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A field experiment of workers' responses to proximity warnings of static safety hazards on construction sites

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ABSTRACT

This paper describes an experimental study of workers' responses to proximity warnings of static safety hazards on construction sites using a location-based proximity warning system named the Proactive Construction Management System (PCMS). A method of evaluating workers' responses to proximity warnings is proposed. The method consists of six variables: warning time and distance (the time and the minimum distance to a hazard when a worker receives a warning), dangerous time and distance (the time and the minimum distance to the hazard when the worker comes close to the hazard), and response time and distance (the difference between dangerous time and warning time, and the difference between dangerous distance and warning distance). Finally, whether a worker responds to a warning is evaluated against a two-second threshold and a two-meter threshold in terms of response time and distance respectively.

The experiment was conducted over 17 workdays with the participation of 72 workers and resulted in 5391 warnings on a real-life construction project in Shanghai, China. The workers' responses were analyzed with respect to two factors: building trades and a-priori risk levels. The research found that workers responded to proximity warnings actively, but slightly differently across the selected building trades; carpenters had longer response latency in hazardous areas than ironworkers did, and response percentages were high for hazardous areas with high risks. The results also show evidence that PCMS has the potential to improve workers' safety performance. The limitations of the present study and future research directions are also addressed.

1. Introduction

Working on construction sites is inherently dangerous because of outdoor operations, working at heights, complicated on-site plants and equipment operation (Choudhry and Fang, 2008). In the safety decision hierarchy, the use of warning systems is an important strategy to minimize safety risk (Manuele, 2005). Numerous proximity-warning systems (PWS) have been developed and used in construction and mining contexts in recent years. They differ in many fundamental ways and, at one level, they may differ in their technology and focus. Several systems take the form of directly estimating the distance between a danger source and objects to be protected with received signal strength. For example, to warn workers on foot as they approach known dangerous areas around heavy mining equipment and other dangerous work zones, the system reported by Schiffbauer and Mowrey (2001) and Schiffbauer (2002) estimates the distance between equipment and workers using signal strength of a magnetic field. Similarly, to warn workers on foot as well as equipment operators, the system reported by Fullerton et al. (2009), Teizer et al. (2010a) and Marks and Teizer (2012) estimates the distance using signal strength of a radio frequency.

Another category of PWS is characterized as 'location-based' in that they use Global Position Systems (Ruff and Holden, 2003; Vega, 2001; Wu et al., 2013), Ultra-Wide Band (Carbonari et al., 2011) or Chirp Spread Spectrum (CSS) (Lee et al., 2014; Li et al., 2015). These systems initially measure locations of objects to be protected and equipment (e.g. trucks, bulldozers, excavators, tower crane hooks, etc.), then identify dangerous proximity by evaluating the relative distance between a danger source and objects to be protected, and finally, verbally warn people of danger, if any.

Undoubtedly, the system performance of PWS is a key factor influencing the decision to adopt them. Previous research efforts

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have primarily focused on evaluating the effectiveness and reliability of PWS (Marks and Teizer, 2012, 2013; Pizarro et al., 1997; Ruff, 2007; Teizer et al., 2010b). However, both technology and workers' responses should be considered when evaluating the effectiveness of PWS. Their performance should be evaluated not only in terms of the systems themselves, but also from the workers' responses to warnings. This study aims to investigate the workers' responses part of PWS evaluation.

This paper reports a field experiment investigating workers' responses to proximity warnings of static safety hazards on construction sites. The following is organized into four sections: (1) review of previous research evaluating PWS; (2) experimental design comprising the PWS used in the experiment and the method of defining and evaluating workers' responses to warnings; (3) experimental settings, procedure and results; and (4) discussion of the findings summarized from the previous results, the limitations of the current research, and the future research directions.

