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Influencing Mechanism of Safety Sign Features on Visual Attention of Construction Workers: A Study Based on Eye-Tracking Technology

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Abstract: Visual attention of construction workers is closely related to their safety performance. Identifying and understanding safety signs on workplace effectively is beneficial to improve visual attention. This study focuses on exploring the influencing mechanism of construction safety sign features on visual attention of construction workers using the eye-tracking technology, in order to improve visual attention and workplace safety performance through optimizing the construction safety signs. A theoretical model of influencing mechanism of safety sign features on visual attention was constructed based on visual information processing theory. To verify the theoretical model, an experiment was conducted as follows: 28 pictures of safety signs including visual and cognitive features were shown on the computer screen, then eye movement data from 41 subjects was obtained using EyeLink1000 Plus. Statistical test methods were employed to analyze the relationship between safety sign features and eye-tracking metrics. The statistical results of theoretical model indicate that, among visual features, red and rectangular safety signs can reduce cognitive load of first fixation, green signs can reduce cognitive difficulties, however visual attention is not closely related to auxiliary words. Among the cognitive features, unfamiliar signs require more cognitive effort, while no significant difference exists in visual attention of different levels of concreteness and sematic closeness. This study provides theoretical and practical basis for improving construction workers' visual attention through optimizing visual and cognitive features of construction safety signs.

Keywords: visual attention; construction safety signs; visual features; cognitive features; construction workers; visual information processing; eye-tracking technology

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1. Introduction

The construction industry contributes to 13.2% of the global GDP in 2020 [1]. Despite its contribution to global economic development, the construction industry is one of the most hazardous industries. There are over 60,000 fatalities in the construction industry globally every year, which is much higher than other industries [2]. The number of accidents and casualties in China's construction industry have shown an increasing trend since 2015. There has been 773 accidents and 904 deaths occurred in 2019 [3]. The accidents mainly include falls from a higher level, collapse, struck by objects and crane-related accidents [4]. Improving safety performance is of great significance to sustainable development of the industry.

Safety accidents at workplace are mainly caused by human errors, such as failure to identify risks or lack of concentration, leading to accidents. Construction workers' visual attention is closely related to hazard identification and safety behavior, therefore increasing their visual attention level plays a vital role in improving safety performance [5,6]. Setting safety signs is an important way of on-site safety management, including design elements such as color, signal word, pattern and format. As construction workers pay attention to the contents of safety signs, they can quickly comprehend dangerous information and take protective measures to avoid accidents [7]. Existing studies mainly analyze the effect of construction safety signs' features on visual attention and comprehension. For example, one study focuses on the color, shape and content of construction safety signs, and analyzes the relationship between these features and participants' attention [8]. Other researchers construct construction workers' mindset model in the process of understanding safety signs according to concreteness, ease of visualization, familiarity and content availability of safety signs [9].

Eye tracker is an instrument which tracks the position of personal eyes by infrared light technology and then measures visual indexes such as fixation frequency, fixation time and pupil diameter [10]. Eye-tracking technology has been used in construction safety studies. For example, some researchers use eye tracker to measure the risk identification abilities of construction workers in different experience levels and find that highly experienced workers can quickly identify hazards [11]. One study collects the perceived load tested in different construction scenarios by eye movement equipment, and points out that measures including increasing the distinctiveness of site hazards, increasing on-site brightness and keeping tidy to improve construction safety performance [6]. However, eye-tracking technology has not been applied in the field of construction safety signs. Previous studies analyzed the influence of safety signs' visual or cognitive features on comprehensive level and cognitive load separately. There is a lack of studies that integrate the effect of the above two features on the visual attention of construction workers.

According to visual information processing theory, visual information is converted into neural signals through the brain, and transmitted to neurons through the frontal lobe and occipital brain, so a person can form attitudes, emotions and behaviors towards what they observe [12,13]. This theory has been applied to eye movement research. For example, one study analyzes the effect of thinking aloud protocol on eye movement metrics, cognitive load and retention performance based on this theory [14]. Some researchers use eye-tracking technology to measure the average fixation duration, fixation count and revisits, then analyze the visual information processing behavior of customers in small restaurants [15]. However, studies on the relationship between construction safety signs' features and visual attention are still lacking. Since construction safety signs contain various visual and cognitive elements, this study will explore the influencing mechanism of safety sign features on visual attention of construction workers based on the theory of visual information processing and use eye tracker to collect eye movement indicators.

Theoretically, this study contributes to the metrics of visual features, cognitive features and visual attention on construction safety signs, and analyzes the influencing mechanism of two types of features on visual attention. Moreover, eye-tracking technology is evolutionarily used to collect experimental data in the field of construction safety signs, which contributes to the advancement of visual information processing theory. In practice, construction companies can enable workers to quickly understand safety signs' meaning, perform corresponding safety behavior and improve safety performance in workplace through improving visual and cognitive features of safety signs.

2. Literature Reviews

2.1. Construction Workers' Visual Attention

As the carrier of personal feelings, emotions and behavioral information, eyes can collect and process visual information, therefore enabling people to form visual attention and spatial cognition [16]. Eye-tracking technology is used to collect gaze, fixation and pupil metrics, which reflect people's cognitive load and visual attention [10,17]. Several research efforts have been devoted to exploring the relationships among visual attention, hazard detection abilities and safety behavior. In high cognitive demand work such as decision making and hazard recognition, visual attention reflects individual perceived status and mental load, which is important to improve construction safety management [5,18]. Area of Interest (AOI) should be defined according to visual attention experiments, and optimizing patterns or text content can be employed to improve visual attention on AOI [19,20]. Eye movement process in AOI includes two types: dwelling and transition. Dwelling reflects that eye gazes in an AOI, and transition is a saccade process between different AOIs, therefore, researchers will analyze visual indicators according to different eye movement patterns in AOI [21].

Fixation indicates a state that eyes remain still for a period of time, lasting tens of milliseconds to several seconds, which indicates personal attention on objects [22]. Time to first fixation is an interval from experiment beginning to the first fixation on AOI, people will notice AOI faster when this time is shorter [23]. First fixation duration indicates the time lapse of first fixation on AOI. A long duration implies that visual information is complex, since it is difficult to understand meaning of visual information in a short time [24,25]. For example, the first fixation duration displays the attraction of workplace hazards to construction workers' visual attention, meanwhile, first fixation duration presents their cognition level on safety hazards [26,27]. Fixation metrics reflect people's cognitive load and understanding degree. Complex visual information means more cognitive load, and people needs longer fixation duration and more counts to comprehend its meaning [17]. Specifically, existing research analyzes construction workers' hazard awareness by measuring fixation duration and count, finally proposes suggestions to improve their abilities on detecting workplace dangers [6]. Saccade shows rapid eye movement in different AOIs, it reflects the changes of attention centers. Visual information can only be processed roughly as the saccade time is limited; thus, it is difficult to obtain valuable information [6,28]. A study illuminates that saccade can define the object shape accurately, however, it is difficult to locate its color and shape [29]. Other studies prove that binocular saccade coordination of people with reading difficulties is low. The slow saccade speed makes them unable to recognize visual scenes quickly, so it lowers their reading efficiency [30,31].

