ICCEPM 2024 https://dx.doi.org/10.6106/ICCEPM.2024.0925
The 10th International Conference on Construction Engineering and Project Management
Jul. 29-Aug.1, 2024, Sapporo

Assessing Multiple Hazard Recognition Abilities of Construction Equipment Operators in Dark Environments Using Virtual Reality

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Abstract: Struck-by accidents on construction sites are one of the major accidents that need to be prevented. Poor visual environments (especially, dark environments) and multiple hazards appearing simultaneously can lead to struck-by accidents due to failure of hazard recognition by construction equipment operators. Therefore, this study aimed to assess multiple hazard recognition abilities of construction equipment operators in dark environments. To this end, virtual reality-based experiments were designed and conducted to collect data on three metrics for multiple hazard recognition abilities: (i) initial recognition time (IRT); (ii) average recognition time per hazard (ART); (iii) the number of false alarms (NoFA). The effect of the number of hazards on multiple hazard recognition abilities in dark environments was analyzed using two statistical methods: (i) Friedman test; (ii) Spearman correlation analysis. The number of hazards has a significant effect on multiple hazard recognition abilities. The data groups for IRT and ART, categorized by the number of hazards, had statistically significant differences. In addition, the number of hazards have negative correlations with IRT and ART. Especially, multiple hazard recognition abilities were lowest when the number of hazards was extremely low (i.e., the number of hazards was 1). Based on these results, construction companies will be able to plan worker allocations that prevent struck-by accidents by increasing multiple hazard recognition abilities in dark environments on construction sites.

Key words: Hazard recognition; Poor visibility; Construction safety; Struck-by accident; Virtual reality

1. INTRODUCTION

The construction industry is one of the industries in which accidents occur frequently and fatally, accounting for approximately 20% of all industrial fatalities in 2022 [1,2]. In response, Occupational Safety and Health Administration (OSHA) has attempted to reduce fatalities in the construction industry by designating major accidents (i.e., caught-in/between, electrocution, struck-by, and fall to lower level) as "Focus Four", but there has been no significant reduction in fatalities [3-5]. Among the Focus Four, struck-by accidents between construction equipment and workers are preventable accidents caused by human errors (e.g., misjudgment of hazardous situation) [6,7]. In other words, one of the primary causes of struck-by accidents is the failure of construction operators to recognize workers as potential hazards. Therefore, construction equipment operators need to be careful to recognize workers while working or moving to prevent struck-by accidents.

Nevertheless, the following visual features of construction sites contribute to hazard recognition failures among construction equipment operators, who visually gather over 90% of their information about hazardous situations [8]. First, construction equipment operators are exposed to poor visual environments that hinder their hazard recognition abilities. Since construction work often takes place outdoors, glare and darkness due to the sun's position, as well as dust generated by the work, can impede visibility [9]. Second, construction sites with high complexity and volatility provide too much visual information to construction equipment operators. The various types of obstacles (e.g., temporal facilities, construction equipment, storage yard, etc.) located at construction sites block the view of construction equipment operators and distract their attention. Even workers, who are potential hazards, appear simultaneously at various locations with obstacles. To prevent struck-by accidents, it's imperative to enhance the hazard recognition abilities of construction equipment operators by considering the visual features of construction sites. Prior to implementing effective improvements, assessing hazard recognition abilities under these conditions is essential.

However, only a few studies have evaluated hazard recognition abilities in poor visual environments on construction sites [10,11]. These studies assessed hazard recognition abilities based on images, so it was impossible to consider potential hazards (i.e., workers) that simultaneously appear in multiple locations, causing struck-by accidents. On the other hand, several studies have evaluated hazard recognition abilities of drivers in poor visual environments, but the visual features of general roads differ from those of construction sites [12-14]. Therefore, this study aimed to assess construction equipment operators' abilities to recognize multiple hazards, such as workers appearing simultaneously in multiple locations, within a representative poor visual environment characterized by darkness. To this end, this study conducted a virtual reality (VR)-based experiment to quantitatively assess hazard recognition abilities.

