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Research Article

Investigation of Fire-Fighting Evacuation Indication System in Industrial Plants Based on Virtual Reality Technology

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The fire safety of industrial buildings has always been a great concern. An excellent evacuation indicator system can guide the personnel to escape quickly, thus reducing the casualties. In this study, we present a virtual simulation fire scene based on virtual reality to explore the impact of different colors, brightness values, and flashing frequencies on escape time in case of fire emergencies. The presented scene can help shorten the time required for evacuation in an industrial plant by identifying the escape path under the fire and smoke environment and improve the escape efficiency. The results show that the green color is the most suitable color for evacuations; the escape efficiency increases with an increase in brightness, and there is no significant difference between the escape times under high and medium brightness; the evacuation time decreases with an increase in the flicker frequency. Based on these experimental results, the fire evacuation indicating system is designed. A virtual reality verification experiment is used to compare the escape efficiency of the improved design with an original factory's indicating system. The verification results show that the improved scheme reduces the evacuation time and significantly improves the psychological stress on the evacuees. This work provides a theoretical basis for safe evacuation designs.

1. Introduction

Recently, the problem of fire has become increasingly prominent. According to the data provided by the Fire and Rescue Department of the Ministry of Emergency Management, 252000 fire alarms were reported in China during 2020, including commercial buildings, industrial plants, warehouses, hotels, museums, and ancient buildings. Among these buildings, the industrial factories usually have high-density products and a considerable economic value [1, 2]. It is well known that fires in industrial plants can easily spread to nearby products, resulting in a series of secondary fires [3, 4]. Furthermore, an incident analysis that focuses on the evacuation phase has indicated the presence of a clear correlation between a delayed evacuation and a high number of fire deaths [5]. In an emergency situation, every single second plays a vital role in reducing the number of claimed lives [6]. Therefore, evacuation efficiency is particularly important.

As it is not possible to completely mitigate the fire risk [7], an effective fire evacuation indication system that enables quick evaluation of people should be designed. The existing work shows that there are three critical factors for successful fire evacuation: (1) organizational evacuation efficiency, (2) information regarding safe navigation, and (3) emotion of the evacuees [8–10]. In addition, a large amount of smoke caused by fire is one of the main reasons leading to human casualties. The smoke not only causes dyspnea but also hinders the vision leading to poor visibility and panic among the affected. An effective evacuation indication system improves the evacuation speed in the presence of dense smoke. Consequently, the number of casualties can be significantly reduced and the evacuation process can be completed calmly and efficiently.

The current research regarding fire safety considers real experiments, such as fire drills and abandoned site experiments. Guillaume et al. conducted real-scale fire tests of one-bedroom apartments [11]. Software-based fire scene simulation models and crowd evacuation simulation models [12], and fire simulation models based on numerical methods [13], have also been used in fire-related research. Furthermore, a large number of scholars have studied the evacuation behavior in fire based on microscopic or macroscopic simulation-optimization [14]. Teng et al. extended object-oriented techniques to solve multi-objective simulation optimization problems by exploiting the concept of Pareto optimality to narrow the search space [15]. Kou et al. proposed an assignment rule integrated with the vector evaluation genetic algorithm (VEGA) to solve the multi-objective simulation optimization problem to improve search efficiency in stochastic environments [16]. Abdelghany et al. proposed a simulation-optimization framework integrating a genetic algorithm (GA) and a microscopic pedestrian simulation allocation model to realize an evacuation plan [17].

It is worth noting that real experiments not only have ethical issues associated with them but also have a high cost. The software-based simulation models and numerical models cannot obtain a realistic dataset directly based on the behaviors and responses of evacuees. Recently, the development of virtual reality has brought a new perspective on the research work regarding fire safety. Kinateder et al. [18] analyzed the strengths, weaknesses, opportunities, and threats (SWOT) of virtual reality as a fire research tool. The results showed that virtual reality could effectively help the researchers in understanding the behavior of individuals who escaped fire. Zou et al. [19] used virtual reality to analyze whether the conflict between social information and emergency signs in a smoke-filled tunnel affected the evacuation process. The results showed that the negative behavior of a few individuals would hinder the process of safe evacuation.

Ronchi et al. [20] suggested the design of flashlights at the emergency entrances and exits of road tunnels based on the experiments performed using virtual reality. The results showed that the performance of green or white flash was better than that of blue; the flash frequencies of 1 Hz and 4 Hz were better than the flash frequency of 0.25 Hz. In addition, the LEDs performed better compared to single-frequency or dual-frequency flashbulbs. Cao et al. [21] performed fire simulation experiments in a virtual museum and showed that providing an escape route plan in case of fire emergency makes evacuation easier and less time consuming. Chobbok et al. [22] conducted experiments using virtual reality and proved that the exit signs with graphic assistance have an obvious guidance value. Max et al. [23] explored the colored signs that the participants were most likely to infer as exit signs in a simulated emergency evacuation using virtual reality.

In short, many researchers have proved that virtual reality can effectively simulate the real scenes with high fidelity [24]. The existing works mostly focus on the role of guiding signs and escape route planning in case of a fire, and the impact of groups on individual escape behavior. However, these works ignore the importance of the visibility of evacuation signs in the presence of fire and dense smoke. A few researchers have objectively put forward specific improvement methods for increasing the evacuation efficiency in the presence of dense smoke. The evacuation signs directly interact with people in the fire evacuation system. The visibility of signs in the presence of fire and smoke determines the evacuation efficiency. The navigation becomes very difficult when the signs cannot provide complete spatial information [25].