In addition to fixation and saccade metrics, other eye-tracking indicators mainly include pupil size and blink counts. Pupil size reflects cognitive status, the size will change with the brightness of environment to adjust the amount of light entering eyes, to be specific, the pupil will enlarge under deep emotions [32]. A study finds that construction workers' pupil size in non-accident group is larger than accident group when they check potential safety hazards, and concentration makes them identify workplace hazards quickly [33]. Blink count shows visual concentration in task implementation. Its count will decrease when the task requires high centralization, however the count will increase as attention is not concentrated enough [34]. Another study finds that fatigue increases construction workers' blink counts and reduces their abilities to identify dangers [35].

To sum up, time to first fixation reflects safety signs' visual attraction to subjects, and first fixation duration shows visual load of subjects' first fixation. Meanwhile, fixation duration and fixation counts illustrate overall cognitive load of subjects. The above indicators can fully reflect short-term and long-term cognitive load of subjects; thus, they are selected as eye movement metrics in this study.

2.2. Construction Safety Signs

Safety signs are composed of color and geometric shape, which convey specific safety information and include three types of prohibition, compulsion and warning (ISO 3864-1 Graphical symbols-Safety colors and safety signs). Vienna Convention on Road Traffic divides safety signs into danger warning, controlling and information delivery, which are represented by triangles, circles, squares or rectangles in turn. Based on Safety Signs and Guideline for the Use, China's safety signs contain red, yellow, blue and green, which convey the message of prohibition, warning, direction and prompt correspondingly. As an approach of safety management, they play a vital role in warning dangers and reducing accidents and casualties [36].

In various fields, safety signs play an important role in reducing unsafe behavior and improving safety performance. For instance, relevant studies find that shape, color, symbol and text of safety signs affect people's cognition, hence they can drive safely through understanding information meaning [37–39]. A study from mining safety signs shows that visual attention in various locations is significantly different, and this study suggests that setting safety signs reasonably can prevent coal mining accidents effectively [40]. Other researchers focus on safety signs' cognitive characteristics, make people guess their meaning and score them. The results present that familiar, concrete, simple, meaningful and semantic-closed safety signs are easier for people to understand meanings [41]. Another study on industrial safety signs exhibits that cognitive features of signs are closely related to their comprehensibility, it proposes that education and training will help people understand signs' meaning [42].

As an important safety measure on-site, construction safety signs convey warning information to construction workers and reduce their occupational risks and injury accidents [9,43]. However, the number of on-site safety signs is not sufficient, and they are not posted appropriately in dangerous areas. Moreover, the deterioration of safety signs makes it worse, since their colors cannot meet the standard requirements, and makes it difficult for construction workers to identify potential safety hazards on workplace [44,45]. To make full use of the warning and prompt, existing studies on construction safety signs mainly concentrate on their visual or cognitive features to propose optimization measures. In terms of visual features, a study compares safety signs optimization before and after, and finds that patterns and explanatory words enhance construction workers' comprehension [46]. Another study compares construction safety signs' color standard in different countries, it finds that blue color should be reduced in workplace so as to ensure that aging workers can identify safety signs effectively [47]. Some researchers conduct an experiment on the characteristics of safety signs, response time and counting accuracy, the results show that red and graphic content help construction workers identify and understand signs' meaning quickly [8]. In a study of cognitive features, the researchers ask the construction workers to draw safety signs to exhibit that their education level and spatial imagery preference effect safety sign redesign, moreover, the more specific the signs are, the easier they are to be redesigned [48]. Furthermore, a mindset model for construction workers on understanding safety signs is established. The results present that concreteness, ease of visualization, familiarity and context availability can affect their mindset, meanwhile, construction workers with high visual imagery vividness are easier to understand meaning of abstract signs [9].

Previous studies on construction safety signs mainly analyze the relationship between visual or cognitive features and construction workers' comprehensibility. Specifically, visual features include color, shape, content and text; cognitive features contain concreteness, familiarity and semantic closeness. The number of studies on construction safety signs has increased in recent years, however, the number of research in the construction industry is still lower than other sectors such as transportation, public environment and occupational health [36]. Moreover, existing studies focus on visual or cognitive features separately, the effect between the above two features on construction workers' visual attention is neglected.

2.3. Construction Safety Signs and Eye-Tracking Experiment

According to visual information processing theory, people will form self-cognition through guessing internal structure and functional composition of things and others' behavior [49]. Visual information will be sent to the end-stopped neurons in visual cortex, and information processing system can be formed through deconstruction and reconstruction of PB neurons, which results in meaningful behavior [50,51]. Studies have shown that parietal lobe has the function of combining color shape features, fusiform and inferior temporal gyri can process visual information and form cognition [52]. Recent studies demonstrate that people can capture and acquire visual information retinal sampling and cortical magnification [53]. Perceptive visual information influences personal attitudes, as the improvement of information quality, it will make positive effect such as enhancing decision reliability, improving attention and making positive feedback [13,15,54].

Based on visual information processing theory, when people observe an object, its characteristics are mapped to cerebral cortex through the interaction between neurons. The processing of information in brain tissues makes them recognize objects and form emotions, attitudes and behavior. At present, this theory has been applied in several fields such as marketing, education and biology. For example, a study on consumers shows that products' color, shape, size and text attributes will influence personal visual perception and behavior, and it is a top-down process [55]. Meanwhile, researchers from education filed find that thinking-aloud protocols can improve visual processing of text information, and increase the effect of understanding and applied learning [14]. One biological study presents that alcohol disrupts protein fiber pathway and causes defects in visual information processing [12]. Another study finds that lack of sleep reduces personal visual information processing rate and loses selective attention, the decline of cognitive control efficiency makes them more prone to cognitive errors [56,57].

Eye-tracking technology is an experimental method that uses cameras and infrared illuminators to track people's eye movements, collect metrics including gaze position, fixation time and pupil size, it can also analyze visual information acquisition process, attention level, emotional state and subsequent behavior [58]. With the popularity of eye-tracking technology, the number of eye-tracking experiment in construction area is increasing. For instance, a study chooses workplace safety hazards as eye movement experiment materials, the results demonstrate that construction workers with over ten-year working experience and injury exposure experience can identify safety hazards accurately and comprehensively [26]. Further research collects eye-tracking indicators of on-site construction workers and finds that workers with high situational awareness pay more attention to tripping hazards [59]. Additionally, work experience can improve hazard identification abilities of construction safety supervisors, therefore inexperienced supervisors should be provided with safety education and training [60].

Safety signs can help people pay attention to potential hazards and effectively reduce workplace dangers. Therefore, it is crucial for personal safety to understand signs' meaning correctly [61,62]. However, existing eye-tracking studies mainly focus on traffic signs, there is a lack of studies on construction safety signs. For instance, one study shows that once the amount of guide sign information exceeds the threshold, it will increase drivers' cognitive load [63]. Another research based on eye movement experiment finds that with the increase of signs' information and cognitive strangeness, and longer gazing time is adverse to safety driving [38]. Hence, directional signs on highway should not contain much information, and single-board signs can be used to reduce drivers' visual workload [37]. Meanwhile, improved traffic signs enable drivers to pay more attention to relative information timely, and they can slow down and brake [64].

