

# Applying Eye Tracking in Virtual Construction Environments to Improve Cognitive Data Collection and Human-Computer Interaction of Site Hazard Identification

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## Abstract –

In the Architecture, Engineering and Construction (AEC) field, eye tracking technology is being applied more frequently in cognitive research such as hazard identification. These studies typically use eye tracking in a diagnostic way and pay less attention to the application of virtual environment. However, in virtual environment, eye tracking not only can enhance the study of the cognitive process but also improves the human-computer interaction. Therefore, this paper elaborates on how we use eye tracking devices to track 3D objects in virtual environments diagnostically and interactively. First, we analyze the existing research gaps of using eye tracking in the construction industry. Then, we follow 3D object identification, diagnostic mode and interactive mode to develop a methodology by HTC VIVE device with Pupil Labs HTC Vive Binocular Add-on based on the research gaps. Finally, an example experiment is provided to demonstrate studying hazard identification using eye tracking in construction safety. For analyzing the eye movement data from the participants, we offer the number of confirmations, the scan path and the 3D heatmap of objects in both static and dynamic construction site scenes. This paper provides an approach of applying eye tracking to gather more data in virtual environment for the future cognitive studies and explores the possibility to improve human-computer interaction using eye tracking in the construction industry.

## Keywords –

Eye Tracking; Virtual Environment; Human-Computer Interaction; Site Hazard Identification

## 1 Introduction

The construction industry has been in an era of transformation and reorganization for years. Not only the complexity of construction projects is increasing, but also the technical challenges influence the work on

the construction site. A high construction quality is to be guaranteed in even shorter time. Health and safety at work is one of the most important goals of a construction project. However, statistics on accidents at work show that workers on construction sites worldwide are exposed to higher risks than in other industries [1]. The identification of hazards on construction sites is therefore becoming increasingly important. However, hazards cannot be entirely identified on dynamic and complex construction sites since humans cannot simultaneously notice all possible hazards at once. Therefore, actions to increase the safety on construction sites include intensive training and a clear hazard identification. Whether a certain object is identified as hazard can only be determined by intensive testing. It is important, especially on complex construction sites, that hazards are identified as quickly as possible. The availability of different technologies means that these studies can now be evaluated more comprehensively, realistically and detailed.

In existing research, eye tracking is commonly used as a tool to study the cognitive process by collecting the eye movement data at the viewing direction from 2D pictures or real sites, but neglecting which particular object the viewer is looking at. In this way, even the 3D objects in real scenes have no connection with the eye movement data. Jeelani et al. [2] presents a method to facilitate the recognition of objects in the real site. As a post-recognition method, it still does not provide a connection between the eye movement and objects. In these cases, by ignoring the distance between viewer and the viewing object, viewing 3D objects will not provide more information than 2D images.

Combining eye tracking with virtual environment can easily build connection between viewer and the viewing objects. Moreover, the eye movement data collected from a digital model of a construction site can also be made available directly in a virtual environment. Using virtual reality allows a realistic representation of a complex situation on a construction site without exposing the viewer to a real danger [3].

In the context of this paper, an approach to the

systematic use of eye tracking and virtual reality for the analysis of eye movement data is presented. It will be shown how objects can be identified based on available technologies and how the data can be collected automatically. Raw eye movement data automatically generated by eye tracker are not structured, which will cause a big difficulty in data analysis. Table-format eye movement data is used in this approach to help researchers in the construction field read and analyze the data easier. Meanwhile, the data can be evaluated how long a certain object has to be viewed in order to be identified as a hazard by detecting confirmation actions from viewers and to find the scan path (sequence of fixations) of identifying these hazards. These results are a helpful basis for developing more effective markings, e.g. heatmap.

## 2 Related Work

Research has shown that different frequencies of eye movement give different information [4]. When continuously watching something, this behavior is called fixation; while frequently moving the eyes is considered as saccades. For example, in reading, saccades are for speed reading, while fixations are for comprehension.

Eye tracking is commonly recognized as a process of measuring the gaze direction and collecting data of human's behavior related to eye movement. Specifically, eye tracking is defined as a technique whereby the position of the eye is applied to identify gaze direction of a person at a certain dwell time and the eye movement trajectory [5]. The existing eye tracking applications could be divided into two categories: Diagnosis and Interaction [6].

