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Measuring the cognitive loads of construction safety sign designs during selective and sustained attention

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ABSTRACT

Many unsafe behaviors in construction are associated with workers' insufficient vigilance and misperception of risks. Safety signs are designed to provide warning and raise worker's attention in hazardous environments. Many researchers conducted interviews and questionnaires to assess the effectiveness of various safety sign designs; however, the results are deemed subjective and biased due to personal differences such as experience, age, attitude, and working environment. This study intends to develop an objective measurement paradigm to assess the cognitive loads of different design features. The proposed method adopts response time and reported accuracies as the metrics to reflect the perceptional efficiency of safety signs under selective, sustained, and divided attention tasks. Statistical analyses are also included to mitigate personal bias. As a demonstration, three design features (color, shape, and content) are examined and the results suggest that the red color and graphic content do not contribute to higher reported accuracies but are faster to be recognized and understood in visual search and scanning activities.

1. Introduction

Safety issues have been regarded as one of the most significant aspects of project success in the construction industry. Lack of a controllable working environment, the temporal and dynamic nature of construction crews, and the complexity and diversification in construction tasks make safety management in construction projects extremely challenging (Kines, 2002; Chen et al., 2017). Chi et al. classify the causes of occupational accidents into three major categories including unsafe behavior, unsafe machines and tools, and an unsafe environment (Chi et al., 2014). Among these causes, unsafe behavior has proven to be the most frequently observed cause of injuries (Fang et al., 2016; Bohm and Risk, 2015). Suraji et al. found that nearly 90% of accidents were related to inappropriate operations in construction activities (Suraji et al., 2001). After studying 100 accident reports, Haslam et al. reported that half of the studied accidents were the result of unsafe behaviors (Haslam et al., 2005). In the same research, Haslam et al. suggested three major types of unsafe behaviors: (1) overlooking safety due to heavy workloads and job priorities; (2) taking shortcuts to save effort and time; (3) inaccurately perceiving risk with feelings of invulnerability and "it won't happen to me." All of these unsafe behaviors are related to the risk perceptibility of workers.

Recent studies suggest that the perceived risk of construction workers is highly related to their attention allocation and surrounding hazard signals (Dzeng et al., 2016; Chen et al., 2016). In order to raise workers' attention to potential hazards, safety signs are designed to promote appropriate safe behaviors. However, the design of safety signs is seldom studied. These signs should be systematically evaluated by their target users before they are placed into service (Wogalter, 2006). Their features and characteristics need to be carefully studied based on their effectiveness and durability (Wogalter, 2006). In addition, construction workers need to pay attention to safety signs while they are performing other construction tasks, which requires the capability of multi-tasking. Therefore, the ideal safety signs not only need to effectively raise construction worker's attention but also be easily identified. Therefore, to evaluate the effectiveness of safety sign designs, this research proposed a quantitative framework to assess the cognitive loads of various safety signs with different design features during two multi-task working conditions (selective attention and attentional blink). The findings of this study can be helpful in comparing the impact of different design features and optimizing the practice of implementing on-site construction safety signs. As a demonstration, the research takes

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three well-studied design features (color, shape, and content) to illustrate the validity of the proposed framework. In practice, the proposed framework also can be used to assess other more complicated design features.

2. Background

2.1. Risk perception and construction safety

One of the most widely accepted theories related to accidents is the domino theory, which suggests that random combinations of safety factors (management policies, procedures, supervision, and training) can cause various types of accidents (Petersen, 2003; Petersen, 2001). Heinrich et al. extended this theory and highlighted three basic causes of accidents: hazardous acts, working conditions, and management policy (Herbert et al., 1980). Abdelhamid and Everett (2000) also proposed that the three root causes of accidents are (1) failing to identify unsafe conditions; (2) deciding to proceed with a work activity under the unsafe conditions; (3) deciding to act unsafely regardless of the work environment. Based on those causes, Deery defined the development of accidents as a four-step process: hazard detection, risk perception/acceptance, self-assessment, and action (Deery, 1999). Several studies found that the early stage of accident development or perceived hazard level had the most significant impact on the occurrence of accidents (Rundmo, 1992a, 1992b; Tomas et al., 1999; Seo, 2005). These studies also revealed a close connection between perceived hazard level and unsafe work behavior, since risk perception and evaluation determine how workers respond to the hazards (Chen et al., 2016; Arezes and Miguel, 2008).