Construction safety signs are one of the most vital safety protection measures on workplace, identifying and understanding safety signs will reduce unsafe behavior of construction workers effectively. Recent studies on construction safety signs have used empirical methods such as questionnaires, case studies and semi-structured interviews to collect subjective research data, however, eye-tracking technology, EEG and other experimental methods have not been fully used to gather objective data. Since construction safety signs are consisted of visual and cognitive features, construction workers will form corresponding cognition through the processing of brain visual nerve when they note the visual information conveyed by these signs. Eye-tracking technology can collect eye movement metrics and objectively analyze the relationship between safety signs' features and construction workers' visual attention, which provides a more scientific basis for optimizing construction safety signs [65]. Hence, this paper will collect eye movement indicators including time to first fixation, first fixation duration, fixation duration and fixation count [5]. Based on the research of Chen et al. [8] and Chan and Ng [66], this study will explore the influencing mechanism of construction safety signs' visual and cognitive features on visual attention through eye-tracking technology. A theoretical model is constructed based on the following hypotheses:

H1. *Significant differences exist between eye movement metrics of different construction safety signs' colors.*

H2. *Significant differences exist between eye movement metrics of different construction safety signs' shapes.*

H3. *Significant differences exist between eye movement metrics of construction safety sign with or without auxiliary words.*

H4. *Significant differences exist between eye movement metrics of construction safety signs with different level of familiarity.*

H5. *Significant differences exist between eye movement metrics of construction safety signs with different level of concreteness.*

H6. *Significant differences exist between eye movement metrics of construction safety signs with different level of sematic closeness.*

3. Research Methodology

As shown in Figure 1, the research process was divided into three parts including material selection, data collection and analysis. This study firstly selected 28 pictures according to the visual and cognitive features of construction safety signs. Secondly, 41 participants' eye movement data was collected by eye-tracking technology. Finally, statistical analysis methods were used to test research hypotheses and explore the influencing mechanism of safety sign features on construction workers' visual attention.

3.1. Experimental Materials

104 pictures of construction safety signs were totally collected in this study, considering that wearing safety helmet is a common measure on workplace, which is of great significance to reduce on-site safety accidents. Through on-site survey and expert consultation, "Must Wear Safety Helmet" was finally selected as the original experiment material. Based on the Safety Signs and Guideline for the Use, construction safety signs contain four colors including red, yellow, blue and green, three shapes including rectangle, triangle and circular and two types including with and without auxiliary words. Thus, according to the above regulations in the Safety Signs and Guideline for the Use, colors of original picture material were set to red, yellow, blue and green, the shapes were set to rectangle, triangle and circular, as well as with and without auxiliary words.

The cognitive features of construction safety signs were based on the safety signs' cognitive model established by Chan and Ng [67]. Familiarity, concreteness and semantic closeness were selected as cognitive features in this study. Familiarity referred to the frequency of on-site safety signs, which can be divided into familiar and unfamiliar signs according to the frequency. Concreteness referred to the similarity between the content of safety signs and actual objects, which can be divided into concrete and abstract signs according to the similarity. Semantic closeness referred to the proximity between auxiliary words and signs' content, which can be divided into semantic proximity and deviation signs according to the proximity.

According to the concept of familiarity proposed by Chan and Ng [67], after counting the frequency of different construction safety signs appearing in 104 photos, "No Drinking", "Pay Attention to Safety" and "Must Wear Safety Helmet" showed the highest frequency in the above photos, while the frequency of "No Closing Gate", "Beware of Explosion" and "Must Hold Certificates" was the lowest. Thus, this study selected "No Drinking", "No Closing Gate", "Pay Attention to Safety", "Beware of Explosion", "Must Wear Safety Helmet" and "Must Hold Certificates" as two groups of safety signs with different level of familiarity. Likert five-point questionnaire was used to evaluate the level of concreteness and semantic closeness in safety signs (from 1 = ”lowest level” to 5 = ”highest level”), the questionnaires were sent to 15 managers through paper form and online platform such as e-mail. They all had obtained a bachelor’s or master’s degree in civil engineering or engineering management, and they had at least 5 years on-site construction working experience. Then the evaluation results of concreteness and semantic closeness of 29 safety signs were collected. Finally, two groups of safety signs with different level of concreteness were selected, including “No smoking”, “No Stocking”, “Beware of Hole” and “Mind Your Head”. And two groups of safety signs with different level of semantic closeness were selected, including “No Smoking”, “No Drinking”, “Caution Hanging” and “Caution Injure Hand”.

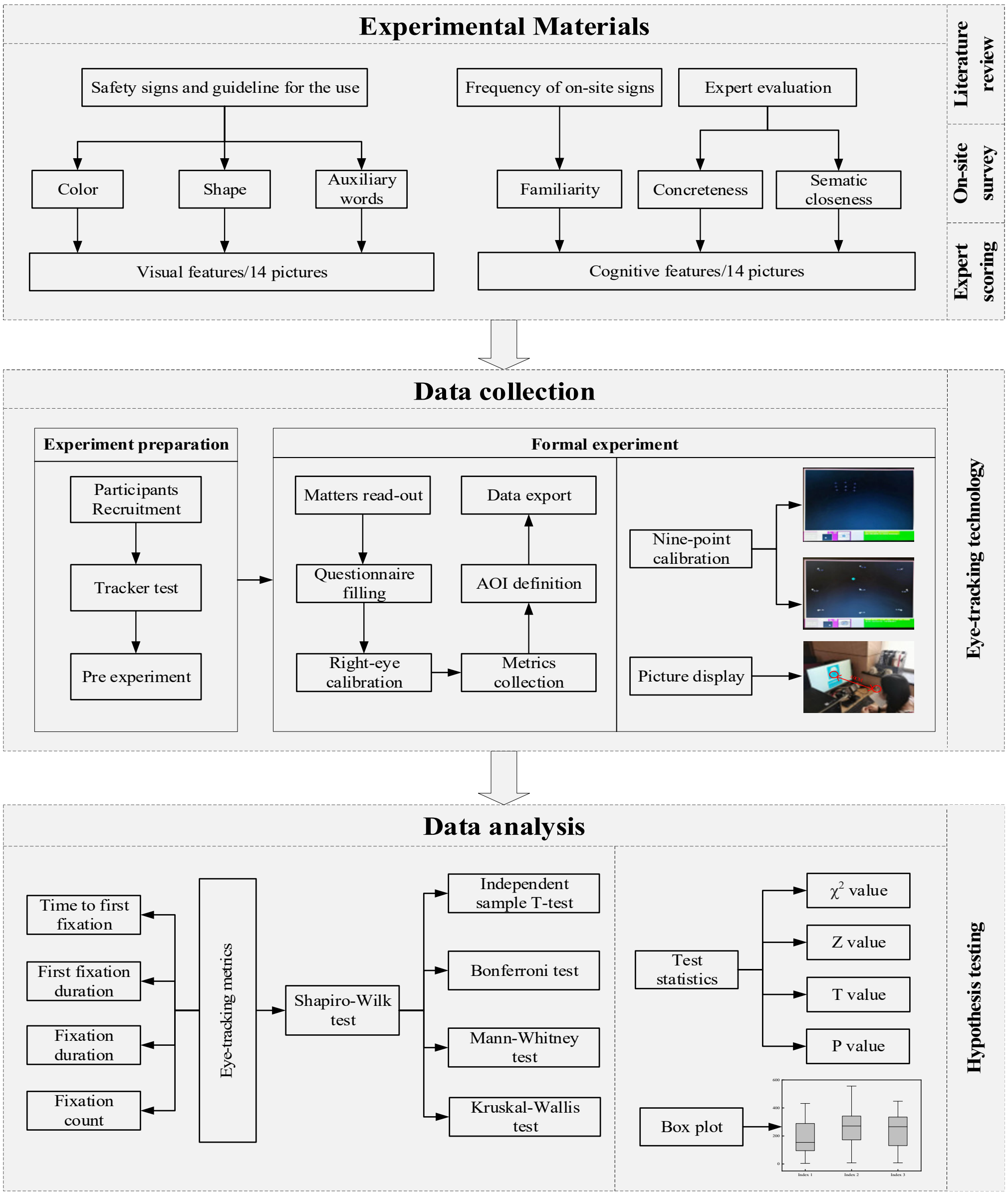
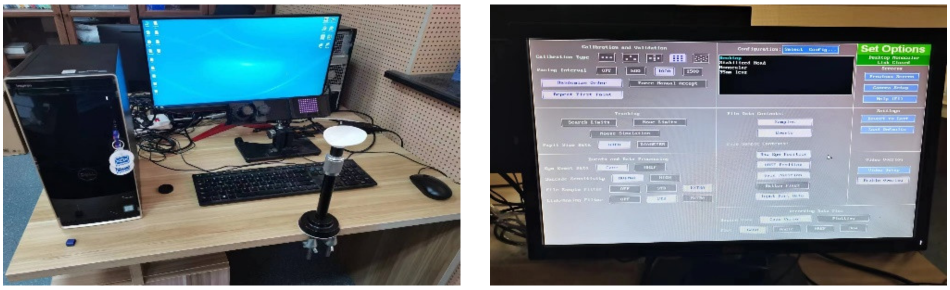