2. MATERIALS AND METHODS

2.1. Virtual reality-based experiment to assess multiple hazard recognition abilities

A VR-based experiment was designed to assess multiple hazard recognition abilities of construction equipment operators in dark environments (refer to Figure 1). First of all, a virtual environment was implemented using Unity software to simulate encounters with multiple hazards in dark environments from the perspective of construction equipment operators. The process of participants recognizing multiple hazards in the implemented virtual environment was as follows. First, construction equipment (i.e., excavator) moves straights at a construction site in a dark environment. Second, while construction equipment is moving, multiple hazards (i.e., workers) appear simultaneously in multiple locations at random times. One to three hazards appear in random locations, with no overlap in where they appear. Third, participants perform actions that recognizes multiple hazards (refer to chapter 2.2). The implemented virtual environment made it possible to assess hazard recognition abilities under identical conditions for all environments. The virtual environment was played on an ultrawide curved monitor to provide a wide field of view, including binocular vision (120°).

A VR-based experiment was conducted for 11 minutes with the following procedures. First, participants were given information about the experiment, including the goal, process, contributions, etc., for 3 minutes. Second, participants were pre-trained for 5 minutes to understand the process of recognizing multiple hazards and to conduct the experiment exactly as intended in this study. Third, participants performed experiments to recognize in a virtual environment for 3 minutes. Depending on the number of hazards (i.e., from one to three), the experiment was repeated three times for one minute each.

Figure 1. Overview of a virtual reality-based experiment

2.2. Metrics for multiple hazard recognition abilities

The metrics for multiple hazard recognition abilities consisted of data collected in the experiment based on the actions performed by participants in the process of recognizing multiple hazards. The process of recognizing multiple hazards was as follows (refer to Figure 2). First, construction equipment starts from a standstill. Second, during the movement of construction equipment, multiple hazards appear at a specific random point in time, t_0. Third, a participant presses the space bar upon first recognizing a hazard, which occurs at time t_1. This action is equivalent to stepping on the brake of construction in real world. Fourth, a participant presses the space bar once more upon determining they have recognized all multiple hazards, which occurs at time, t_2. This action is equivalent to stepping on the accelerator in the real world after recognizing multiple hazards. Fifth, a participant checks the location and the number of hazards, and then answers. This action is equivalent to finding a safe path based on their hazard recognition.

Therefore, through this process, three metrics for multiple hazard recognition abilities were defined: (i) initial recognition time (IRT); (ii) average recognition time per hazard (ART); and (iii) the number of false alarms (NoFA). First, IRT refers to the time it takes for construction equipment operators to recognize multiple hazards for the first time after they appear. This metric assesses how quickly a construction equipment operator responds to hazards and is calculated by subtracting t_0 from t_1. Second, ART refers to the time it takes for construction equipment operators to recognize each individual hazard. This metric assesses how short the time it takes for a construction equipment operator to recognize a hazard and is calculated by dividing t_2 minus t_1 by the number of hazards. Third, NoFA refers to the number of hazards for which construction equipment operators responded incorrectly about location or presence. This metric assesses how accurately a construction equipment operator recognize multiple hazards. The shorter the IRT and ART and the lower the NoFA, the higher the hazard recognition abilities.