2. Background

System performance is a key factor influencing the decision to select and adopt PWS. Over the past decade, several studies concerning the evaluation of PWS have been noted, which vary in their purpose and focus. For instance, Pizarro et al. (1997) examined the effect that an auditory collision warning signal's pulse rate, pulse pattern and onset distance has on subject braking response in a simulated crane/overhead power line collision scenario. Teizer et al. (2010b) proposed a blind spot measurement tool to help identify the blind spots of equipment in order to quantify and protect the required safety zone(s) for such equipment. With this tool, they (Marks and Teizer, 2012, 2013) designed a testing method for evaluating the effectiveness and reliability of proximity detection and alert technologies in terms of alert distance and positive alarm rate. Ruff (2007) evaluated several proximity warning technologies, including sonar, radar, magnetic field and radio frequency, on surface mining equipment. These technologies were evaluated according to a set of criteria including adjustable detection ranges, maximum detection range, minimum number of sensor units required for front and rear coverage, two-way alarming, relative frequency of false alarms, relative frequency of nuisance alarms, tolerance to mud, dust, dirt buildup, installation and setup difficulty, and cost per piece of equipment. While these evaluation methods and results provide insights into the effectiveness and reliability of PWS, they do not provide a profile presenting how workers react to alarms.

Other studies have focused on improving existing warning technologies and evaluating the effects of proposed changes. Blackmon and Gramopadhye (1995) proposed providing positive feedback on backup alarms to address vigilance decrement that can be attributed to the use of discriminating personal alarms on construction sites. Sammarco et al. (2012) reported an experiment in the form of a simulated environment that used a high-definition video-based continuous mining machine (CMM) simulator to determine if a visual warning system can improve visual performance to detect CMM movements, so that miners can avoid 'struck-by' or 'pinning' hazards. To decrease false alarms, Wang and Razavi (2015) proposed and developed an unsafe proximity detection model with the consideration of the headings, speed and distance between entities.

However, despite the value of these studies in evaluating PWS, there is a need to investigate how users respond to these technologies in a construction project environment. Their performance should be evaluated not only from a systems viewpoint, but also from the users' responses. How workers will respond to warnings of danger on construction sites is an important question, but is currently not addressed in the construction safety literature. In contrast, the operators' responses to warnings have been extensively investigated in other settings such as intensive care units (Bitan et al., 2004; Chambrin et al., 1999; Cvach, 2012; Lawless, 1994; Meredith and Edworthy, 1995; O'Carroll, 1986; Tsien and Fackler, 1997) and complex systems operation and control (Bliss et al., 1995; Getty et al., 1995; Mosier et al., 1998; Parasuraman et al., 1997; Parasuraman and Riley, 1997; Sorkin, 1988), where users are being exposed to and are required to utilize automated aids to perform their jobs and make decisions. Cvach (2012) reviewed extensive research on alarm fatigue caused by numerous medical devices and summarized:

- *"Medical devices generate enough false alarms to cause a reduction in responding known as the 'cry wolf' effect."*
- *"When the alarm is viewed as a 'nuisance,' the caregiver may disable, silence or ignore the warning that is intended to make the environment safer. Rather than creating a safer environment, a large number of nuisance alarms have an opposite effect, resulting in desensitization."*
- *"Perceived alarm urgency contributes to the nurses' alarm response, but nurses use additional strategies to determine response including the criticality of the patient, signal duration, rarity of alarming device, and workload."*

Despite the intensive care setting, these summaries reinforce the significant impact of the operators on the performance of these automated systems and thus, decision makers need to carefully consider how operators respond to automated warnings in assessing performance.

There has been little attempt to address these noted potential problems in the construction setting. The unique, dynamic and complicated nature of construction projects poses a major challenge to researchers in the project context in comparison to other research domains, since the response data is difficult to collect through manual observation or recording by systems. However, it is argued that if such challenges are addressed, the performance of PWS can be improved with further understanding of the workers' responses. This experimental study investigates the workers' responses to proximity warnings on construction sites and can be viewed as an initial effort in addressing the challenges noted.

3. Method

In this section, the location-based PWS that was used in the experiment is introduced. Its features and operational procedure are described in detail. Next, a method of evaluating workers' responses to proximity warnings is proposed according to the system's features.

3.1. Proximity warning system

3.1.1. System overview

In this study, a location-based PWS, termed the Proactive Construction Management System (PCMS) was developed and used. PCMS was originally designed to help workers detect imperceptible or unnoticeable hazards (e.g., unwittingly entering a laydown area or being approached by a heavy machine from behind) and provides proactive warnings in real-time to workers when they are exposed to dangerous situations. The location feature of PCMS was built with the CSS technology, considering its balance across ranging accuracy, ease of deployment on construction sites, costs of purchase, use and maintenance (Li et al., 2015). Specifically, the location accuracy of CSS is argued to be better than that of