Figure 1. Flow chart of eye-tracking experiment.

3.2. Data Collection

The Eyelink 1000 Plus (SR Research Ltd. in Ottawa, Canada) used in this study was an eye tracker produced by Canadian SR Research company. It had a binocular sampling rate of 2000 Hz and could record both eyes’ movement speed at 2000 frames per second. The measurement accuracy can be controlled within 0.15° [68]. Figure 2a showed an Eyelink

1000 Plus connected to a computer, which can display the selected pictures to the participants and collect eye movement indicators. In Figure 2b, an experimental host was used to set parameters of the eye tracker, calibrate eyes and control the experimental process.



(**a**) Display PC (**b**) Host PC

Figure 2. Eyelink 1000 Plus.

The chin bracket was set up to hold the participant's head position and reduce fatigue, which can also reduce missing and erroneous data caused by head movement during the experiment. The participants recruited in this study were all students with civil engineering background. And they were selected with similar demographic characteristics to control experimental errors. Dzeng et al. [11] compared the differences between experienced and novice workers in hazard identification through eye tracker, they recruited 10 experienced construction management with 5 years work experience and 6 h of formal safety training per year, and 15 graduate students from construction engineering and management without work and training experience. The construction management and graduate students respectively represented experienced and novice construction workers, the results showed that search patterns between the above two groups were similar. It indicated that university students could stimulate novice construction workers. Considering that this was a bottom-up study, thus, homogeneity of university students could reduce demographic and experiential bias [69]. On the one hand, university students acquired the knowledge in the field of civil engineering, their demographic characteristics including age, education level, working experience and safety knowledge level had little differences. On the other hand, many researchers recruited university students to participate in eye movement experiment in the area of construction safety. For example, one study recruited students from civil engineering and construction management to participate in eye movement experiments, as construction workers' hazard recognition performance would be affected by demographic factors while students from the same background were more suitable to participate in the experiment, thus they were required to identify potential safety hazards in different construction scenarios [6]. Another research selected 32 students majoring in architecture and engineering to participate in the eye movement experiment, after receiving relevant safety training, their eye movement parameters were collected in virtual construction environment [33].

In this study, 28 construction safety signs with visual and cognitive features were selected as eye movement experiment materials, each pictures included 10 s display time and 5 s interval time. 5 students participated in a pilot experiment, we found that they all understood the information conveyed by construction safety signs and had physical abilities to complete this experiment. Based on the experiment results, the researchers adjusted the distance between eye tracker and participants, and changed position and height of eye tracker to ensure that the device can collect eye movement data precisely. Subsequently, after knowing that all the subjects participate in the experiment voluntarily, the researchers promised that all experiment data from subjects would be private and anonymous, and the data was only used for academic research. They were asked to have a good rest the day before eye movement experiment and avoided fatigue, stress and drinking alcohol. Participants' vision or corrected vision was normal, they had no astigmatism, strabismus or color blindness. The formal experiment was conducted in the laboratory environment. Temperature, brightness and noise factors were controlled to minimize the impact of environment. Firstly, this experiment was conducted in a comfortable and constant temperature. Then, the indoor brightness was adjusted to the minimum to highlight the construction safety signs on the computer screen. Finally, only one subject was allowed in the laboratory in each eye movement experiment, while others were forbidden to speak as to reduce noise. The formal experiment steps were as follows: (1) Researchers read out experiment contents and precautions, to be specific, the researchers firstly welcomed and thanked to all the subjects; then, experimental materials and process were introduced to all of them, the researchers clearly explained three cognitive features including familiarity, concreteness and sematic closeness to all the participants; finally, they were asked to observe 28 construction safety signs' pictures appearing on the computer screen and thought about the visual and cognitive differences of these pictures; (2) Participants filled in the demographic characteristics scale including the information of age, gender, major, the level of safety knowledge and working experience; (3) Researchers adjusted the height of chin bracket and calibrated the right eye; (4) Eye tracker were used to collect eye-tracking metrics; (5) Participants were given gifts or 30 yuan after the end of experiment; (6) Areas of interest were determined to derive eye movement metrics.

After removing the incomplete and abnormal eye movement data, 41 valid samples were received. Pernice & Nielsen [70] believed that appropriate sample size for eye movement experiment ranged from 6 for qualitative research to 30 for quantitative research. Furthermore, one study used eye tracker to collect data from 27 construction workers, another study obtained visual attention indicators from 12 participants through eye-tracking technology [26,35]. Therefore, sample size in this study was scientific and reasonable. The results of scale presented that all of the participants had good health and mobility abilities. Specifically, all the samples ranged from 20 to 30 years old, and they can be divided into 23 males and 18 females, 11 undergraduates and 30 postgraduates. 28 students majored in engineering management, 9 students majored in civil engineering and 4 students were from other disciplines. Most of them had studied the course of construction safety, and they had internship and formal work experience on construction workplace.

3.3. Data Analysis

Considering that hypotheses proposed in the theoretical model were whether significant differences existed in the visual attention of construction safety signs' visual and cognitive features, thus parametric and non-parametric tests were used to analyze the above data. SPSS24.0 (IBM Corporation in Armonk, NY, USA) was used to test significant differences in eye movement indicators and analyze the influencing mechanism between safety sign features on visual attention of construction workers. Since the number of experimental samples was less than 50, Shapiro-Wilk method was used to test the normality of samples. When the p value was greater than 0.05, it demonstrated that the sample followed a normal distribution [71]. The parameter test was used to analyze significant differences between eye movement data. Independent sample T-test was used for 2 groups of sample data, and Bonferroni test was used when sample data were 3 groups and more [72,73]. Nonparametric test was used to analyze significant differences between non-normal eye movement data. Mann-Whitney test was used for 2 groups of sample data, and Kruskal-Wallis test was used when sample data were 3 groups or more [74,75].