In the diagnosis of eye tracking, many researchers focus on studying the cognitive process. Salvucci and Goldberg [4] give evidences of utilizing eye tracking in image scanning, driving, arithmetic and analogy. In the computer science area, Bednarik and Tukiainen [7] study program comprehension by tracking the eye movement process of programmers with different experiences reading code. Recently, Meißner and Oll [8] point out eye tracking is widely used in various academic disciplines: information search and decision making, learning, training systems, and expertise.

However, eye tracking technology could not only help studying the cognitive process, but also improve human-computer interaction. Jacob and Karn [6] state the research of human-computer interaction using eye tracking emerged in the 1980s, but the main application is in helping disabled people, e.g. eye typing. Jacob [9] deems that studying cognitive processes only involves recording and follow-up analyzing of eye movement data but has no effect on the computer interface at

runtime.

Mine [10] summaries that the fundamental forms of interaction in a virtual world are movement, selection, manipulation and scaling. As one of the fundamental forms of interaction in virtual environments, selection has three steps to follow: indication of object, confirmation of selection and feedback [11].

In the construction industry, the research of studying cognitive process using eye tracking has commenced from the past few years. Among them, the safety awareness for safety training is frequently discussed [2, 12-14]. In addition to studying safety awareness, researchers use eye tracking to study the end-user satisfaction in building design [15], the 2D-construction-drawings interpretation process [16], the architectural features in building design [17] and other applications. Currently, most of the researchers use static images to study safety awareness, which cause problems since the construction site is dynamic [2, 12, 13]. Considering this limitation, Jeelani et al. [2] and Hasanzadeh et al. [13] collect eye movement data from real scenes under construction instead. However, studying cognitive processes on real construction sites has limitations. For example, it is difficult and time-consuming to build or find real sites. Moreover, it is unsafe for the participants to be in the real scene. To address all the problems above, Sacks et al. [3] suggest using virtual reality to demonstrate the construction site. Besides, they underline that using virtual construction sites is feasible, safer and more effective [3].

In summary, there are still gaps in research for the identification of hazards on construction sites:

- A large amount of eye movement data is needed in order to better study the behavior of hazard identification on different construction sites. Using eye tracking in different virtual environments can easily demonstrate different construction sites and generate many eye movement data accordingly.
- Using 2D images to firstly collect the eye movement data and then identify the objects from the images is ineffective. This problem can be solved by having interaction between eye tracker and hazards in the virtual environment.
- Construction sites are hazardous and dynamic. Using virtual environments are always safe to the workers for the cognitive study and fully demonstrate dynamic construction sites at the same time.

## 3 Methodology

Eye tracking technology is implemented within a virtual environment for the comprehensive study of the identification of hazards on construction sites. This

allows not only for realistic testing but also automated evaluation. The first step is to create virtual and dynamic environments of construction sites with possible hazards. On the one hand, digital planning models are used, which today can already be adopted automatically. On the other hand, special object libraries are integrated for the realization of the construction site equipment. It is important to create dynamic hazards in a virtual scene so that the hazards generated because of the dynamic situations on the construction sites can be demonstrated. The tests can then be carried out based on such virtual environments.

On the device, we use HTC Vive Binocular Add-on provided by Pupil Labs to track the eye movement and attach the Add-on to the VIVE device for tracking eye movement in virtual environment. To make the process of using eye tracking in virtual environment diagnostically and interactively manageable for researchers in the construction industry, the following concepts have been implemented in the Figure 1:

- Systematic calibration of the eye movement by Pupil Labs is for enhancing the ability of object indication based on the eye movement habit of different users.
- Recording the eye movement data with the name and dwell time of objects in certain duration as standardized output.
- Interactive selection of an object as marking a dangerous situation with the help of an external controller.

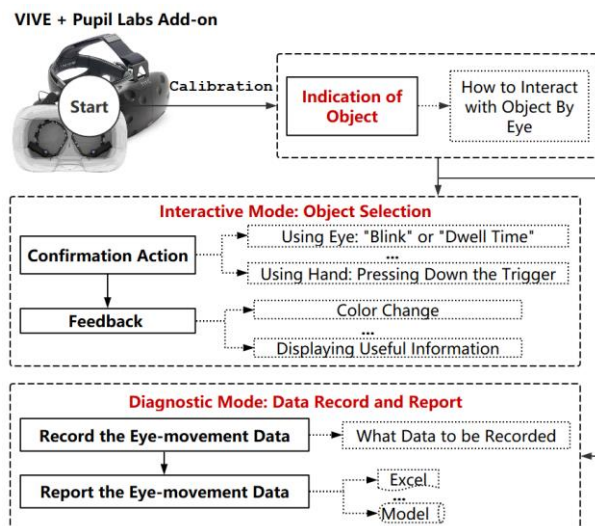


Figure 1. The workflow of methodology

In the following sub-sections, the *Indication of Object*, the *Diagnostic Mode* and the *Interactive Mode* are described in detail.