Therefore, in order to fill the research gap and address the problems of poor escape efficiency of traditional evacuation indication systems, first, this work simulates a factory fire smoke scene based on virtual reality to explore the effects of different colors, brightness, and flicker frequencies on evacuation time. Second, based on the experimental results, the best color, brightness, and flashing frequency are selected to improve the evacuation indication systems in industrial plants. Last, by considering an industrial plant as the prototype, comparative verification experiments between the original evacuation and improved evacuation indication systems are performed. Figure 1 shows the experimental process. The schemes are evaluated in terms of reaction and evacuation time, psychology state assessment, and the system usability scale (SUS). The experimental results show that the improved evacuation indication system significantly enhances the escape efficiency and reduces the short-term pressure on evacuees in the presence of a fire. The highlights of this study are as follows: (1) smoke, flame, and sound effects are added to the virtual fire environment to improve the authenticity of the environment; (2) based on virtual reality technology, the influence of the evacuation indication system color, brightness, and flicker frequency on evacuees is explored; (3) the evacuation indication system is improved based on the experimental data.

2. Materials and Methods

2.1. Experiment Method. In these experiments, 3 Dimensions Studio Max (3D Max) software is used to design the 3D scenes in the virtual environment and V-Ray is used to render the real scenes. We use Unity to develop a factory scene similar to the real world. The programming language C# is used to realize the interaction between the participants and the experimental scene. A virtual factory environment includes the factory equipment and materials. Additionally, it also includes static fluorescent lamps and dynamic exit sign lamps. The lighting effect of the real factory scene is fitted through parameter design. Furthermore, we use a particle system for simulating a real fire smoke scene.

2.2. Design of Experiment. The experiment is divided into two stages: a pre-experiment and formal experiment. During the former, the participants play a simple virtual reality maze game. Its purpose is to enable the participants to adapt to the virtual environment, get familiar with the operation mode, and complete the adaptive training. The formal experiment is based on an existing evacuation indication system and depicts a real scene of a factory fire. This experiment is further divided into three sub-experiments to explore the influence of different color indicators on the direction selection by the participants, the visibility of indicators with different brightness, and the visibility of different flicker frequency indicators when a fire occurs in an industrial plant. During the evacuation process, different aspects of participants' behavior are recorded to form the dataset.

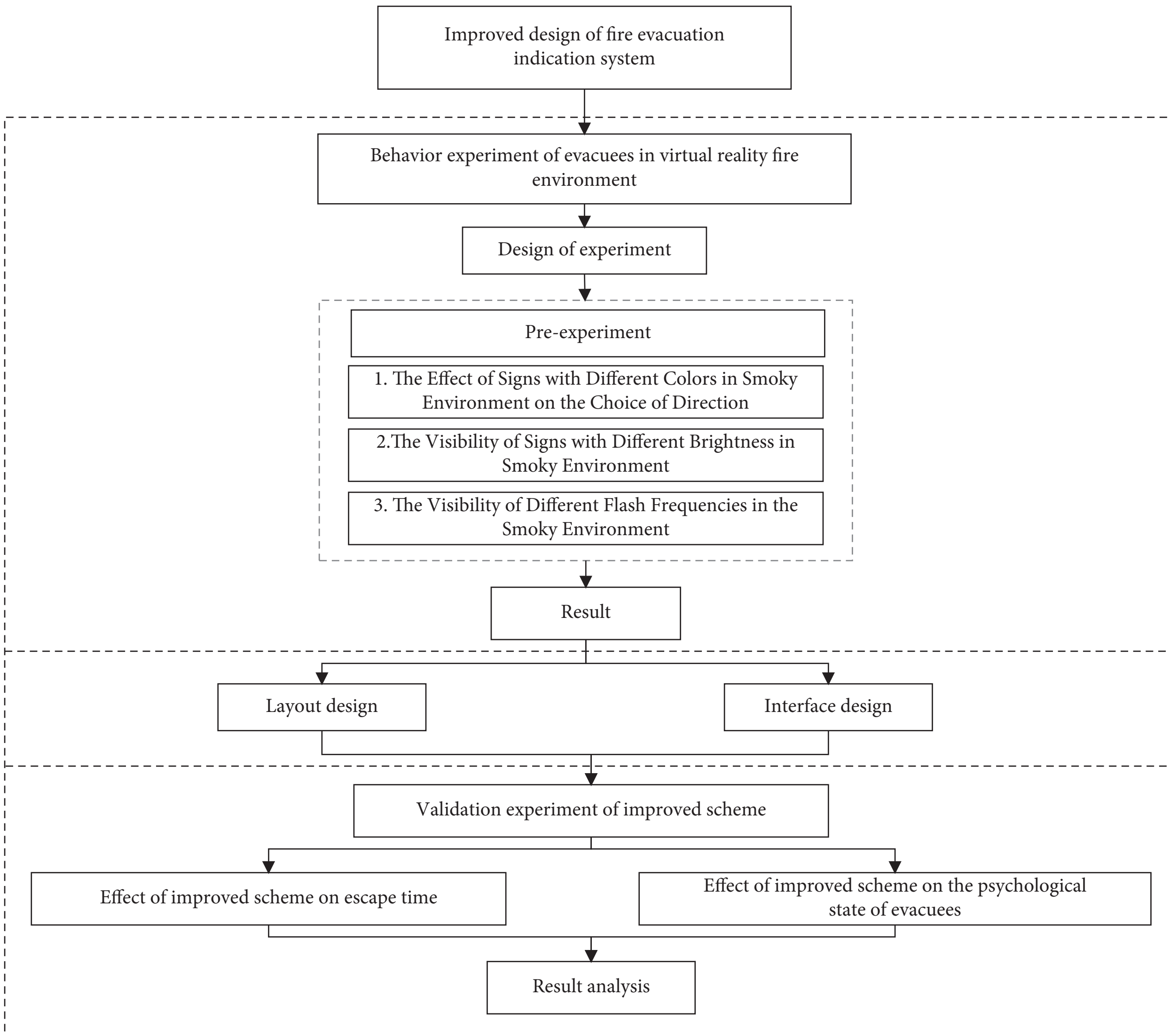


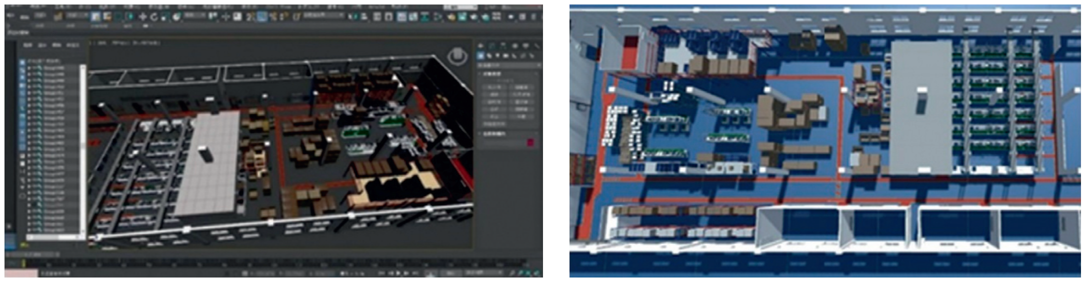
Figure 1: Experimental evacuee behavior and verification process.