4. Results

4.1. Visual Attention of Construction Safety Signs with Different Visual Features

4.1.1. Colors

In the theoretical model, the impact of construction safety signs' colors on eye movement metrics was verified. Shapiro-Wilk method was used to test normality of sample data. The p values of Time to First Fixation (TFF), First Fixation Duration (FFD), Fixation Duration (FD) and Fixation Count (FC) were less than 0.05, which indicated that all visual attention indicators were not normally distributed. Therefore, Kruskal-Wallis method was used for nonparametric test. As shown in Table 1, there were no significant differences in TFF of different colors' construction safety signs ($\chi^2 = 1.818$, $p = 0.552 > 0.05$). But there were significant differences in FFD, FD and FC ($\chi^2 = 7.317$, $p = 0.015 < 0.05$; $\chi^2 = 12.000$, $p = 0.019 < 0.05$; $\chi^2 = 34.847$, $p = 0.000 < 0.001$). Thus, hypothesis 1 was supported as significant differences existed in three eye movement indicators of different construction safety signs' colors.

Table 1. Eye-tracking metrics in construction safety signs with different colors (N = 41).

Variables	**TFF (ms)**		**FFD (ms)**		**FD (ms)**		**FC**	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Red	107.25	163.15	211.48	127.95	7946.88	694.09	32.55	5.57
Yellow	86.28	134.18	259.90	150.49	7968.94	966.29	26.51	6.61
Blue	86.78	158.44	297.27	272.00	7869.61	848.20	26.75	8.48
Green	72.70	117.24	323.87	519.96	7693.94	1164.33	27.11	8.14
Test statistics	1.818		7.317		12.000		34.847	
p	0.552		0.015 *		0.019 *		0.000 ***	

Note: TFF = Time to First Fixation, FFD = First Fixation Duration, FD = Fixation Duration, FC = Fixation Count, SD = Standard Deviation, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Further studies showed that FFD in red signs and blue signs was significantly different ($p = 0.023 < 0.05$). Figure 3 was a box plot of FFD in different colors, the median of FFD in red signs was 184 ms and the median in blue signs was 272 ms. The FFD of red signs was significantly lower than blue signs. It indicated that red signs could reduce the visual load of first fixation. FD was significantly different between yellow and green signs ($p = 0.017 < 0.05$). Figure 4 was a box plot of FD in different colors, the median of FD in yellow signs was 8142 ms and the median in green signs was 7752 ms, which indicated that green signs could significantly reduce overall cognitive load. FC in red was significantly different from yellow, blue and green ($p = 0.000 < 0.05$). In Figure 5, the box plot showed that the median of FC in red signs was 33.00 while the median in green signs was 28.00, which indicated that green signs can significantly reduce visual load and it was consistent with test results of FD.

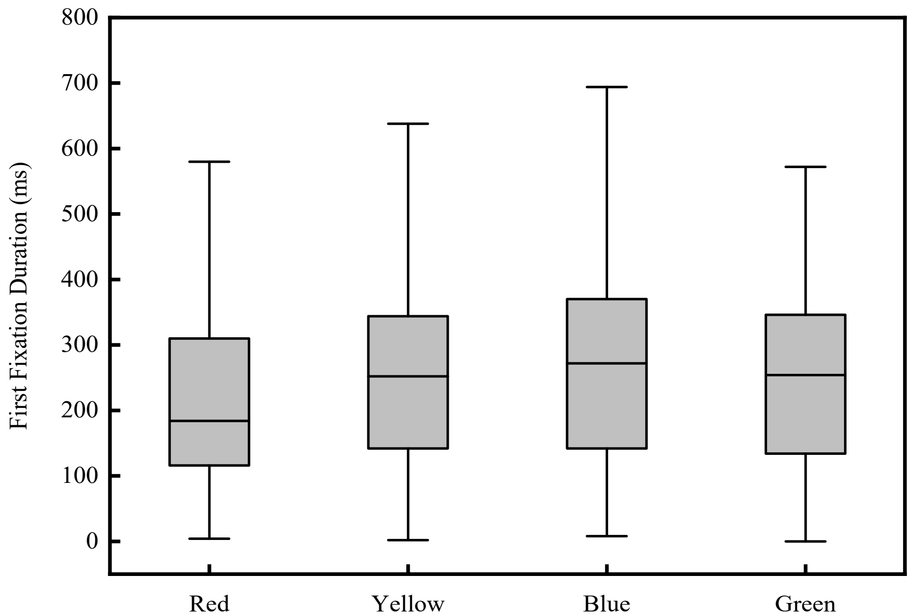


Figure 3. Box plot of construction safety signs' first fixation duration in different colors.

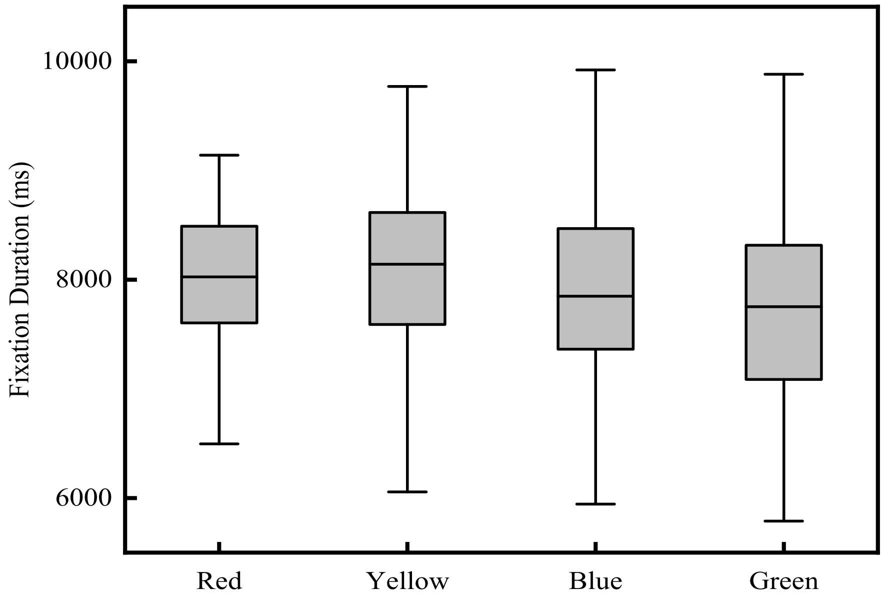


Figure 4. Box plot of construction safety signs' fixation duration in different colors.

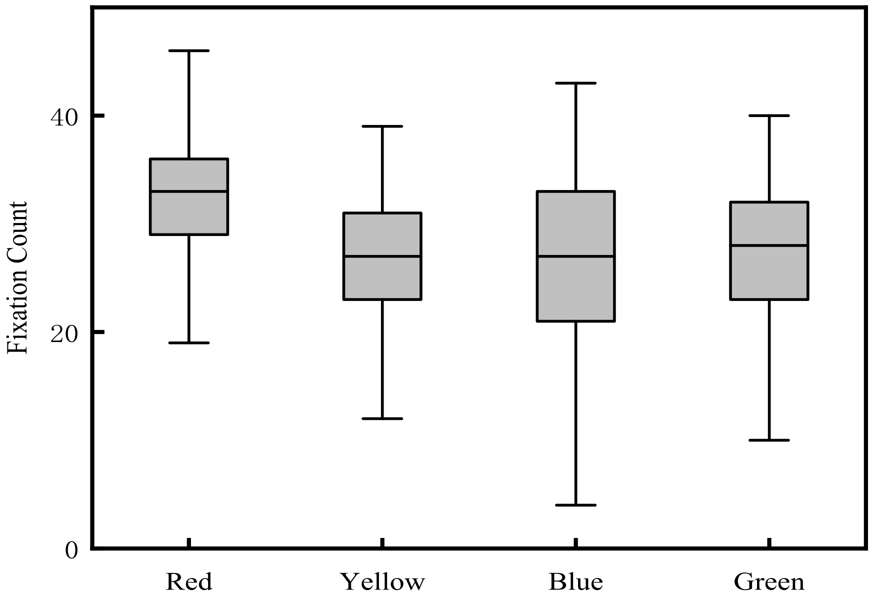


Figure 5. Box plot of construction safety signs' fixation count in different colors.