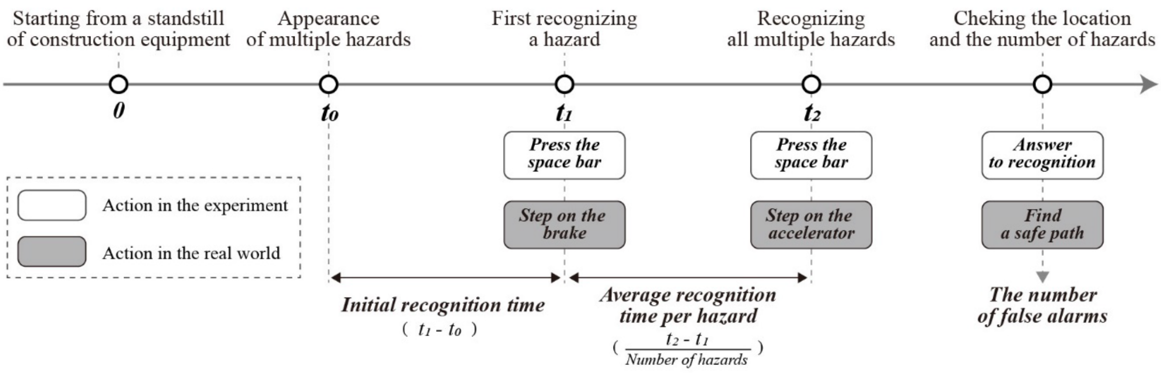

Figure 2. Metrics for multiple hazard recognition abilities

2.3. Data analysis

To quantitatively assess the abilities to recognize multiple hazards in dark environments on construction sites, the data collected for the defined metrics were statistically analyzed using SPSS Statistics 25 software in two ways.

First, this study sought to assess the effects of the number of hazards on multiple hazard detection abilities in dark environments. The data groups for each metric for multiple hazard recognition abilities, categorized by the number of hazards, did not exhibit normal distribution according to the Shapiro-Wilk test [15]. Therefore, the Friedman test, a non-parametric method of Repeated one-way analysis of variance (ANOVA), was used to analyze the statistical differences in multiple hazard recognition abilities according to the number of hazards [16]. The Friedman test reject the null hypothesis that the mean of the data group in all the number of hazards is the same when the *p*-value is less than 0.05. In other words, when *p*-value is less than 0.05, it indicates a statistically significant difference between at least one pair of data groups. When the null hypothesis is rejected, the Bonferroni correction method, a post hoc analysis, is used to identify data groups with significant differences.

Second, this study sought to analyze the correlation between the number of hazards and multiple hazard recognition abilities. The data groups for the number of hazards and multiple hazard recognition abilities did not exhibit normal distribution according to the Shapiro-Wilk test. Therefore, Spearman correlation analysis, a non-parametric method, was used to analyze correlations [17]. Spearman correlation analysis reject the null hypothesis that the correlation coefficient between the two data groups is zero when the *p*-value is less than 0.05. In other words, when p-value is less than 0.05, it indicates a correlation between the two data groups. When the null hypothesis is rejected, the sign and absolute value of the correlation coefficient (from -1 to 1) indicate the direction and degree of the correlation, respectively. If the correlation coefficient is positive, the two data groups have positive correlation, and if it is negative, they have negative correlation. Also, the larger the absolute value of correlation coefficient, the stronger the correlation between two data groups

2.4. Participants

From among the volunteers who wished to participate in the experiment, participants were recruited based on the following criteria. First, participants were selected as unskilled operators with little experience in construction projects to minimize the effects of experience on hazard recognition abilities. Second, participants were selected as adult males, who comprise about 95% of workers in the construction industry. Third, health people without diseases (particularly eye diseases) were selected as participants to minimize the effects of health on hazard detection abilities. As a result, a total of 18 health men aged between 19 and 35 years (mean and standard deviation (SD) were 26.00 and 3.76, respectively) were selected as participants. Prior to the experiment, participants were advised to get enough sleep, avoid caffein, alcohol, and smoking to ensure optimal condition.

3. RESULTS AND DISCUSSIONS

3.1. Effect of the number of hazards on multiple hazard detection abilities

Data on metrics for multiple hazard recognition abilities (i.e., IRT, ART, and NoFA) were collected according to the number of hazards, and the effect of the number of hazards on multiple hazard recognition abilities were assessed (refer to Figure 3).

First, the mean IRT was 1.38 s, 0.82 s, and 0.97 s when the number of hazards was 1, 2, and 3, respectively. The mean IRT was shortest when the number of hazards was 2 and longest when the number of hazards was 1. In other words, the multiple hazard detection abilities in terms of IRT were higher for the number of hazards in the order of 2, 1, and 3. Like these results, the IRTs between the number of hazards between 1 and 2 and between 2 and 3 were statistically significant. It was analyzed that took a long time to recognize hazards was extremely small (i.e., there was less visual information about the hazards), as various obstacles on the construction site distracted their attention and dark environments hindered visual information acquisition.

