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Experimental field testing of a real-time construction hazard identification and transmission technique

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Hazard identification and communication are integral to most construction methods, and every construction safety management activity. Unfortunately, in practice, significant hazards are often not recognized and communicated leading to sub-optimal hazard awareness at the crew level. To bridge this gap in performance, we conducted a two-year intensive research project focused on developing a strategy that increases the proportion of hazards identified, communicated, and managed. Specifically, we designed a hazard identification and transmission (HIT) board that is used in conjunction with energy-based retrieval mnemonics and facilitates identifying and communicating hazards during both the planning and the execution phases. The strength of this strategy lies in the fact that workers are able to detect and communicate hazards in real time using energy-source mnemonic cues, which significantly reduces cognitive demand. Following development, we conducted immersive field studies to evaluate the impact of the devised strategy on two projects in the United States. Data from six crews were gathered using the rigorous multiple baseline testing experimental approach and analysis was conducted using interrupted time-series regression models. The results indicate that the crews were able to recognize and communicate only an average of 54% of hazards in the baseline phase, but were able to recognize and communicate 77% during the planning phase after using the intervention. An additional 6% of hazards were identified and communicated in the execution phase. This represents the first known formal effort to evaluate a real-time hazard identification and communication strategy for the construction industry.

Keywords: Communication, hazard identification, hazard recognition, health and safety, safety.

Introduction

Because of the dynamic and dangerous nature of construction projects, workers are exposed to a wide array of safety hazards and risks, which results in unacceptable injury and fatality rates (Mitropoulos and Cupido, 2009). Worldwide, the construction industry has consistently accounted for a disproportionate injury rate (International Labour Organization, 2013). In the United States, for example, construction activities were responsible for 755 fatal injuries in 2012, a 5% increase from 2011 rates (Bureau of Labor Statistics, 2013). Such high injury rates partly occur due to construction workers' inability to recognize and respond to hazards in rapidly changing and sometimes unpredictable environments (Goh and Chua, 2009). In fact, several other studies also reveal that designers, planners and managers are unable to predict and recognize significant hazards (Fleming, 2009).

To describe the relationship between hazard recognition and injury occurrence, we offer Figure 1, a simple conceptual model of the safety management process centred on hazard recognition and communication. As indicated by the model, there is a possibility of injury when a hazardous situation exists and workers are exposed to the hazard in the absence of adequate safety controls. Exposure to safety hazards is often triggered by poor worker behaviour (Abdelhamid and Everett, 2000). As shown, typical safety management in commercial, industrial and heavy construction involves the identification, communication and assessment of safety risk, and the

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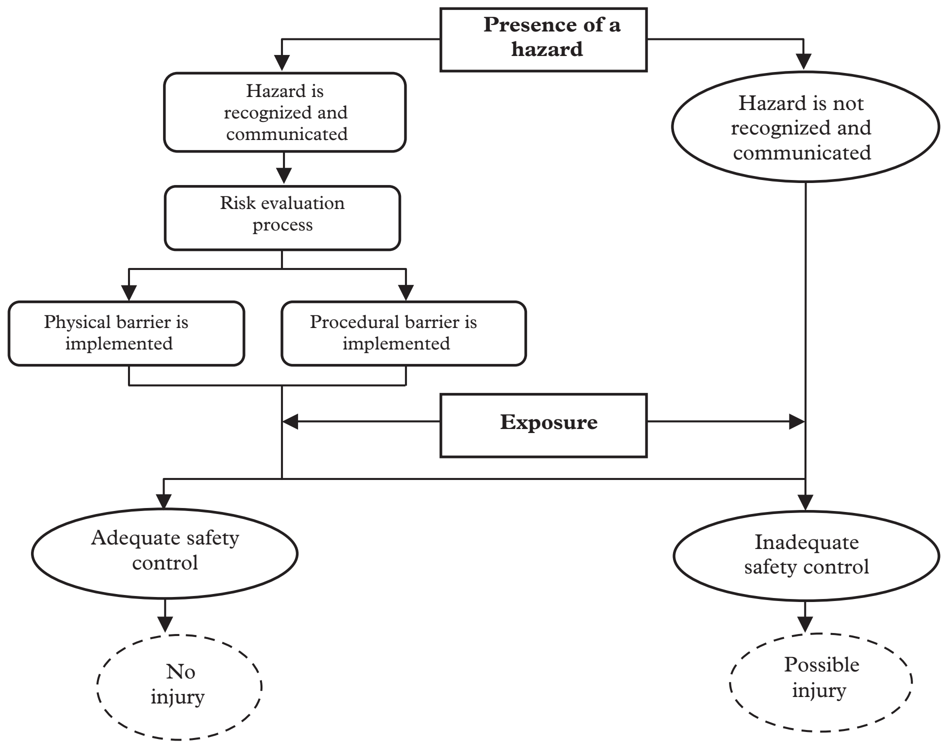