4.1.2. Shapes

The relationship between construction safety signs' shapes and eye movement data in the theoretical model was tested. According to the Shapiro-Wilk test, the p values of TFF, FFD, FD and FC of construction safety signs of different shapes were less than 0.05, thus the visual attention did not follow the normal distribution. The Kruskal-Wallis nonparametric test results were shown in Table 2. FFD existed significant differences in different construction safety signs' shapes ($\chi^2 = 4.537$, $p = 0.024 < 0.05$), so hypothesis 2 was supported. Moreover, FFD of rectangular and circular signs was significantly different ($p = 0.031 < 0.05$), Figure 6 showed that the median of rectangular signs was 222 ms and the median of circular signs was 279 ms, which indicated that rectangular signs reduced the cognitive load of first fixation. No significant differences existed in FD from different shape safety signs, but the median of rectangular signs was 7905 ms, while the median of triangular and circular signs were 8033 and 8043 ms respectively, which indicated that rectangular signs may reduce overall cognitive load.

Table 2. Eye-tracking metrics in construction safety signs with different shapes (N = 41).

Variables	TFF (ms)		FFD (ms)		FD (ms)		FC	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Rectangle	106.32	159.87	246.74	200.00	7819.74	885.48	29.07	7.40
Triangle	84.56	130.93	274.22	436.00	7871.59	1048.45	28.02	7.69
Circular	73.88	140.29	298.43	246.73	7918.20	871.57	27.60	8.00
Test statistics	3.413		4.537		2.390		2.103	
p	0.148		0.024 *		0.584		0.286	

Note: TFF = Time to First Fixation, FFD = First Fixation Duration, FD = Fixation Duration, FC = Fixation Count, SD = Standard Deviation, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

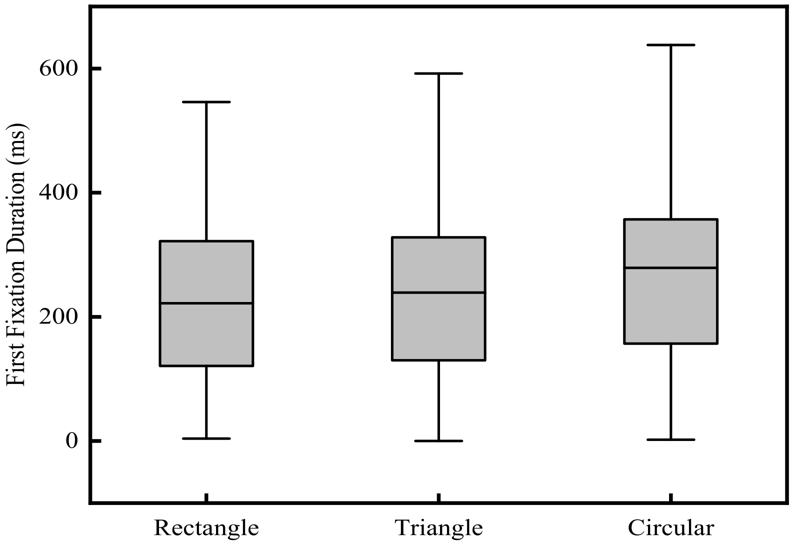


Figure 6. Box plot of construction safety signs' first fixation duration in different shapes.

4.1.3. Auxiliary Words

The hypothesis of the effect of auxiliary words on visual attention proposed in the theoretical model was analyzed. According to the results of Shapiro-Wilk test, *p* values of TFF and FFD were less than 0.05, and *p* values of FD and FC were greater than 0.05. Therefore, Mann-Whitney nonparametric test was used for TFF and FFD, independent sample T-test was used for FD and FC. As shown in Table 3, there were no significant differences between TFF and FFD in auxiliary words ($Z = -0.230$, $p = 0.818 > 0.05$; $Z = -1.118$, $p = 0.264 > 0.05$). But the median of FFD was 286 ms in signs with auxiliary words and 294 ms in signs without auxiliary words, which indicated that auxiliary words may reduce the cognitive difficulty of first fixation. There were no significant differences between FD and FC in auxiliary words ($t = -1.601$, $p = 0.113 > 0.05$; $t = -1.695$, $p = 0.094 > 0.05$). Therefore, hypothesis 3 was not supported. But FD and FC of construction signs without auxiliary words were significantly lower, which indicated that auxiliary words may increase the overall visual burden.

Table 3. Eye-tracking metrics in construction safety signs with and without auxiliary words (N = 41).

Variables	TFF (ms)		FFD (ms)		FD (ms)		FC	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Without auxiliary words	122.88	247.35	367.80	367.67	7167.80	1132.92	24.71	6.69
With auxiliary words	67.02	114.19	258.10	124.57	7541.17	973.05	27.15	6.33
Test statistics	−0.230		−1.118		−1.601		−1.695	
p	0.818		0.264		0.113		0.094	

Note: TFF = Time to First Fixation, FFD = First Fixation Duration, FD = Fixation Duration, FC = Fixation Count, SD = Standard Deviation, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

4.2. Visual Attention of Cosntruction Safety Signs with Different Cognitive Features

4.2.1. Familiarity

The verified results of the relationship between construction safety signs' familiarity and visual attention proposed in the theoretical model were as follows. According to Shapiro-Wilk test, p values of TFF, FFD and FC were less than 0.05, and p value of FD was more than 0.05. Therefore, Mann-Whitney nonparametric test was applied to TFF, FFD and FC, and independent sample T-test was applied to FD. Table 4 showed that there were no significant differences between TFF and FFD of construction safety signs in different familiarity levels (Z = −0.586, p = 0.558 > 0.05; Z = −0.019, p = 0.985 > 0.05), while FC was significantly different (Z = −3.469, p = 0.001 < 0.01). As shown in Figure 7, It was a box plot of FC index of familiar and unfamiliar safety signs, in which the median of familiar signs was 29 and unfamiliar signs was 33. It showed that familiar safety signs can reduce cognitive load. The results of FD showed that there was no significant difference in safety signs of different level of familiarity (t = −1.838, p = 0.067 > 0.05). But the mean of FD in familiar signs was 7638.13 ms and the mean in unfamiliar signs was 7821.94 ms, which also indicated that familiar signs could reduce the overall cognitive difficulties. Thus, hypothesis 4 was supported as significant differences existed in one eye movement indicator of construction safety signs with different level of familiarity.

Table 4. Eye-tracking metrics in construction safety signs with different level of familiarity (N = 41).

Variables	TFF (ms)		FFD (ms)		FD (ms)		FC	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Familiarity	78.89	142.30	222.73	135.08	7638.13	855.00	29.61	6.30
Unfamiliarity	75.50	123.91	215.76	114.68	7821.94	706.71	32.08	6.25
Test statistics	−0.586		−0.019		−1.838		−3.469	
p	0.558		0.985		0.067		0.001 **	

Note: TFF = Time to First Fixation, FFD = First Fixation Duration, FD = Fixation Duration, FC = Fixation Count, SD = Standard Deviation, * p < 0.05, ** p < 0.01, *** p < 0.001.