Two groups of factors (internal and external) impact an individual's perceived risk (Krallis and Csontos, 2006). The internal factors are related to an individual worker's experience, training level, and emotion. The external factors are related to the work environment, such as site conditions and safety programs. Promoting proper risk perception and assessment could encourage safe behaviors and provide early warnings for construction crews. The most popular programs related to internal factors are safety training programs. These training programs can significantly reduce accident and fatality rates (Taylor, 2015). External factors can be resolved by implementing protection devices and safety signs on construction sites (Rogers et al., 2000). Although safety signs have proven to be an effective approach to raise worker's attention and assist their risk perception, few research studies evaluate their design and quantify their effectiveness (Matthews et al., 2014). The features and characteristics of these construction safety signs need to be examined before they are placed into service (Wogalter, 2006).

2.2. Safety sign design

The role of a warning sign in the construction industry is regarded as a static communication tool for three purposes: (1) providing information; (2) influencing behavior; (3) serving as a reminder (Laughery and Wogalter, 2014). In terms of providing information, warning signs should deliver information about hazards, potential consequences, and suggested behaviors. Successful information delivery requires the information to be accurately and clearly reflected and its subjects to successfully receive it. The reminder requires the warning signs to cue construction workers' relevant information from memory into awareness. This requires construction workers to recall the warning or knowledge at the proper time. To serve such functions, safety signs need to be carefully designed. A substantial amount of research has investigated the characteristics of safety signs to assess whether the messages had been noticed and encoded (Wogalter, 2006; Laughery, 2006; Laughery and Wogalter, 2006). Based on Laughery and Wogalter's theory (Laughery and Wogalter, 2014), five design factors showed significant effect, including location, size, color, contrast, and format. These design factors should assist users in comprehending the hazards, consequences, and instructions. Therefore, Laughery and Wogalter organized the design elements into three categories:

(1) Terminology, brevity, and format. Textual warnings should use terminology with higher frequency and familiarity to users. Color can provide meaningful connotation and brevity. Formats such as lists and bullets can provide organized information.
(2) Explicitness. Explicitness means the information delivered by the safety sign should be specific, detailed, and clear.
(3) Pictorial symbols. Pictorials can convey a large amount of information quickly.

Although the majority of safety sign designs follows these fundamental design principles, they lack a quantitative measurement of their effectiveness. In a study of warning signs' effectiveness at beaches, Matthews et al. reported that more than half of the respondents (55%) failed to notice the signage, even if the aquatic safety signs were specially designed to protect beachgoers (Matthews et al., 2014). Duarte et al.'s study of the safety sign comprehension of students and adult workers found that most of the subjects did not well understand the shape-color codes. Ng and Chan investigated the sign-referent characteristics of construction safety signs and concluded that construction workers prefer signs with higher spatial imagery over unfamiliar and abstract referents (Ng and Chan, 2015).

To assess the signs' effectiveness, the most popular instruments are interviews and questionnaires. For example, Marks proposed a Visual Vividness Imagery Questionnaire to assess the visual imagery design (Marks, 1973). Ng and Chan's Object-Spatial Imagery Questionnaire introduced Blajenkova et al. (Blajenkova et al., 2006) to evaluating the users' object imagery preference of construction safety signs (Ng and Chan, 2015). However, both methods depend on the subjective opinions and personal experiences of respondents, which lack objectiveness and uniformity for rigorous comparisons. Therefore, it is necessary to have a quantitative and objective approach to supplement the subjective approaches and extend our understanding of safety signs' effectiveness. This paper intends to fill in the research gap by utilizing attention measurement instruments adopted from cognitive psychology theories to investigate the major design factors of construction safety signs.

2.3. Selective, sustained, and divided attention

Attention, as the human information processing process, enables the detection, filtering, and comprehension of stimuli. Attentional processes facilitate cognitive and behavioral performance through extracting, reducing, and selecting salient information and allocating cognitive resources (working memory) (Cohen, 2013). Measuring the attention allocated to a stimulus, such as a warning sign, could potentially help identify the stimulus's effectiveness. Several well-recognized manifestations of attention could be used for the measurement such as focused attention, selective attention, divided attention, sustained attention, effortful attention, and intention and directed attention (Parasuraman and Davies, 1984). Among these manifestations, selective, divided, and sustained attention are closely related to hazardous stimuli. Selective attention relates to focus and determines which information is given priority over others, divided attention relates to the division of cognitive resources among multiple cognitive tasks, and sustained attention refers to long-time focus and is typically related to vigilance (Cohen, 2013).

A widely accepted paradigm in selective and divided attention research is visual search tests (Cohen, 2013). In a typical visual search paradigm, the subjects are presented with a display containing both target stimulus and distractor stimuli (Müller and Krummenacher, 2006). These tests examine whether the subjects are able to rapidly and