### 3.1 Indication of object

In the real world, to touch an object by hand, the distance to the object should be reachable. In order to realize interacting with an object by eyes in distance, we are inspired by Mine's study [10] of using laser beams or spotlights that protrudes from the user's hand and intersects objects in virtual environment. Unlike using the hand as the launch source of a laser pointer, we use the eye. One advantage of using laser pointers to indicate an object is that we can easily change the width of the laser in the virtual environment. By setting the gradient of the laser pointer, we can adjust the visual angle to enhance the accuracy of the particular object we select. Another advantage is that the laser pointer can be invisible in virtual environment by setting its transparency to 100 percent. Therefore, the laser pointer will not affect the eye movement data when studying the identification of hazards.

### 3.2 Diagnostic Mode: Data Record and Report

In diagnostic mode, recording the eye movement data is essential. To study cognitive processes, the dwell time of an object and process tracking (i.e., scan path) are vital. To avoid missing any important data, we recorded the object data (i.e., object ID, start time, end time and dwell time) line by line based on the eye-movement process. To make those data more intuitive, we put them into a file with a CSV-format file.

Once the laser pointer "hits" an object, we record the object ID to identify the object and the start time to know when the person starts looking at the object. When the laser pointer releases the object, we record the end time to know when the person stops looking at the object and calculate the dwell time. All those data will be outputted as a line in a table-format file. Forming such a table, we know when and how long a person looks at which object, the sequence of eye movement for objects and the individual and total time of an object.

Alternatively, collecting other eye movement data related to an object (e.g. the focusing parts, the position and the shape of the object) could form a file in another format (e.g. OBJ-format and FBX-format) as needed.

### 3.3 Interactive Mode: Object Selection

As input medium in interactive mode, eye movements as well as other input devices (e.g. mouse, keyboard and controller) are possible. Blink or dwell time can be used as a confirmation action [9]. In addition to using eyes, hand (e.g. pressing down the trigger of controller manually) is another option to confirm in virtual environment. Among these three options, blink as an input medium is difficult to control

[6, 9]. Therefore, in this subsection, we will discuss only the use of dwell time or pressing down the trigger to confirm the selection.

When using the dwell time, the main factor is to select a suitable duration to activate confirmation action. If the duration is too long, the user is forced to wait for a long time to confirm his/her selection. This would be unfriendly and inefficient. Furthermore, it can be difficult to identify the object. The user then looks at such an object for a longer time without wanting to select it. If so, pressing down the trigger might be a better option for a normal user (without disable). In order to allow a short reaction time, the position of the controller should be neglected. Thus, the user does not have to align the object when pressing down the trigger.

If the trigger is used, a late reaction or multiple confirmation may be possible for one-time selection. Therefore, an *isClickRecord* flag is implemented to store the recording of the selection. If the user triggers a manual confirmation, but the identification of the object by the laser pointer has just ended, a false confirmation may occur. In this case, either no or the next object will be selected. However, it is difficult to define the behavior of late reaction. Consequently, we omit the late reaction and record the confirmation action when the user is looking at the object. A multiple selection can simply be ignored, i.e. the *isClickRecord* flag is only set once and cannot be deactivated.

Without feedback, the user cannot know exactly whether the desired object is selected successfully [10]. There are different ways of giving feedback, e.g. changing the color of a selected object or showing a message to the user.

## 4 Example Application

To show how this methodology address the research gaps mentioned in this paper, an example application as an experiment in construction safety is designed. To introduce the experiment clearer, the *Experimental Procedure*, the *Results* and the *Discussion and Limitations* are provided in the following.