2.3. Participants' Information. We recruited 24 participants to perform this experiment, including 10 males and 14 females. The ages of all the participants range from 20 to 28 years (mean age = 22.9, standard deviation = 1.44). The participants are required to be in good emotional and physical conditions. In addition, they should have a normal or corrected vision. Before the experiment, the participants are required to sign an information and consent form. The participants are also informed of the precautions required during the experiment. Each participant takes part in three experiments. If any participant feels any physical discomfort during the experiment, he/she can exit the process at any time.

2.4. Instruments Used in Experiment. The experiment is performed in the virtual simulation laboratory of Mechanical Engineering College, Donghua University. The effective space of the laboratory is three meters in both length and width. The indoor floor of the laboratory is flat and there is no interference from any other electronic devices, which ensures the normal operation of the virtual experiment.

The hardware used in the experiment includes HTC VIVE virtual reality equipment and laptops. Similarly, the software includes the game development engine Unity. The HTC VIVE VR device consists of a head-mounted display (HDM), two handheld controllers, a tracking display, and a two-controller locator (lighthouse).

2.4.1. Building of Visual Factory Fire Scene. The internal structure of a certain motor assembly plant is considered as the prototype for this experiment. We use 3D Max to model the factory, which is then imported into Unity for scene editing and development. Scripts enabling the participants to interact with the scene are written in the C programming language, as shown in Figure 2. In addition to the original production equipment in the workshop, fire-fighting equipment related to the experiment, such as indicators,



(a) (b)

Figure 2: The 3D factory model. (a) Model in 3D Max. (b) Model in Unity.

emergency lights, and fire extinguishers, are also present. The flame and smoke of incendiary objects lead to low visibility and creation of psychological panic and tension.

In the Unity framework, various parameters in the particle system provided by the software are adjusted to simulate the effect of real flame and smoke environment. In addition, the smoke alarm is triggered at the onset of the fire, and the sound module is added when the scene is restored. The direction of rotation of head-mounted display is controlled, and the speed is set equal to the speed of normal walking. The height of the human head-mounted display in the virtual scene is similar to that in the real environment. The scripts on the left- and right-hand controllers are added to achieve forward control. A camera script to control the helmet is added to realize the field of view and change the direction.

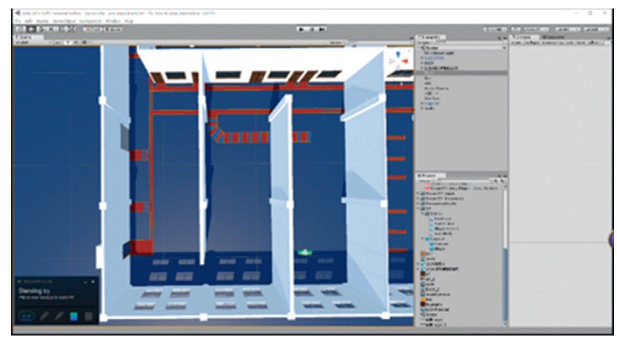


Figure 3: Adaptive environment scenario.

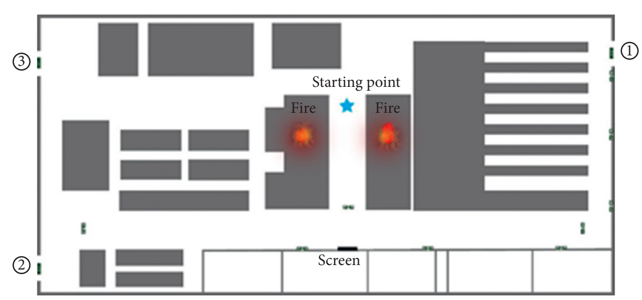


Figure 4: Floor plan of the test environment.

2.5. Experimental Procedure

2.5.1. Pre-Experiment. Prior to participating in the formal experiment, all the participants played a simple visual reality game of labyrinth, as shown in Figure 3. The aim of this game is to allow the participants to adapt to the visual environment and become familiar with the experimental operations. When the participants exit the door of the labyrinth, "Mission Complete" is displayed on the interface, which indicates that the participants have completed the adaptive training.

2.5.2. Formal Experiment

Experiment 1. Effect of Signs with Different Colors in Smoky Environment on the Choice of Direction

During the testing phase, the participants are present in a virtual factory scenario. Each participant is assigned a head-mounted display and a handheld controller, and a virtual factory fire scene is presented as the program starts. In order to control other variables in the experiment, the participants make choices based on the variables without being affected by the surrounding environment. Artificial changes are made to the virtual factory so that the surrounding environment is consistent. In Figure 4, the red flame icon in the factory plan denotes the location of fire. There are fire locations on the left and right sides of the start point, and the smoke fills the surroundings of the participants. The fire is large enough to release the smoke that spreads to the whole factory. After the onset of fire, the smoke alarms on the left and right sides go off. There is an arrow indicating the direction of evacuation on the monitor in front of the participants. The participants are required to make an escape choice according to the arrow indication and their experience, that is, they can choose to leave from either left or right. A transparent collider is set up in the Unity system when a participant traverses a certain distance after the T intersection. When the participant hits this collider, the virtual device displays "Mission Complete." The colors selected by each subject are recorded during the experiment.