Second, the mean ART was 1.10 s, 0.85 s, and 0.56 s when the number of hazards was 1, 2, and 3, respectively. The mean ART was shorter as the number of hazards increased. In other words, the multiple hazard detection abilities in terms of ART were higher as the number of hazards increased. Like these results, the ARTs between the number of hazards between 1 and 2 and between 1 and 3 were statistically significant. The reason for these results that after the first hazards is recognized, the area where the other hazards are located becomes smaller. Specifically, in dark environments on construction sites where hazard recognition is challenging, the smaller recognition area further enhances recognition speed.

Third, the mean NoFA was 0.17, 0.00, and 0.11 when the number of hazards was 1, 2, and 3, respectively. In other words, 3 and 2 out of 18 participants failed to recognize hazards when the number of hazards was 1 and 3. When the number of hazards was 1, three participants were not aware of the existence of the hazard. On the other hand, the number of hazards was 3, two participants checked the location of the hazard incorrectly. However, because the frequency of false alarms was so low, there was no statistical difference based on the number of hazards. The need for improved multiple hazard recognition abilities in dark environments was identified, as false alarms can led to fatalities, even if the frequency of false alarms was low.

In summary, the number of hazards in dark environments on construction sites has a significant effect on multiple hazard recognition abilities. Especially, multiple hazard detection abilities were low when the number of hazards was extremely low (i.e., the number of hazards was 1). These results indicate that multiple hazard recognition abilities were lower when there was less visual information about hazards due to visual features of dark environments on construction sites that provide abundant visual information but are difficult to perceive. Therefore, construction companies can enhance the multiple hazard recognition abilities of construction equipment operators by clustering multiple workers in a small area during dark environments.