### 4.1 Experimental Procedure

In this experiment, two different construction-site scenes (shown in Figure 3 and Figure 4) are provided to indicate the simplicity of creating multiple scenes at the same time by the methodology. To differentiate these two scenes, the first scene is considered as a static construction-site scene and the second as dynamic with two moving vehicles. The eye-movement data collected by this method could be analyzed from three angles: *the number of confirmations*, *the scan path* and the *3D heatmap*. To make the process of the experiment

intuitive for researchers, the following use case is provided in Figure 2:

- The operator provides some explanation of possible hazards in the construction site to guarantee every participant has basic knowledge about construction safety.
- After calibration, the participant can navigate through two different virtual construction sites (shown in Figure 3 and Figure 4).
- In these two scenes, a task, namely perception of the possible hazards, needs to be accomplished. Once an object is considered as a hazard, the trigger of the controller is used for confirmation.
- Every eye movement and the according confirmation action data will be recorded and reported in a CSV-format file automatically (shown in Figure 5).
- Feedback on feelings about the scenes compared with 2D images and the real construction site.

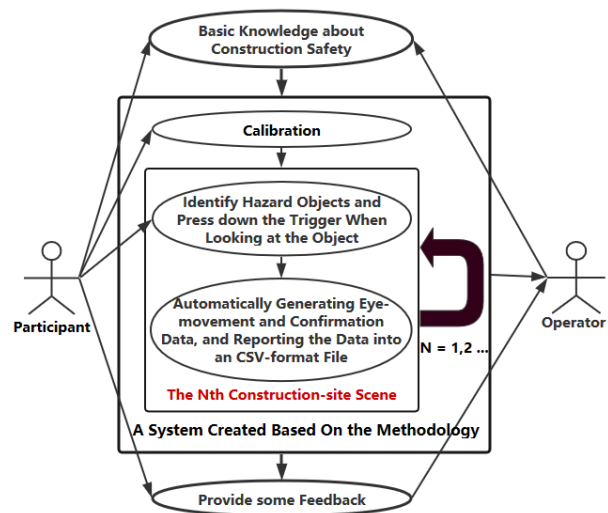


Figure 2. The use case of example application

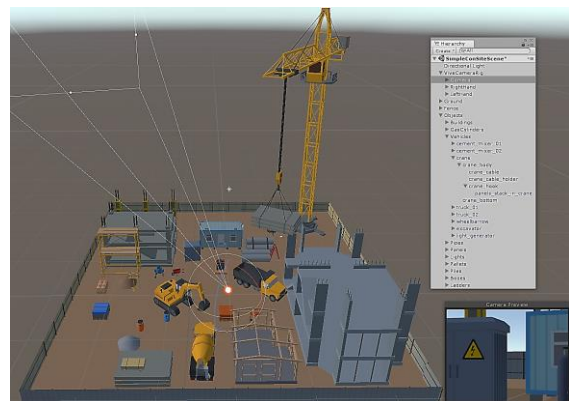


Figure 3. The static construction-site scene



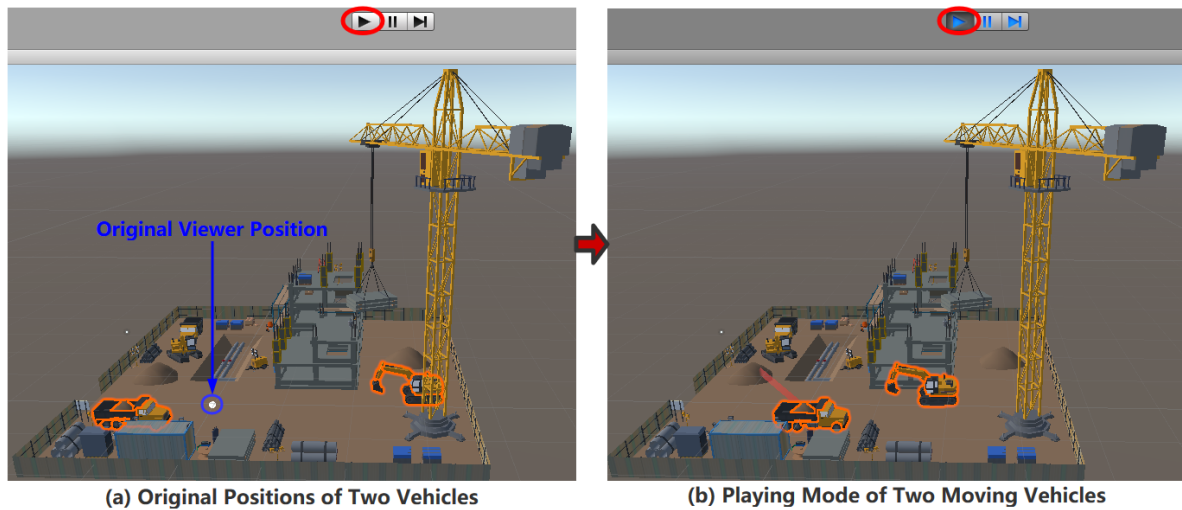


Figure 4. The dynamic construction site scene

In the static construction-site scene, objects with some possible hazards are reachable from the original viewer position (the position of *Camera* shown in Figure 3).

In the dynamic construction-site scene (see Figure 4), two moving vehicles are hazards with the danger of hitting the participant or the participant being stuck in between. However, without moving, the two vehicles would not be hazards. Therefore, it is important to make one of the scenes dynamic in order to test if the participants can notice hazards on real dynamic construction sites.

Fourteen participants in the range of 20 to 60 years old with basic construction background are invited in the experiment. Since none of the participants had practical construction-site background, the explanation of possible hazards in the construction site (e.g. falls, stuck by objects, electrical hazards, caught-in-between and hazardous materials) was provided to guarantee each participant could find out some hazards in the scenes.

