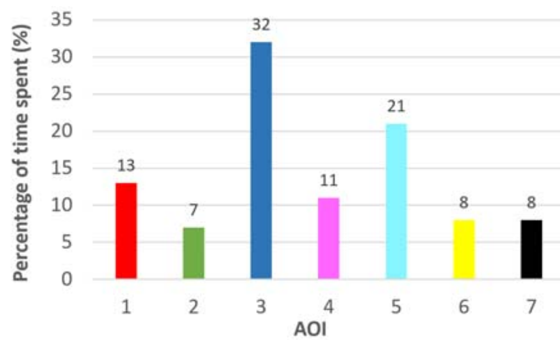


Figure 9. Proportion of gaze duration on each AOI

From the checklist, it was possible to identify the order of recognition of each hazard. Among all the hazards on the checklist, "Personal protective equipment" was the most recognized and fastest identified item in the pictures, by all participants (Figure 10). The fact that the helmet is one of the most well-known personal protective equipment, used in any construction site, might have facilitated its identification before other items. "Dust exposures", on the other hand, was the least recognized item, which was expected, since this item was listed on the checklist, but it was not represented on the images. A study lead by Bhoir et al [13] indicated low levels of attention on danger signs and most of the participants did not even look at it.

5.2 Non-construction Students vs Construction Students

Heat map is another method that can be used to analyze the results. It shows the areas of most interest and the cumulative eye fixations of those areas. The scale

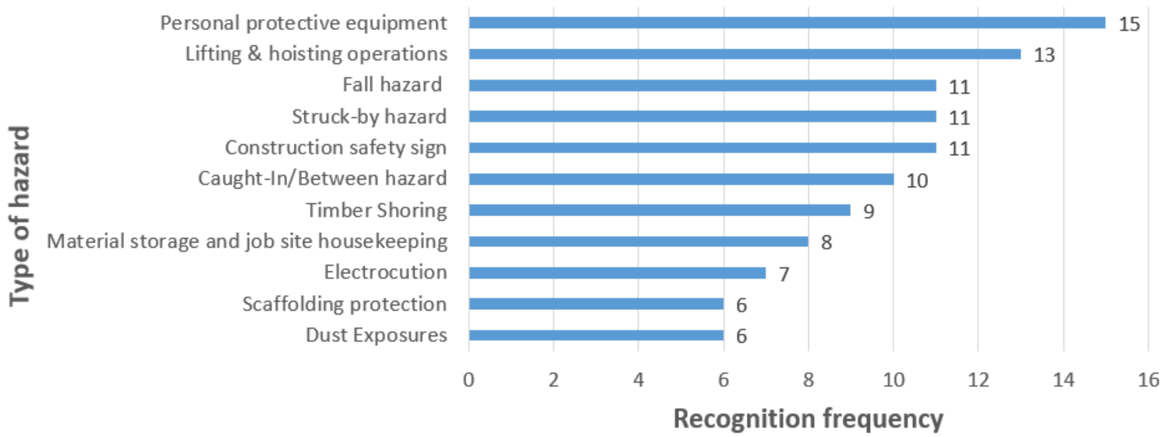


Figure 10. Frequency of hazard recognition

color changing from green to red represents the amount of fixations while the red spots indicate increased duration of fixations. The heat maps generated by the eye tracking software combined data from all participants, divided into four groups: construction and non-construction students, 2D representation and photoshopped image. Visual analysis of the maps show that non-construction students spent more time looking at areas out of the AOI, showing a more spread visualization distribution in the map and focused in the workers, whereas construction students have focused more on the AOI's.

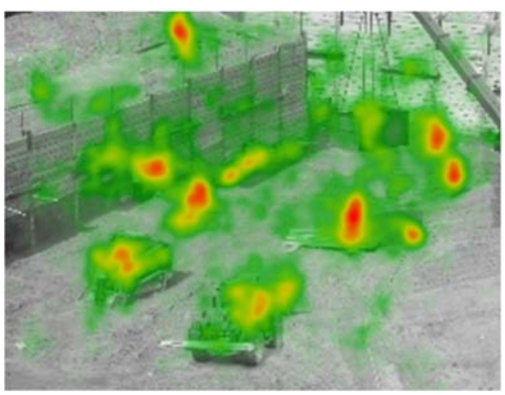


Figure 11. Non-construction students' heat map

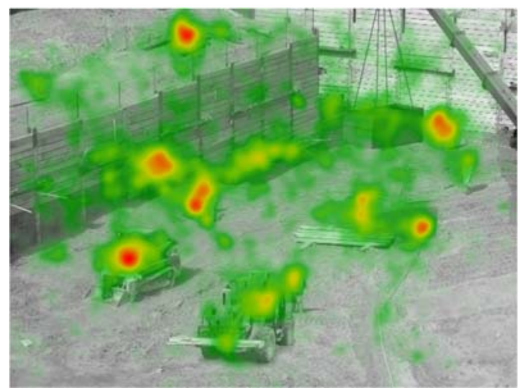


Figure 12. Construction students' heat map

The heat maps generated for all subjects who observed the photoshopped image and 2D representation, illustrate that user's attention is considerably spread out in the 2D representation, while in the photoshopped image the attention is more directed to the AOI. Also, during the experiment, the subjects spent 18% less time observing the 2D representation than the photoshopped image. The subjects were not restricted by time to identify the hazards in the image. In this context, data collected from photoshopped image constituted to 55% of the total gazing data while only 45% of the data came from 2D representation as shown in Figure 13. Despite the real picture being more realistic and detailed, identification of elements were faster than in the 2D representation. One possible reason might be the minimal level of shadow/highlight and distinctly defined element boundaries, which simplifies shape, contributing to a faster recognition.

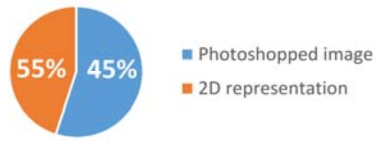


Figure 13. Proportion of time spent on photoshopped image and 2D representation

6 Conclusion

Even though varieties of new technologies have been increasingly being utilized in construction industry, safety scenario still yields unsatisfactory results. When it comes to training, it is very essential to apply something beyond the conventional approach, investing on more dynamic learning methods, such as virtual environments. Eye-tracking technology, still under-utilized in construction industry, is a promising alternative to analyze the efficiency of safety training. The analysis of workers' perception can determine the understanding level of safety requirements and guidelines adopted by a company or even indicate layout problems in the construction site planning. The use of real pictures or ultra-realistic 3D models can produce valuable results. As observed in these results, there was a slight difference between the perception of the photograph and the 2D image, implying more research needs to be done to use of 2D drawings or basic 3D models for scene-perception studies. The camera position and viewing angle of the picture might also influence the perception of an element instead of another.

An eye-tracking experiment performed in a 3D environment simulating a construction jobsite, would allow students and workers to be exposed to different types of hazards prior to going to a real jobsite. Furthermore, head-mounted eye trackers, such as glasses, can potentially lead to walkthrough experiments in real construction sites. From eye-tracking data, it would be possible, during and after training sessions, to assess the safety knowledge level of each individual, analyze group patterns and develop new prevention measures.

Interactive methods as video games also can be integrated in these experiments. Further research in this area may include eye movement combined with other types of data such as think aloud method. Equipped with a microphone, the participants would provide a verbal feedback, describing their experiences and thoughts while doing the tasks or after tasks are completed.

It is necessary to provide effective learning methods and training programs, encouraging protective measures to ensure a safe working habit. Due to its dynamism, eye-tracking experiments and tests can be a helpful tool to complement traditional training approaches and evaluation methods.

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