The red color has the best visibility and strongest penetration ability in the presence of smoke or smog. The green color has the best semantic meaning. The blue color is particularly effective as an emergency signal [26]. Therefore, we use green, red, and blue colors in the experiment, as shown in Figure 5.

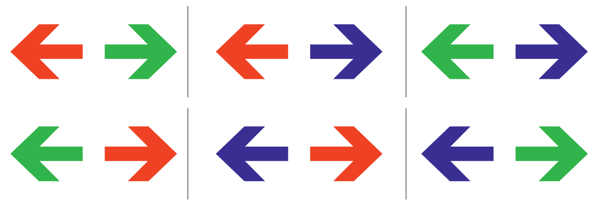


Figure 5: Arrow color map used in the experiment.

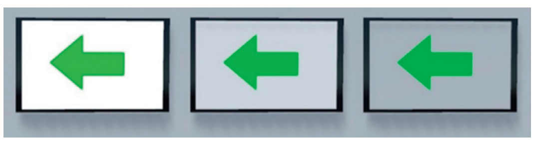


Figure 6: Schematic diagram of indicator brightness.

Experiment 2. Visibility of Signs with Different Brightness in Smoky Environment

The scene and interaction in this experiment are similar to the first experiment. In this experiment, the monitor shows a green arrow. The participants are asked to make an escape choice according to the direction indicated by the arrows. Note that the arrows appear randomly indicating either left or right direction.

Considering the human visual system, the brightness of an acceptable liquid crystal display (LCD) is up to 400 cd/m^2. The range of brightness of the human eye without fatigue is between 120 cd/m^2 to 150 cd/m^2. It is stipulated that the minimum brightness of white and green or white and red multi-color sign lamps in the factory should not be less than 5 cd/m^2, and the maximum brightness should not be more than 300 cd/m^2. Therefore, the maximum, minimum, and intermediate values, that is, 300 cd/m^2, 150 cd/m^2, and 5 cd/m^2, respectively, are selected as the experimental variables in this experiment. During the experiment, the brightness of the screen is changed each time, as shown in Figure 6. Three variables, namely high brightness, low brightness, and medium brightness are used for the convenience of subsequent statistics, and their corresponding parameter values in Unity are 1, 0.5, and 0.017, respectively. In order to eliminate the influence of other factors, the participants repeat two groups of experiments, that is, each participant completes six experiments. The random brightness sequence also appears six times. The brightness and completion time of each occurrence are recorded.

Experiment 3. Visibility of Different Flash Frequencies in the Smoky Environment

Nilsson et al. [27] observed that compared with the standard emergency exit design, the flashing lights increase the recognition of personnel. In daily life, the frequency of flashing lights working as a warning, such as the flashing light used in the car turn indicator and traffic signal light, is about 1 Hz. Therefore, 1 Hz is selected as the lower frequency. In order to ensure that normal people can observe the flickering warning light in any state, including fatigue and high tension, 30 Hz is selected as the higher flickering frequency. In order to systematically study the influence of different scintillation frequencies on the visibility in the presence of smoke, 1 Hz, 15 Hz, and 30 Hz frequencies are selected as the analysis parameters.

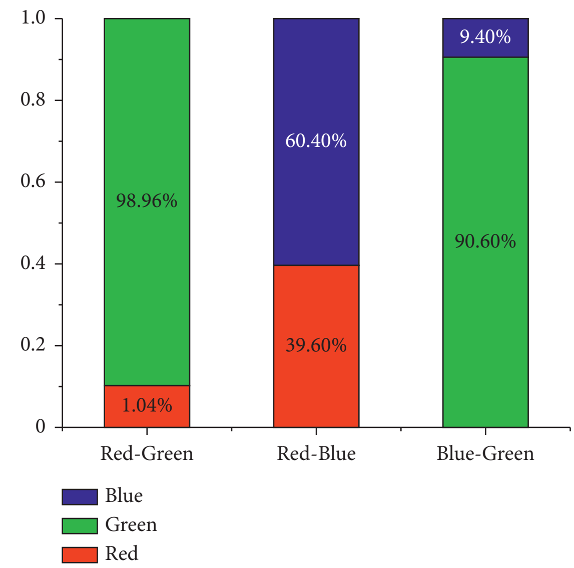


Figure 7: Statistics of experimental results.

In this experiment, the scenes and interactions are exactly similar to those of experiments one and two. There is only one green arrow on the monitor, which appears randomly towards the left or right. The participants see three different flashing frequencies, each of brightness 300 cd/m^2, which is similar to the brightness used in experiment two. The flashing frequencies are 1 Hz, 15 Hz, and 30 Hz. In order to ensure that the flickering is not affected by other factors, the random brightness sequence appears six times, and the flickering frequency is recorded each time. The participants repeat two groups of experiments, and each group participates in all six experiments. The resulting data of these experiments are included in the final statistics.

3. Results and Discussion

3.1. Analysis of the Influence of Different Color Indications on Direction Selection. Based on the statistical analysis of choices made by the participants, it can be gathered that the number of effective choices per person is 12, with a total of 24 participants. There are a total of 288 choices, among which the red is selected 39 times, green is selected 182 times, and blue is selected 67 times. According to the statistics, when the graph consists of red and green arrows, the proportion of choosing green is 98.96%; when the graph consists of blue and green arrows, the proportion of choosing green is 90.6%; and when the graph contains red and blue arrows, the proportion of selecting blue is 60.4%. As shown in Figure 7, green is the most selected color, indicating that it is considered as the safest color and can help the participants to respond quickly.