As a confirmation of selection, pressing down the trigger of controller is provided to record the time of confirmation every time the participant selects an object. However, in order to avoid affecting the awareness of the participant, we decided not to provide any feedback to the user during but after the experiment. In this case, the feedback will not affect the cognitive study. After the experiment, the 3D heatmap is generated according to the different dwell time of viewing different objects (see Figure 9). The position of the controller is neglected, but the participants must look at the object when they press down the trigger.

A sample CSV-format file is provided in Figure 5. For each participant, the *ObjectName*, the *StartTime*, the *ConfirmTime*, the *EndTime* and the *TimeDuration(ms)* are recorded based on his/her eye movement behavior

and confirmation action. From the table, the number of selected hazards, the scan path of those hazards and the dwell and confirmation time of each hazard are shown.

ObjectName	StartTime	ConfirmTime	EndTime	TimeDuration(ms)
building_01	2019-01-18 14:20:40.36213		2019-01-18 14:20:40.47307	110
wheelbarrow_body	2019-01-18 14:20:40.48507		2019-01-18 14:20:40.57402	88

Figure 5. Data of one participant

## 4.2 Results

After collecting the eye movement data and the feedback from the fourteen participants, the number of confirmations, scan path and 3D heatmap are offered to demonstrate the data analysis based on the data we collected in the experiment.

### 4.2.1 Number of Confirmations

After the experiment, we realized that the recorded hazards were not always the participants expected. Since the accuracy of the approach is not high enough yet, it is worthy to calculate the accuracy rate of this approach in this experiment to evaluate the usability of this approach so far for the future cognitive study. In this evaluation, the number of missed, wrong-recorded and well-recorded confirmations with respect to each participant is shown in Figure 6. In the experiment, we did not consider the fences or the ground in the scenes as objects. Therefore, looking at fences, the ground or without objects when pressing down the trigger and a wrong use of the trigger could cause missed-recorded situation. Based on Figure 6, the missed rate and wrong rate overall and separately are calculated, and the corresponding results are in Table 1 and Table 2 to have a better evaluation about the methodology.

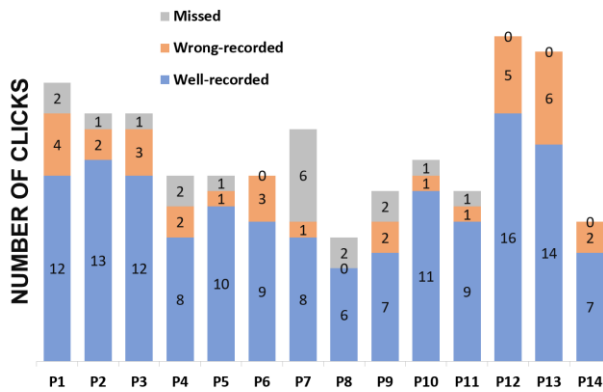


Figure 6. Histogram and table of all the results in both scenes related to confirmation action