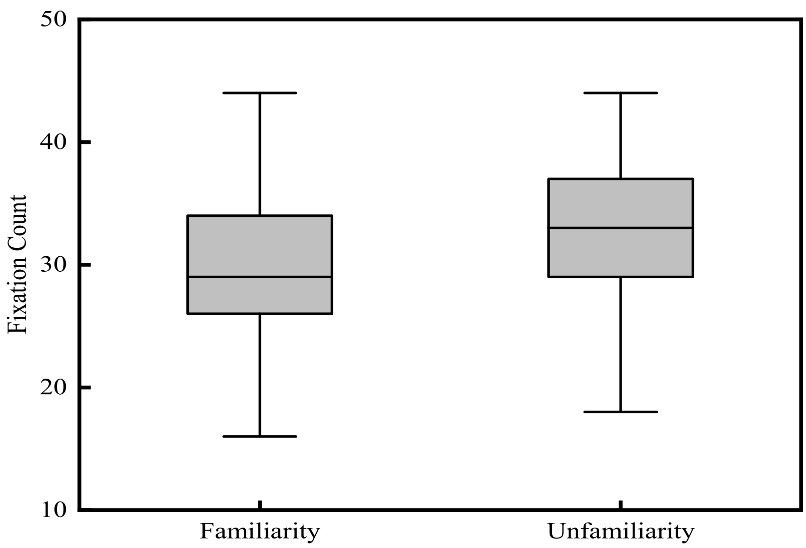


Figure 7. Box plot of construction safety signs' fixation count in different level of familiarity.

4.2.2. Concreteness

The effect of construction safety signs' concreteness on visual attention in the theoretical model was tested. The results of Shapiro-Wilk test showed that p values of TFF, FFD and FC were less than 0.05. Therefore, Mann-Whitney nonparametric test was used for TFF, FFD and FC. The p value of FD was greater than 0.05, and independent sample T-test was used for FD. As shown in Table 5, there was no significant difference in construction safety signs between TFF, FFD and FC in different familiarity levels (Z = −0.658, p = 0.511 > 0.05; Z = −0.016, p = 0.987 > 0.05; Z = −0.466, p = 0.641 > 0.05). And there was no significant difference in FD (t = 0.383, p = 0.702 > 0.05). It indicated that different level of concreteness in safety signs did not influence cognitive burden. Thus, hypothesis 5 was not supported.

Table 5. Eye-tracking metrics in construction safety signs with different level of concreteness (N = 41).

Variables	TFF (ms)		FFD (ms)		FD (ms)		FC	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Concreteness	98.39	192.86	227.34	112.95	7788.71	862.43	28.33	5.89
Abstractness	91.39	186.63	240.78	194.23	7736.27	889.50	27.70	6.06
Test statistics	−0.658		−0.016		0.383		−0.466	
p	0.511		0.987		0.702		0.641	

Note: TFF = Time to First Fixation, FFD = First Fixation Duration, FD = Fixation Duration, FC = Fixation Count, SD = Standard Deviation, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

4.2.3. Sematic Closeness

The relationship between construction safety signs' sematic closeness and eye movement parameter in the theoretical model was verified. The results of Shapiro-Wilk test showed that p values of TFF, FFD, FD and FC were all less than 0.05, so Mann-Whitney non-parametric test was used. As shown in Table 6, there were no significant differences between TFF, FFD, FD and FC in different level of semantics closeness (Z = −0.429, p = 0.668 > 0.05; Z = −1.018, p = 0.309 > 0.05; Z = −1.288, p = 0.198 > 0.05; Z = −0.631, p = 0.528 > 0.05). It indicated that different level of semantic closeness of construction safety signs did not affect cognitive load. Thus, hypothesis 6 was not supported. In FFD, the median of the semantic closeness signs was 228 ms and the median of semantic deviation signs was 245 ms. With the increase of sematic closeness, the cognitive load of first fixation may decrease. Meanwhile, the median of semantic proximity signs in FD was 7718 ms and the median of semantic deviation signs was 7976 ms, which indicated that the safety signs of semantic proximity may reduce the overall cognitive burden.

Table 6. Eye-tracking metrics in construction safety signs with different level of sematic closeness (N = 41).

Variables	TFF (ms)		FFD (ms)		FD (ms)		FC	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Sematic closeness	88.83	145.01	237.78	232.42	7622.78	1057.50	27.61	7.57
Sematic deviation	102.61	205.88	231.90	114.40	7822.63	904.63	28.68	5.20
Test statistics	−0.429		−1.018		−1.288		−0.631	
p	0.668		0.309		0.198		0.528	

Note: TFF = Time to First Fixation, FFD = First Fixation Duration, FD = Fixation Duration, FC = Fixation Count, SD = Standard Deviation, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

5. Discussions

5.1. The Relationship between Construction Safety Signs' Visual Features and Visual Attention

This study finds that the time to first fixation of red construction safety signs is the shortest, thus red color significantly reduces visual load of personal first fixation. This is consistent with the research results from Chen et al. [8], which proves red safety signs are easier to be recognized and noticed by people. Red color can convey prohibition and warning messages, and it is used in road safety signs and traffic signs to attract attention [76,77]. Compared with other colors such as yellow, blue and green, red safety signs make people notice potential safety hazards more quickly. Therefore, red signs are mainly used in dangerous areas at workplace, so that construction workers can take protective measures to prevent accidents. The fixation duration of green construction safety signs is shortest, which indicates that green color can reduce overall cognitive load, this is supported by the research of Rana et al. [78]. The brain will generate more stimuli especially in the sympathetic nervous system after observing green color, thus people can maintain concentration status [79,80]. Green color can reduce personal visual fatigue, people can continue reading without fatigue under green and white light conditions [81,82]. Another study presents that green and black safety signs improve subjects' searching efficiency and reduce their cognitive load, thus should be used in evacuation [83]. Green safety signs are mainly used at workplace safety exits and emergency shelters, they can alleviate construction workers' anxiety and uneasiness, and help workers follow the guidance to avoid dangers.

The first fixation duration of rectangular construction safety signs is the shortest, it exhibits that rectangular signs can reduce cognitive load on first fixation. A study on marketing shows that consumer initial attention is significantly different in different commodity shapes, specifically, high slim commodities can attract consumers' following attention and form purchasing behavior [84]. This result is coinciding with the research of Martín-Santana and Beerli-Palacio [85], which finds that rectangular advertisements improve recognition, so people can effectively identify brand advertisements and generate positive attitudes. Circular safety signs play the role of prohibition and information, and triangular signs play the role of warning. Compared with the above two safety signs, rectangular signs can remind construction workers to take safety measures and avoid hazards, they can convey safety information intuitively and clearly. Additionally, these signs play the role of advising, which can reduce psychological load compared with prohibition and warning signs, hence, the workers can understand their meanings quickly.