In the presence of a green arrow, 21 participants choose the green arrow, accounting for 87.5% of the total selections. The statistics show that there are only three participants who make a random choice when the green arrow appears. After the experiment, these three participants are interviewed briefly and asked about the reasons behind their choices. The participants elaborate that they are more focused on the scene and their own experience during the experiment; therefore, they choose the direction they think is safer instead of making a choice indicated by the arrows. In fact, these participants also consider the green indicator to be safe. When red and blue arrows appear, 87.5% of the participants choose blue, and a small number of participants sometimes choose red due to the repetition of the experiment. These participants explain that the red and blue colors do not have any clear semantics regarding the safe direction. Therefore, these participants make choices according to their personal preferences. Note that 33.3% of the participants do not choose the red arrow in any case. In the postexperiment interviews, the participants explain that they consider red as the "dangerous" color; therefore, they choose the direction opposite to that shown by the red arrow.

3.2. Analysis of Visibility of Indicators with Different Brightness. The completion time and corresponding data of all the participants under different frequencies and brightness are used in the SPSS software for one-way ANOVA. In this experiment, the one-way ANOVA is used to analyze the influence of brightness on the time consumed for choosing the direction of evacuation. As listed in Table 1, the completion time in the brightness variable experiment is termed as "Time 1."

The one-way ANOVA shows that the brightness significantly affects the evacuation efficiency, with $F_{0.05}$ $(2,141) = 17.469$, $p < 0.05$. Note that there is a significant difference between the average brightness of three cases, that is, 9.100 s (5 cd/m^2), 6.922 s (150 cd/m^2), and 6.324 s (300 cd/m^2), among all the three groups. The higher the brightness, the shorter the completion time of the experiment. The average completion times corresponding to low, medium, and high brightness are 9.100 s, 6.922 s, and 6.3240 s, respectively. There is a large difference between the average completion times for the low and medium brightness, and a small difference between the medium and high brightness. Table 2 lists the test results.

The analysis shows that the significance of low and medium brightness is $p < 0.05$. Therefore, the difference between the low and medium brightness significantly impacts the evacuation efficiency. The significance of low and high brightness is $p < 0.05$. Therefore, it can be concluded that in a scene, the difference between low and high brightness significantly affects the evacuation efficiency. However, the significance of medium and high brightness is $p > 0.05$. Therefore, it can be concluded that the difference between medium and high brightness has no significant impact on the evacuation efficiency.

The experimental results show that higher brightness leads to higher evacuation efficiency. However, there is no considerable difference between the effects of medium and high brightness values on the evacuation efficiency. The difference may lie in other errors in the experiment. Therefore, high or medium brightness can be selected when designing the evacuation indicating system.

3.3. Analysis of the Visibility of Indicators with Different Flickering Frequencies. The completion time in the flickering frequency variable experiment is termed "time 2." The one-way ANOVA of this experiment is used to analyze the effect of frequency on the time required to choose the direction of evacuation. We use SPSS to perform variance analysis of time 2 as compared to different flickering frequencies. The results are listed in Table 3.

According to the experimental results, $F_{0.05}$ $(2,141) = 11.165$ and $p < 0.05$. The one-way ANOVA shows that brightness has a considerable impact on the evacuation efficiency. There is a significant difference between the average times of three cases, that is, 7.886 s (1 Hz), 6.716 s (15 Hz), and 5.825 s (30 Hz). The average completion times corresponding to the low, middle, and high frequencies are 7.886 s, 6.716 s, and 5.825 s, respectively. The higher the frequency, the lower the completion time. The difference between the two adjacent groups needs to be tested afterwards. The test results are provided in Table 4.

The analysis shows that the significance values of low and medium frequencies, low and high frequencies, and medium and high frequencies are $p < 0.05$. Therefore, the difference between low, medium, and high frequencies has a significant impact on the evacuation efficiency. The experimental results show that the higher the frequency, the faster and more effective the evacuation process.

4. Scenario Design

4.1. Factory Instructions Layout Design. We present a case study of the layout of an indicating system using an unmodified electrical plant as a factory prototype. The main purpose of the system is the efficient evacuation of the people. Therefore, it provides escape information to the individuals at each decision point to facilitate fast and appropriate decision making. The green squares in Figure 8 represent the location of the display, which are installed on the nearby walls by considering all the safety factors.

4.2. Indicating Interface Design. We arrange the colors selected in experiment 1 to highlight the escape direction, route, and exit. The arrows, routes, and safety exits are presented in bright green. The overall background is presented in dark blue. The base map represents a real-life view of a factory. The interface displays the location of the flame and the surrounding smoke and its concentration. Thus, it is convenient for the trapped individuals to recognize the magnitude of the fire. Additionally, the interface also displays the density of the individuals on a particular route, which is useful to the escapees for independently choosing a more efficient route. The indicated direction changes based on the amount of smoke diffusion, as shown in Figure 9. The route displayed on the system interface denotes the safest and most efficient path obtained based on the real-time analysis of data using various factors. Note that the maps in

Table 1: Analysis of completion time in brightness variable experiment.

Time1	Square sum	Degrees of freedom	Mean square	F	Significance (n_p^2)
Intergroup	204.940	2.000	102.470		
Intragroup	827.099	141.000	5.866	17.469	0.000
Total	1032.038	143.000			

Table 2: Standard error and significance of reaction time between two different brightness values.

Brightness (cd/m^2)	Mean difference (I–J)	Standard error	Significance (n_p^2)
5–150	2.178313*	0.494383	0.000
5–300	2.776042*	0.494383	0.000
150–300	0.597729	0.494383	0.229

Note. *The significance level of the mean difference is 0.05.

Table 3: Experimental data analysis results of time 2.

Time 2	Square sum	Degree of freedom	Mean square	F	Significance (n_p^2)
Intergroup	102.591	2	51.296		
Intragroup	647.795	141	4.594	11.165	0.000
Total	750.386	143			

Table 4: Standard error and significance of reaction time between two different frequencies.

Frequency (Hz)	Mean difference (I–J)	Standard error	Significance (n_p^2)
1–15	1.17063*	0.43753	0.008
1–30	2.06119*	0.43753	0.000
15–30	0.89056*	0.43753	0.044

Note. *The significance level of the mean difference is 0.05.