Table 1. Rates related to the number of confirmations

Rate	Value (%)
Missed Rate	9.79
Wrong Rate	17.01

Table 2. The sum of the rates of each participant related to the number of confirmations

Participant	$R_M + R_{Wr}$ (%)	Participant	$R_M + R_{Wr}$ (%)
P1	33.33	P8	25.00
P2	18.75	P9	36.36
P3	25.00	P10	15.38
P4	33.33	P11	18.18
P5	16.67	P12	23.81
P6	25.00	P13	30.00
P7	46.67	P14	22.22

Conclusion about the accuracy of the technology cannot be drawn based on the limited number of confirmations. However, based on the rates, there are still room for improving the accuracy of the methodology.

#### 4.2.2 Scan Path

The data collected in the experiment can tell the scan path of each participant. For example, the confirmations shown in Figure 8 were in line 110<sup>th</sup>, 112<sup>th</sup>, 113<sup>th</sup>, 120<sup>th</sup> and 129<sup>th</sup>. One sample scan path of the five selected objects is established in Table 3 based on these objects were recorded in chronological order in the data.

Table 3. Sample scan path of confirmations based on the data in Figure 8

Scene	Scan Path
Static	building_01 > fuse_box > gas_cylinder_01 > panelsstack_in_crane > cement_mixer_01_body

The corresponding selected order of the participant could be examined from the static scene (shown in Figure 7).

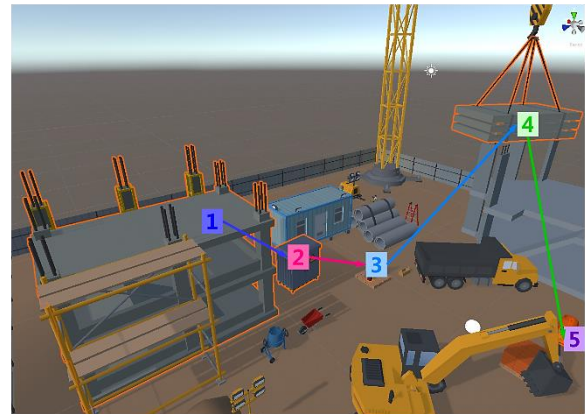


Figure 7. The sample scan path in static scene

110	building_01	2019-01-18 14:21:18.64684	2019-01-18 14:21:18.88218	2019-01-18 14:21:19.18320	536	1
111	building_01	2019-01-18 14:21:19.28314		2019-01-18 14:21:20.24210	958	2
112	fuse_box	2019-01-18 14:21:20.33093	2019-01-18 14:21:20.99223	2019-01-18 14:21:21.33884	1007	3
113	gas_cylinder_01	2019-01-18 14:21:21.40680	2019-01-18 14:21:22.62426	2019-01-18 14:21:25.02520	3618	4
114	portable_cabin	2019-01-18 14:21:25.22630		2019-01-18 14:21:27.04817	1821	5
115	truck_02_dump	2019-01-18 14:21:27.11513		2019-01-18 14:21:27.37127	256	
116	truck_02_body	2019-01-18 14:21:27.39326		2019-01-18 14:21:27.56112	167	
117	truck_02_dump	2019-01-18 14:21:27.98449		2019-01-18 14:21:28.25440	269	
118	building_02	2019-01-18 14:21:28.45529		2019-01-18 14:21:28.47628	20	
119	panels_stack_in_crane	2019-01-18 14:21:28.67826		2019-01-18 14:21:29.21455	536	
120	panels_stack_in_crane	2019-01-18 14:21:29.25952	2019-01-18 14:21:29.54937	2019-01-18 14:21:29.88418	624	
121	crane_body	2019-01-18 14:21:31.38257		2019-01-18 14:21:31.39257	9	
122	crane_body	2019-01-18 14:21:31.40456		2019-01-18 14:21:31.41571	11	
123	truck_02_dump	2019-01-18 14:21:31.79439		2019-01-18 14:21:32.28601	491	
124	building_02	2019-01-18 14:21:32.68736		2019-01-18 14:21:32.93394	246	
125	building_02	2019-01-18 14:21:32.94493		2019-01-18 14:21:32.97891	33	
126	building_02	2019-01-18 14:21:33.00090		2019-01-18 14:21:33.02289	21	
127	building_02	2019-01-18 14:21:33.06787		2019-01-18 14:21:33.30374	235	
128	cement_mixer_01_body	2019-01-18 14:21:33.31373		2019-01-18 14:21:33.35827	44	
129	cement_mixer_01_body	2019-01-18 14:21:33.39226	2019-01-18 14:21:33.89272	2019-01-18 14:21:34.11660	724	

Figure 8. Data for scan path in static scene

However, in addition to the lines with confirmation data in Figure 8, the other lines tell the dwell time of each object. To make it intuitively, the concept of heatmap needs to be introduced.