Figure 1 The role of hazard recognition and communication in injury prevention

subsequent selection of appropriate safety measures (Goetsch, 1996; Holt, 2006). Therefore, from a behavioural standpoint, which has training implications, the process requires both acquired skills and knowledge (Haro and Kleiner, 2008). When hazards are not properly recognized, and communicated, however, the devised safety management programme may not be effective. Therefore, hazard recognition and appraisal skills should be considered a prerequisite for effective safety management (Cooke and Lingard, 2011; Behm and Schneller, 2013).

Unfortunately, research has shown that many construction hazards are not recognized, valued, or adequately controlled prior to worker exposure. For example, Haslam *et al.* (2005) found that 42% of construction injuries occur due to workers' lack of safety knowledge and hazard recognition skills. In another study, Carter and Smith (2006) evaluated typical activities in three construction projects and concluded that 10–33.5% of construction hazards were not adequately recognized or assessed. More shockingly, Bahn's (2013) recent study revealed that novice workers, on average, failed to identify 57% of hazards in work-representative environments. When hazardous construction work situations are not appropriately identified or communicated, workers are unable to alter behaviour in order to avoid hazard exposure.

Although safety research has focused heavily on construction risk assessment and the selection of appropriate safety programme elements, the fundamental prerequisite to improving safety (hazard recognition skill and knowledge) has received relatively limited attention. Therefore, it is of utmost importance that effective and robust hazard recognition and communication methods be developed that overcome the inherent limitations associated with current methods. The purpose of this study was to develop and experimentally field test a promising new strategy based on the underlying concepts of mnemonics which involves reorganizing critical information in a specific fashion that is easy for the human brain to retain and retrieve (Scruggs *et al.*, 2010), andragogy, and dynamic safety planning. Essentially, the goal was to develop and make tangible improvements to current dynamic safety hazard recognition processes which are generally predominant in high risk industries such as nuclear and petrochemical facilities to assist workers in hazard management. To accomplish this goal, we reviewed literature on existing hazard recognition methods and identified associated limitations. Following this, the research team addressed some of the limitations by designing and empirically testing the impact of a real-time hazard recognition method (the hazard identification and transmission board) using multiple baseline experimental studies.

Hazard recognition background

Outside construction, several hazard recognition programmes are broadly implemented. For example, hazard and operability (HAZOP) reviews are conducted to systematically identify hazards that may result from operational deviations (Mushtaq and Chung, 2000) in such domains as energy; failure modes and effects analysis (FMEA) helps workers to proactively identify possible failure modes and their undesirable outcomes (Stamatis, 2003) in such domains as manufacturing; and cause-consequence analysis (CCA) combines attributes of fault tree and event tree analyses and graphically illustrates the relationship between causes and impacts of potential accidents (Ortmeier *et al.*, 2006) in such domains as air transportation. Although such methods have been used to identify and manage hazards and risks in highly specialized and standardized scenarios within the construction sector (Abdelgawad and Fayek, 2012; Zhou *et al.*, 2012), they are generally not suitable for construction because of the dynamic and transient nature of construction tasks, and the perceived complexity, and thus, time/cost of the methods.

In construction, potential hazards are typically identified using less sophisticated and more informal techniques. Most site-based hazards are recognized by workers based on their experience and knowledge of operations through brainstorming-type sessions (Albert and Hallowell, 2013; Wang and Boukamp, 2011). Most advanced approaches, like the job hazard analysis (JHA), generally involve reviewing the project scope, defining construction tasks, identifying potential hazards relevant to the defined task, assessing risk, and designing a safe work plan (Rozenfeld *et al.*, 2010). Although this method is highly useful, there are several limitations, including: (1) hazards imposed by adjacent tasks are ignored (Rozenfeld *et al.*, 2010); (2) workers are often unable to predict how tasks will be performed in the planning phase (Borys, 2012); and (3) workers are not fully competent in recognizing the plethora of possible hazards. Some of these limitations have been addressed in practice by using combinations of techniques that range from regular inspections to behavioural safety programmes in high risk industries. However, most dynamic safety hazard recognition methods still operate under the assumption that workers are inherently capable of predicting and identifying hazards.