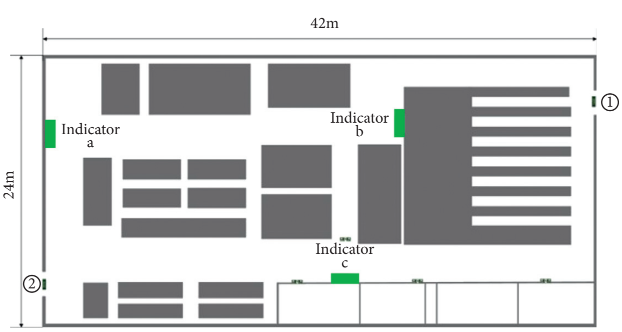


Figure 8: Layout of the factory instructions.

the display devices at different locations are different or are partially enlarged instead of a fixed and static standard map.

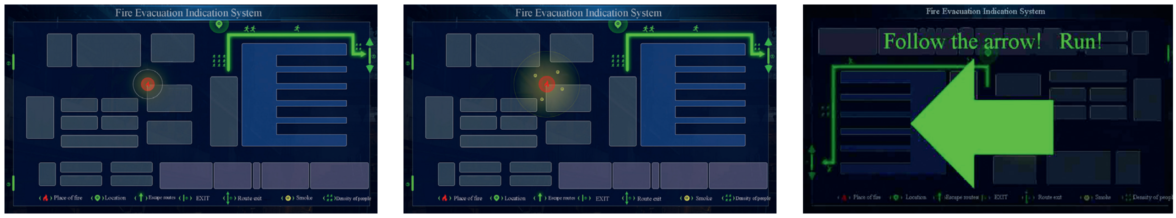
In experiment 2, the required evacuation time should decrease with an increase in the brightness. However, the difference between the times for high and medium brightness values is not significant ($p > 0.05$). Therefore, the energy-saving factors are also considered in the design. In case of an emergency power-off, the brightness on the display device lies in the medium range, that is, 150 cd/m^2.

In experiment 3, we observe that the escape efficiency is higher in the presence of high flickering compared to that in its low. In case of an emergency, it is necessary to transmit the most straightforward information to the individuals. Therefore, the system uses the simplest and most intuitive arrows to indicate directions, and the warning light flashes at a frequency of 30 Hz. At the same time, the warning light flickering is accompanied by a brief text, that is, “Follow the arrows and escape quickly!” to warn the individuals to evacuate quickly.

5. Design Verification and Evaluation

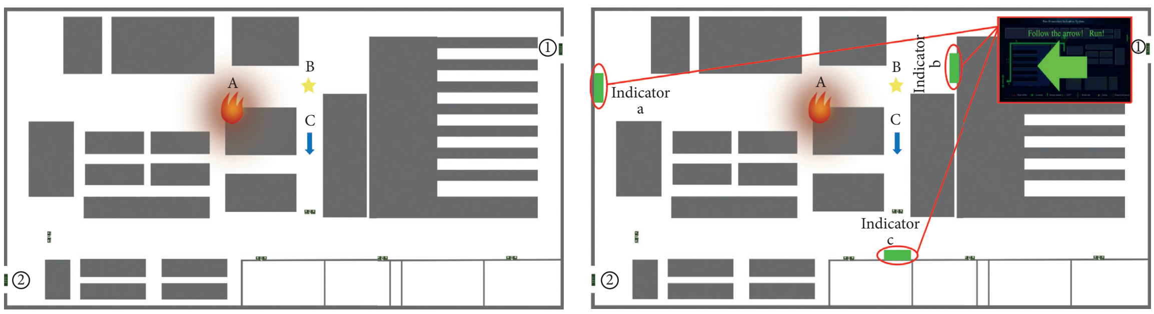
5.1. Instruments Used. The instruments used in the verification experiment are the same as those used in the experiments in Section 2. In addition, short stress state questionnaire (SSSQ) [28] is introduced to measure the psychological level of participants. It is a short stress state questionnaire prepared according to the Dundee Stress State Questionnaire (DSSQ) [29] and appears to be a reliable short measure of stress state, which is sensitive to task stressors. At present, the SSSQ has been widely used in the evaluation of short-term mental state changes in medicine, virtual reality, and other fields [30, 31]. It is a 24-item questionnaire that divides stress into three high-order factors: engagement, distress, and worry, which reveals the changes of emotional status throughout the experiment. Each question in the SSSQ has a score between 0 and 5, indicating totally inconsistent to totally consistent.

5.2. Participants. We recruit 36 participants to verify the proposed design. All the participants are between 18 and 28 years old, with a moderate male to female ratio.



(a) (b) (c)

FIGURE 9: Indication presented in the interface; (a) small smoke concentration; (b) dense smoke; (c) arrows indicating the escape routes.



(a) (b)

FIGURE 10: Top view of the experimental scene. Points A, B, and C represent the fire source, starting position, and route of travel, respectively. (a) Control group; (b) experimental group.

5.3. Verification of Experimental Design. Based on virtual reality technology, we explore the changes in the escape times and psychological states to verify the effectiveness of the improved scheme. The safety exit signs, emergency lights, smoke alarms, and other necessary devices are added to the scene according to the original evacuation instruction system. The scene represents an unmodified motor packaging factory, as shown in Figure 10.

There are two exits in the factory building denoted as ① and ②. The arrows representing the safety exit signs at each location point to the safety exits. The safety signs at each T-shaped intersection are two-way arrows. The experiment is divided into two groups: 18 participants take part in the original industrial plant scene experiment, that is, the control group; the remaining 18 participants take part in the industrial plant scene experiment of the newly designed evacuation indicator system, that is, the experimental group. Compared to the control group, the experimental group has the same factory facilities except for the indicator system. In addition, the starting positions of participants in the scene at the time of accident are also the same. The moving speed in the scene is about 1.5 m/s in reality.