#### 4.2.3 3D Heatmap

Heatmap is frequently used in eye tracking research to visually show the dwell time of eye movement in 2D displays. However, compared to 2D heatmap, 3D heatmap will be more suitable in our approach.

3D heatmap can be generated as well by changing the colours of the objects based on the overall dwell time of each object. Based on the colour bar we designed as an example, a 3D heatmap is shown in Figure 9. By using 3D heatmap, we can visually see the overall dwell time of each object from the participants based on the changed color of those objects.

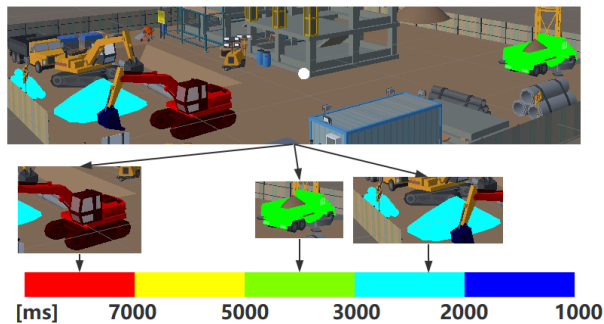


Figure 9. 3D heatmap based on the dwell time in dynamic scene

### 4.3 Discussion and Limitations

In this experiment, 86% of the participants agreed that standing in a virtual environment is more realistic than watching a 2D image and 100% of them felt safer than standing in the real construction site. However, from the perspective of the participants, the scenes still looked unreal. Based on the Results section, we draw a conclusion that the table data shown in Figure 5 represents human's eye movement to a large extent and can be analyzed in three different angles (i.e., *the number of confirmations*, *the scan path* and *3D heatmap*). Since the number of participants, the number of confirmation action by each participant and the number of construction-site scenes are too low, and none of them had construction-site experience, we cannot simply draw conclusions based on the data we collected. In addition, from the rates shown in Table 1 and Table 2, we know the accuracy of the method still has room for improvement.

Even though this experiment demonstrated how to address the research gaps of combining eye tracking with virtual reality in studying hazard identification as

an example, it contains limitations. First, due to only two scenes used in the experiment, the diversity of data is insufficient. Second, the data were analyzed manually. Third, the results of the experiment are not convincing enough based on the inadequate number of participants. Fourth, the accuracy of the eye tracking in virtual environment could be improved by ameliorating the implemented programming algorithms. Fifth, only one possible application is provided in this experiment. Sixth, the dynamic construction-site scene cannot fully represent the dynamic construction site.

## 5 Conclusion and Outlook

Technological innovations are gradually changing the landscape of the construction industry. Such innovations could improve some remaining industrial issues, e.g. the on-site hazard identification. To study the hazard identification, many researchers use eye tracking technology to collect eye movement data from pictures or real construction sites. However, drawbacks e.g. the poor immersion feelings with pictures and the non-storable real site environment in a one-off project, could occur from these two ways of collecting data. For addressing those drawbacks, we provided an approach to use eye tracking in virtual environment diagnostically and interactively. By this approach, a large amount of different eye movement data could be collected. To verify our method, we conducted an example application using eye tracking in two different construction-site scenes (with static and dynamic objects respectively) to collect different eye-movement data. We analyzed the data quality of the confirmation actions of the experiment participants. We explored how to use the experimental data to generate the scan path and 3D heatmaps.

Future studies should focus more on improving the efficiency of the data collection approach and the accuracy of the collected data on the implementation (e.g. using filtering and smoothing algorithms). Efforts also should be made in digging out more possible applications in the construction industry. Meanwhile, we will focus on building more real and dynamic scenes to improve the immersion feelings and the human-computer interactivity in the demonstration of construction sites. Furthermore, after collecting abundant eye movement data from multiple types of participants in various scenes, studying the cognitive process by data mining would be a better idea to analyze the "big data".

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