Although no significant differences exist in visual attention between auxiliary words, the means of fixation duration and fixation count in construction safety signs with auxiliary words are higher than those without words, which indicates that auxiliary words increase the cognitive load to some extent. As this study is conducted in laboratory environment, factors of realistic construction workplace have not been considered. Moreover, the distance between subjects and computer screen is 40 cm, all participators can observe auxiliary words clearly, which result in no significant differences in safety signs with and without words. Similar studies have found that auxiliary words increase personal cognitive load and lead to distraction. For instance, one study finds that with the increasement of words in roadside advertising signs, the drivers will subconsciously read text content and leads to the decline of driving attention [86]. Meanwhile, compared with safety signs only with patterns, words contain more visual information, so it takes longer time for people to understand their contents [38]. However, harsh working environment and huge pressure make it difficult for construction workers to fully observe and understand the meaning of safety signs with auxiliary words. Moreover, the education levels of most construction workers are lower than college students in this experiment, which would increase their cognitive load, hence they need to spend more fixation duration understanding the meaning of these signs.

5.2. The Relationship between Construction Signs' Cognitive Features and Visual Attention

The results show that fixation count of familiar construction safety signs is significantly shorter than unfamiliar signs, which indicates that the familiarity of safety signs can reduce cognitive load. This is supported by the research of Duarte et al. [87], which shows that people have a wrong understanding of unfamiliar safety signs and designers should redesign signs to improve safety performance. Specifically, people are easy to guess the meaning of familiar safety signs, but they will misread the meaning of unfamiliar signs [67]. Familiar safety signs at workplace appear more frequently, with the increasement of fixation count, construction workers can gradually understand and memorize the meaning of these familiar signs, therefore it is easier for them to visualize the contents of safety signs [9]. Yet familiar safety signs can only indicate that they are common at workplace, excessive elements and details will increase personal visual load [63]. Consequently, the design of construction safety signs should follow simple principles, especially familiar signs should take the visual and cognitive feelings of construction workers into account, to further reduce their cognitive load through optimizing design elements of these signs.

No significant differences exist in visual attention between construction safety signs with different level of concreteness, which indicates that concrete signs cannot reduce cognitive load. As the pattern of safety signs used in this experiment is close to real objects, which helps subjects quickly focus and understand the information conveyed by the safety signs, thus reducing their cognitive difficulties. There are no significant differences existing in eye-tracking metrics in construction safety signs with different level of sematic closeness, but it is noteworthy that the median of first fixation duration and fixation duration in semantic closeness safety signs is lower than that of sematic deviation signs, which implies that sematic closeness signs may reduce cognitive load of first and overall fixation. Existing study has found that sematic closeness in current objects can attract people's visual attention and affect their naming behavior [88]. When the auxiliary words are close to safety signs' pattern, construction workers only need to focus on the text or pattern information to understand the meaning of safety signs. However, if there is a large difference between the text description and the pattern, workers need to pay attention to both the text meaning and signs' pattern, which increases their cognitive load and reduces signs' functions of conveying dangerous information. Accordingly, pattern information of construction safety signs should be consistent with auxiliary words, which is conducive for workers to understand the meanings of safety signs quickly and intuitively [67].

5.3. Research Implications

Theoretically, this study clarifies the influencing mechanism of construction safety sign features on visual attention of construction workers and enriches the application of visual information processing theory in the field of construction safety signs. Based on the design features of construction safety signs established by Chen et al. [8], this study further tests the relationship between safety signs' visual features and eye-tracking metrics and finds that significant differences exist in visual attention of signs with different colors and shapes. To be specific, red color can reduce visual load of first fixation, green color can reduce overall cognitive difficulties, and rectangular signs help workers understand the meaning of signs more quickly. Although there are no significant differences in eye movement data of safety signs with and without auxiliary words, the signs with words increase cognitive load. Meanwhile, this paper analyzes the relationship between the cognitive features of construction safety signs and visual attention. Based on the cognitive model established by Chan and Ng [67], this study finds that familiar safety signs reduce cognitive load. The design of safety signs should follow the principle of simplicity, which is simplifying signs' elements and text information to reduce understanding difficulties of construction workers. Although eye movement indicators of safety signs with different level of concreteness and sematic closeness are not significantly different, signs with sematic closeness can reduce cognitive load of workers to some extent, which is consistent with the results of Chan and Ng [41].

In practice, according to the test results of construction safety signs' visual features, red color and rectangle shape should be used in prohibition and warning signs. Specifically, red is a striking color which can attract construction workers' visual attention and reduce visual load of first fixation. At the same time, rectangle-shape signs help workers understand meanings quickly, which enables them to identify potential safety hazards fast on workplace and improve safety performance. Green color should be applied in instruction and prompt signs, as it can reduce cognitive load and anxiety of construction workers, so they can understand information on signs, implement corresponding instructions and avoid on-site hazards. Although eye-tracking indicators of safety signs with and without auxiliary words are not significantly different, the words in signs need to be concise and clear. For instance, fluorescent paint can be used to ensure that construction workers can notice word information even at night. In dangerous area, text information can be broadcast through voice, so that construction workers can understand signs' meaning clearly and reduce their cognitive difficulties. On the other side, the results of cognitive features indicate that unfamiliar safety signs increase visual load of workers. The management should hold safety education and training regularly to popularize the meaning of safety signs. Moreover, designers can design safety signs from the perspective of construction workers and simplify elements to avoid their complication. Eye movement data of safety signs with different levels of concreteness and sematic closeness are not significantly different, nevertheless, the signs should be as close to real objects as possible in the design process to improve the level of concreteness. Meanwhile, auxiliary words should be consistent with signs' patterns, which means that graphic information irrelevant to the words need to be eliminated, so workers will understand the meaning of safety signs according to the words or pattern.

To sum up, this study contributes to the index system of visual features, cognitive features and visual attention in construction safety signs, it establishes a theoretical model between the features of safety signs and construction workers' visual attention, the influencing mechanism between safety sign's features and visual attention is also revealed. Meanwhile, this research firstly uses eye-tracking technology to collect visual attention indicators in the field of construction safety signs, which expands the research scope of eye movement experiment in this area. Finally, improving measures on construction safety signs' visual and cognitive features are proposed in this paper, which provides practical support to reduce construction workers' cognitive difficulties to improve safety performance at workplace.

5.4. Limitations and Future Research

This research still has several limitations. Firstly, eye movement experiments are conducted in laboratory settings, which is different from actual environment in workplace. Meanwhile, most participants in this experiment are university students from civil engineering and engineering management, the majority of them have internship or work experience and have taken safety courses. Nevertheless, real construction workers have more work experience and safety knowledge, they are more familiar with the meanings of construction safety signs. Therefore, portable eye-tracking technology can be used to collect real construction workers' eye movement metrics on-site in future studies. Secondly, this is a bottom-up study, all participants have similar background. In the future, researchers can consider background information of real construction workers such as work experience, safety training and safety knowledge, and establish the relationship between these variables and eye-tracking metrics [26]. Finally, construction safety signs are based on China's construction industry in this study. Future research can analyze the relationship between the features of international construction safety signs and visual attention, which will provide cross-cultural measures to optimize construction safety signs.

6. Conclusions

This study establishes a theoretical model of construction safety signs' features and visual attention based on the visual information processing theory, eye-tracking technology is used to collect visual attention metrics and statistical methods are applied to test research hypotheses. The results indicate that among visual features of construction safety signs, red and rectangular safety signs can reduce cognitive load of first fixation, green safety signs can decrease overall cognitive load, however, no significant differences exist in eye movement indicators of safety signs with or without auxiliary words. Among cognitive features, familiar safety signs can reduce cognitive load, whereas visual attention of safety signs in different level of concreteness and sematic proximity is not significantly different.

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