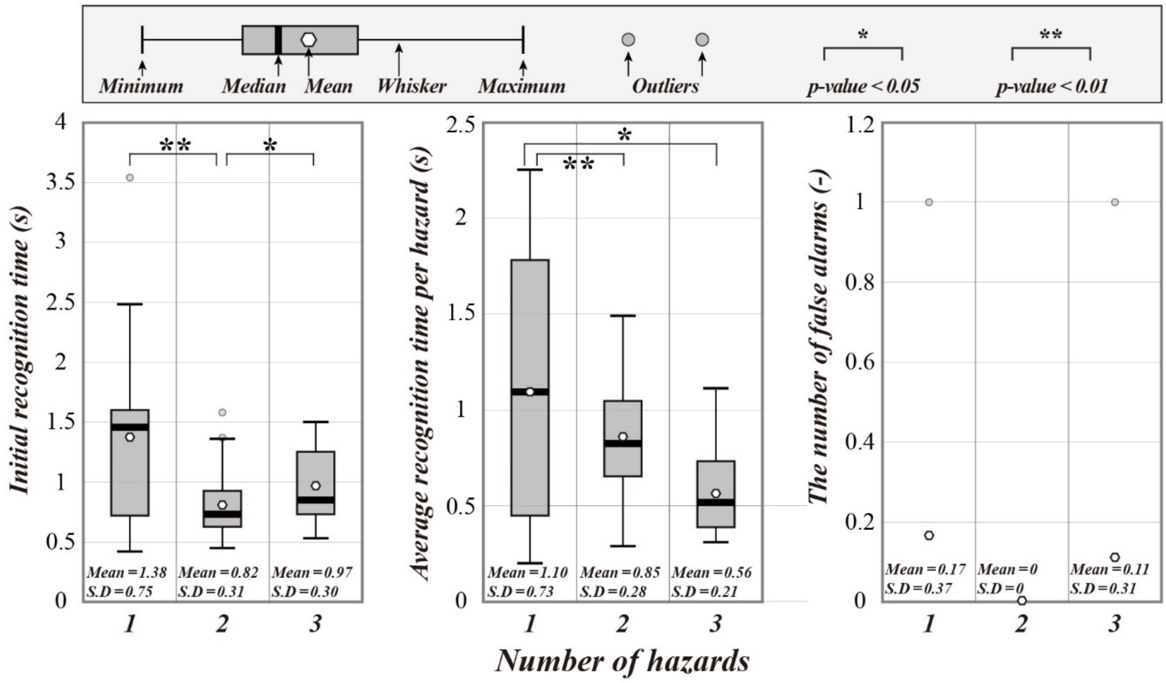

Figure 3. Metrics for multiple hazard recognition abilities

3.2. Correlation between the number of hazards and multiple hazard recognition abilities

The correlations between the number of hazards and three metrics for multiple hazard recognition abilities (i.e., IRT, ART, and NoFA) in dark environments on construction sites were analyzed (refer to Table 1). The number of hazards has negative correlations with both IRT and ART. In other words, as more hazards appeared, multiple hazard recognition abilities in terms of IRT and ART increased. In addition, IRT has negative correlation with ART. A longer IRT indicates that hazards were first recognized after exploring a larger area. Consequently, fewer areas were left to explore afterward for recognizing other hazards. Therefore, the longer the IRT, the shorter the ART. On the other hand, the frequency of false alarms was so low that NoFA had no correlation with the number of hazards and other metrics. In summary, similar to chapter 3.1, it was confirmed that the number of hazards statistically significantly influences multiple hazard recognition abilities. To enhance multiple hazard recognition abilities and prevent struck-by accidents, it is necessary to allocate workers based on the results of this study.

Table 1. Correlation between the number of hazards and multiple hazard recognition abilities

Classification		No. of hazards	IRT[a]	ART[b]	NoFA[c]
No. of hazards	Correlation coefficient	1	**-0.303***	***-0.420****	-0.078
	p-value	-	0.026	0.002	0.574
IRT	Correlation coefficient	**-0.303***	1	**-0.332***	0.251
	p-value	0.026	-	0.015	0.067
ART	Correlation coefficient	***-0.420****	**-0.332***	1	-0.211
	p-value	0.002	0.015	-	0.130
NoFA	Correlation coefficient	-0.078	0.251	-0.211	1
	p-value	0.574	0.067	0.130	-

Note: IRT[a] stands for initial recognition time, ART[b] for average recognition time per hazard, NoFA[c] for the number of false alarms, ** for statistical significance at 0.01 level, highlighted in bold with italics, and * for statistical significance at 0.05 level, highlighted in bold.

4. CONCLUSIONS

A VR-based experiment was designed and conducted to assess multiple hazard recognition abilities of construction equipment operators in dark environments on construction sites. Three metrics for multiple hazard recognitions (i.e., IRT, ART, and NoFA) were defined and the statistical relationship between the number of hazards and these metrics was analyzed using the Friedman test and Spearman correlation analysis. According to the results, the number of hazards had a statistically significant effect on multiple hazard recognition abilities. In detail, the IRT and ART showed statistically significant differences according to the number of hazards, and they were negatively correlated with the number of hazards. These results support the notation that when the number of hazards is very small (i.e., the number of hazards is 1), multiple hazard detection abilities are low, thus increasing the likelihood of struck-by accidents between construction equipment and workers. In other words, in cases where it is necessary to allocate workers along the path of construction equipment in dark environments on construction sites, it is advantageous for preventing struck-by accidents to allocate a large number of workers rather than a few. This study is expected to help prevent struck-by accidents at construction sites in dark environments. Future research should extend the scope (e.g., type of visual environments, hazards, etc.) of this study and validate the results of this study through field studies in actual construction sites.

ACKNOWLEGEMENTS

The support of the National Research Foundation of Korea (NRF) grand funded by the Korea government (MSIT; Ministry of Science and ICT) (NRF-2018R1A5A1025137) is gratefully acknowledged.

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