Prior to the experiment, all participants are required to fill the SSSQ independently as the pretest data. After the participants put on the virtual reality devices, the starting scene is represented by B in Figure 10. The arrow points represent the forward direction of the subject. The fire starts at the predefined position and will gradually increase during the experiment. There will be a large amount of smoke in front of the participants, hindering the vision, as shown in Figure 11. The inspection team adds the proposed fire-fighting evacuation system-related equipment and display

FIGURE 11: A participant is experimenting in the VR fire environment.

instruments. When the fire is small, there is no safety hazard on the path leading to ②, and the indicating system starts to show the escape route through ②. As the fire spreads, there is a safety hazard on the path leading to ②, and the instructing system changes the display of the escape route to ①. The remaining conditions and operations are the same as those of the control group. In addition, all participants are required to fill the SSSQ as post-test data after the completion of the experiment, and the participants in the experimental group are required to fill out the SUS questionnaire.

Three times are recorded during the two sets of experiments, that is, the time when the participant starts moving denoted as reaction time 1, the time after passing a T-shaped intersection denoted as reaction time 2, and the time required to reach the exit denoted as the escape time. The usual path is blocked due to the location of the fire. At the same time, a collider is set up in the Unity software around the fire so that the individuals cannot escape from the usual path. Therefore, each subject passes through a T-junction in the forward direction.

5.4. Verification of Experimental Results and Analysis

5.4.1. Effect of the Improved Scheme on Escape Time. In the control group, 16 participants choose exit ① and two participants choose exit ②. After the experiment, the individuals report that the main reasons for choosing ① are as follows: first, the individuals think that the fire location is on the right-hand side. Therefore, they consider the exit as unsafe and choose the direction opposite to the fire source. Second, the individuals think that there is a door on the left, which seems to be closer to the direction of the safety exit. All the participants in the experimental group escape according to the instructions, that is, nine people choose ① and nine people choose ②. All the data are imported into SPSS. The three datasets collected from the two sets of experiments are compared separately, and the relevant sample t-test is performed. The results are shown in Figure 12.

Figure 11 compares the average time of the two groups of experiments. Based on the data of reaction time 1, reaction time 2, and the escape time, the time spent by the experimental group in each stage is less compared to the control group. This proves that after adding the improved evacuation indication system, the time required by the evacuees to select the path at each intersection is shortened. However, whether the design of fire evacuation indication system affects the escape efficiency needs to be discussed. Assumptions are present as follows:

> Null hypothesis H0: The design of the fire evacuation indication system does not affect the escape efficiency.
>
> Alternative hypothesis H1: The design of the fire evacuation indication system impacts the escape efficiency.

For each pair of data samples, the relevant sample t-test is performed, as listed in Table 5.

The significance level is $\alpha = 0.05$, which is a two-tailed test. The degree of freedom is df = 15, and the critical value is equal to tcrit = 2.131, which is obtained by checking the t critical value table. The corresponding t-values of the three data sets are 3.440, 2.747, and 3.322, respectively. The 95% confidence interval of the difference does not contain zero, and tobs > tcrit in the three sets. The actual t score is higher than the critical value. Therefore, the null hypothesis H0 is rejected, showing that the design of the fire evacuation indicating system has a significant impact on the evacuation efficiency.

The results of data processing show that the reaction time 1 (1.375 ± 0.549, average = 1.375 s, standard error of mean (SEM) = 0.549 s) of the experimental group is significantly less compared to the reaction time 1 (2.109 ± 1.066) of the control group, which is 0.734 s and $p < 0.05$ (two-tailed test). The reaction time 2 (8.130 ± 1.032) of the experimental group is significantly less compared to the reaction time 2 (9.878 ± 3.268) of the control group, where the difference between the two is 1.748 s and $p < 0.05$ (two-tailed test). The escape time of the experimental group (25.284 ± 3.061) is

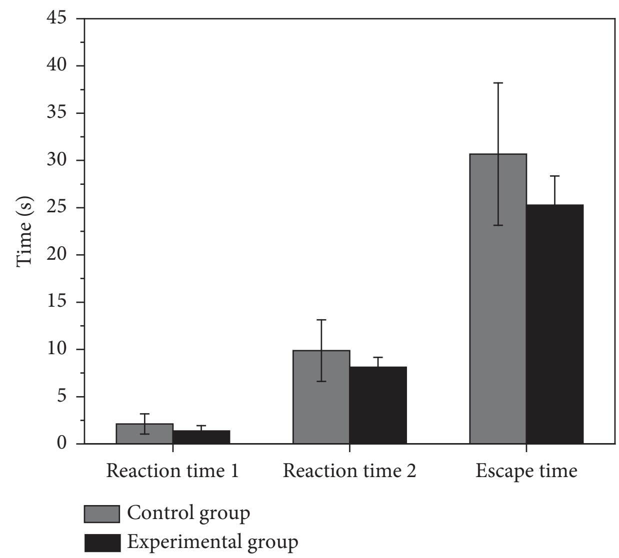


Figure 12: Average time for the control and experimental groups after the VR evacuation experiment. The error bars represent the standard error of the difference between the two groups.

significantly less compared to the escape time of the control group (30.664 ± 7.531), that is, the difference between the two is 5.380 s and $p < 0.05$ (two-tailed test).

Reaction time 1 is the first intuitive reaction of the participants entering the scene. The experimental group is 0.734 s faster compared to the control group. The results of reaction time 2 show that the average reaction time of the experimental group is 1.748 s less compared to the control group, and the experimental group avoids hesitation during decision making. Especially when people are in a state of tension and panic, they subconsciously follow the instructions of a clear escape direction. The final escape time of the experimental group is 5.380 s less than that of the control group, which is 17.5% higher compared to the original setting. The movement speed set in the experiment is constant; therefore, the difference in the escape times is caused by the time to make decisions. The hesitation at each T-junction leads to additional time consumption. Reducing the reaction time can quicken the response in the branch road, avoid congestion, and speed up the escape from the scene. It shows that the improved scheme significantly impacts the reaction and escape times, which greatly improves the escape efficiency: the escape efficiency increases by 17.5% compared to the original evacuation system. Grosshandler et al. found that the heat flow and temperature could be determined by a formula based on exponential growth [32]. The oxygen concentration decreases quickly, and the smoke concentration rises sharply, which can cause death in a short time [33]. Therefore, improving the evacuation efficiency can effectively reduce the physiological injuries to the evacuees and improve the survival rate.