In addition to the JHA, other common hazard recognition methods include lessons-learned and the use of safety checklists (Fleming, 2009; Zou and Zhang, 2009; Behm and Schneller, 2013). These techniques enable valuable information to be gathered for future improvement from past injury records, which is disseminated through safety training programmes. Unfortunately, these methods have several significant inherent limitations as well. First, the underlying databases are often not complete because they do not include near-misses and unreported injures (Gyi *et al.*, 1999). Second, injury records only reflect a small subset of hazardous work scenarios that resulted in injuries, and information from past incidents is not generalizable across diverse, dynamic and different settings (Rozenfeld *et al.*, 2010). Third, these methods require that an enormous amount of information is effectively transferred through instructional methods. Finally, the cognitive demands of predicting hazards are very high and often inefficient because of the difference that exists between tasks as they are imagined and tasks as they are performed (Borys, 2012). Also current methods that may assist in hazard recognition do not necessarily facilitate communication which is integral to ensure hazard awareness at the crew level.

In the last decade, with increased cost implications of occupational injuries (Waehrer *et al.*, 2007) and in the pursuit of zero injury projects (Hallowell *et al.*, 2013), safety professionals have sought to design and explore more proactive and real-time hazard recognition and communication strategies. In light of the aforementioned limitations associated with current hazard recognition programmes, there is an imminent need to design, develop, and test new proactive strategies. Most real-time safety hazard management techniques identified in literature are technology driven to identify specific hazard types (Carbonari *et al.*, 2011). Broader strategies to detect diverse hazard types are necessary.

Theoretical and practical contributions

In response to the limitations discussed with current hazard recognition and communication methods we attempted to design, develop, and empirically field test a new, real-time hazard identification and transmission technique that was inexpensive, efficient and effective. Specifically, we (1) devised a new cost-effective strategy for improved hazard identification and communication using principles of retrieval mnemonics for cued recall; (2) established an efficient protocol for successful and undisruptive field implementation using questionnaire survey instruments and through subject matter expert (SME) brainstorming sessions; and (3) conducted field experiments using the rigorous, but underutilized multiple baseline experimental testing approach to determine the efficacy of the devised strategy for improving hazard recognition and communication. Throughout the paper, we provide relevant justification for the research methods used and the design of the developed hazard recognition strategy based on established research. This research represents the first known attempt to develop and empirically test a worker-centric, proactive, and real-time hazard recognition and communication technique.

The method designed and tested is based on several new principles that we hypothesize will cause significant improvement in hazard recognition and communication. The entire study is built on the new premise that hazard recognition should be integrated in all phases of work, including planning, work execution, and post-work assessment. Since methods exist for pre-task hazard recognition (e.g., job hazard analyses), the new strategy presented here is designed to aid workers in hazard recognition and communication as they assess and adjust to changes in the work tasks and environment. Also, as will be discussed, the strategy is designed around the concept of energy mnemonics, a new ontology for hazard recognition that requires proper tools for integration. Finally, the strategy and method of hazard recognition management facilitates management–worker interactions and learning for both parties as work and hazardous exposures are reviewed and discussed after the work period.

Research methods

The project objectives were accomplished in two distinct phases. In the first phase, with help from a panel of subject matter experts (SMEs), we developed the hazard identification and transmission (HIT) board, a hazard recognition and communication technique designed and built based on retrieval mnemonics. Also, a field implementation protocol was developed using expert input gathered using questionnaire survey instruments, which was then refined through SME brainstorming sessions. The second phase focused on field experiments that attempted to test the impact of the HIT board as an intervention on real construction projects in the US.