5.4.2. SSSQ Result and Analysis. Four groups of questionnaire data prior to and after the experiment are collected. The final data are obtained by subtracting the score obtained

Table 5: Outputs of sample t-tests of three groups.

	Mean difference	95% confidence interval of difference		t	Significance (two tailed)
		Lower limit	Upper limit		
Reaction time of control group 1−reaction time of experimental group 1	0.734	0.279	1.189	3.440	0.004
Reaction time of control group 2−reaction time of experimental group 2	1.748	0.392	3.105	2.747	0.015
Escape time of control group−Escape time of experimental group	5.380	1.928	8.832	3.322	0.005

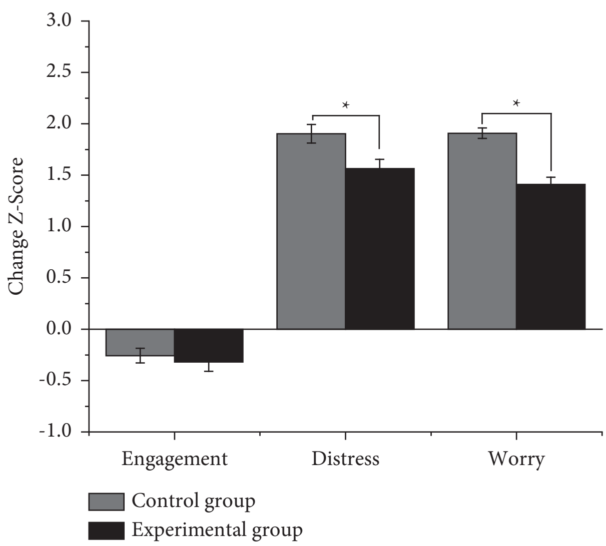


Figure 13: The average score for the control and experimental groups. The error bars represent the standard error of the difference between the two groups. Asterisks denote significant differences between the control and experimental groups. Change Z-score = post-test score−pretest score.

after the experiment from that prior to the experiment. Six groups of data are obtained according to three high-order factors in the questionnaire. All data are imported into SPSS. Six datasets collected from the two groups of experiments are compared, and the relevant sample t-test is performed. The results are shown in Figure 13.

The statistical analysis in Figure 13 shows that the average "Engagement" scores decrease in two groups. The "Engagement" score is -0.26 ± 0.07 (average ± SEM) in the control group, while it is -0.32 ± 0.09 in the experimental group. No significant difference is found between the Engagement scores in the control and experimental groups (t $(18) = 0.529$, $p = (0.605)$, $p > 0.05$). Note that the "Distress" and "Worry" scores of both groups increase after the virtual reality fire experiment. The average "Distress" score of the control group (1.90 ± 0.09) increases more than that of the experimental group (1.56 ± 0.09). The average "Worry" score of the control group (1.91 ± 0.05) increases more than that of the experimental group (1.41 ± 0.07). In the postexperiment interviews, the participants explain that they are the most confused and afraid when facing the choice of fork roads. The evacuation indication system of the experimental group points out a clear direction, alleviating the inner pressure and fear and giving hope. The control group faces a randomly selected branch road during the escape process. It is not known whether the road ahead is safe in the smoke environment; therefore, the whole process is carried out under great pressure. We find a significant difference between the control and experimental groups in terms of SSSQ distress (t $(18) = 2.636$, $p = 0.002$, $p < 0.05$) and SSSQ worry (t $(18) = 5.757$, $p = 0.000$, $p < 0.05$). This means that the evacuation indication system of the experimental group has obvious interactions with the evacuees in the virtual reality fire environment, consequently reducing the pressure on the evacuees.

5.5. Usability Questionnaire Analysis. The SUS is a simple and quick questionnaire used to assess the usability of a specific device or product. It can produce accurate overall results in case of a small dataset. The SUS system availability scale is used to evaluate the availability of the improved fire evacuation system.

The 18 participants of the control group who participated in the verification experiment are required to fill the SUS system availability questionnaire after the completion of the experiment. The final score of the fire evacuation indication system is equal to 86.806 points. Considering the SUS score curve classification range [34], the corresponding level is $A+$, and the overall usability evaluation standard is satisfied.

6. Conclusions

Based on an existing virtual reality simulation experiment, this work investigated the influence of different colors, brightness values, and flicker frequencies on escape efficiency in case of a fire emergency. The main conclusions of this work are as follows:

(1) Green color was the most suitable escape indicator in case of a fire and smoky environment.

(2) Among the brightness levels of 300 cd/m^2, 150 cd/m^2, and 5 cd/m^2 selected in the experiment, the escape efficiency increased with an increase in the brightness. It was the highest when the brightness of the escape indicator was 300 cd/m^2.

(3) Within the identifiable range of human vision, the required escape time became shorter as the flicker frequency increased. The flicker frequency of 30 Hz resulted in the highest escape efficiency.

In addition, the fire evacuation indication system was designed according to the experimental results. The escape efficiency for the improved design and the original factory indication system was compared based on virtual reality verification experiments to verify the effectiveness of the proposed scheme. The experimental results showed that the response and escape times in the improved scheme were reduced by 0.734 s and 5.380 s, respectively, and the overall escape efficiency increased by 17.5%. In addition, the evacuation indication system of the experimental group had obvious interaction with the evacuees in the virtual reality fire, which reduced the stress of the evacuees. The SUS score was *A*+, which met the availability standard.

The results of this work not only provided the designers with a theoretical basis and practical value for building fire evacuation system design but also highlighted the value of virtual reality for collecting human behavioral data during fire incidents. The high effectiveness of the scheme also emphasized the potential of virtual reality in future research.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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