For the two-year research initiative, we began by recruiting SMEs to assist with the development of the tool and organizing site visits for field testing. Our subject matter experts were predominately from Construction Industry Institute (CII) member organizations that represent organizations with exceptional safety records. This collaborative endeavour between construction domain experts and academic researchers was undertaken to ensure both the rigour of the research methods and the applicability of the research to practice. By attacking a prevalent problem using established academic research processes, we intended to provide practical solutions for improving construction hazard recognition (McCoy *et al.*, 2012). Fourteen highly experienced safety professionals with a cumulative experience of more than 352 years in the industry participated in the study. Seven of the identified experts were Certified Safety Professionals, and five others were Certified Hazardous Materials Managers. Several experts held other relevant licences or certifications including: Professional Engineers, Occupational Health and Safety Technologists, Compliance Safety and Health Officers, and Certified Industrial Hygienists. Also, the members were active in a number of occupational health and safety committees like the American Society of Safety Engineers, National Safety Council, and the Industrial Accident Prevention Association. In addition to these affiliations, several of the members held advanced degrees related to construction, industrial production, and occupational health and safety. Specifically, five experts held a master's degree, and another six held a bachelor's degree in relevant and related fields. In addition, two experts had authored construction safety articles for industry conferences and publications. In summary, the identified expert panellists were highly experienced in construction safety topics and qualified as subject matter experts (SMEs) which is an effective qualitative method for conducting rigorous research (Hallowell and Gambatese, 2009).

Phase I: Development of the HIT board

When developing the HIT board, the team focused on ensuring that the new tool was built on the principles of effective retention and retrieval of information. Thus, we integrated retrieval mnemonics and the functionality for dynamic safety planning as fundamental aspects of the tool.

Retrieval mnemonics for improved safety interaction, and cued hazard recognition

Safety interaction and communication among construction workers is critical for optimal safety performance (Alsamadani *et al.*, 2012). In practice, however, active and productive discussions among workers during pre-task safety planning and the preparation of the JHAs are minimal. In fact according to Borys (2012), 90% of the JHAs are prepared by supervisors or a foreman, and only passed on to the workers for a quick review. Although during the review process the workers may or may not add to the JHA content, this is in direct contradiction to research that advocates improved worker engagement and accountability in safety activities (Meldrum *et al.*, 2009; Alsamadani *et al.*, 2012; Sherratt *et al.*, 2013). Further, this problem is aggravated when JHAs contain abbreviated and generic hazards (e.g. fall, pinch-points, trips, etc.) that are vague and non-specific resulting in poor communication of critical hazards (Fleming, 2009; Borys, 2012).

This unguided hazard recognition activity does not adequately facilitate the identification of several latent uncommon hazards that may pose significant threat to workers' safety. For example, although ignition sources and toxic chemicals are present in almost every construction site they rarely appear on the JHAs of typical construction crews (e.g. carpenters, iron workers, masons, etc.) despite working in close proximity to these hazard sources.

To improve worker interaction, engagement, collaboration, and hazard recognition we used retrieval mnemonics. Retrieval mnemonics is a method in which information is transformed or reorganized in a specific fashion that is easy for the human brain to retain and retrieve (Scruggs and Mastropieri, 1990; Scruggs *et al.*, 2010). In other words, new information is encoded and structurally transformed to an alternative form which is consistent with the learners' existing knowledge (Cook, 1989; Mastropieri and Scruggs, 1998). Several empirical studies endorse the effectiveness of such methods to improve learning and memory (Mastropieri and Scruggs, 1991; Levin, 1993; Eslinger, 2002). For example, organizational mnemonics including acronym mnemonics, (Wilson, 1987) story mnemonics (Herrmann *et al.*, 1973), and simple rhymes (Worthen and Hunt, 2011) have been used to improve the retrieval process in applied settings. Our motivation in integrating mnemonic concepts was to provide workers with a general framework or starting point for improved safety discussions, and to provide recall mental cues to assist in identifying hazards more thoroughly. Studies indicate that individuals provided with recall cues are better able to retain, retrieve, and recognize necessary patterns (Weisberg and Reeves, 2013).

When selecting the appropriate recall cues and retrieval mnemonics, we borrowed the overarching principle from Haddon's (1970, 1973) energy release theory. According to this theory, inappropriate contact with energy sources can potentially harm individuals and result in foreseeable injuries. Accordingly identifiable and specific energy sources (e.g., motion, gravity, radiation, etc.) are responsible for all injuries and occur when energy is released contrary to operational objectives of work tasks being performed. Using Fleming's (2009) work as a primer, the expert panel defined and operationalized the definitions of 10 energy sources pertinent to construction operations to serve as recall cues. For example, when a worker conducts work adjacent to a leading edge on a roof, then there is potential for fall and the associated energy source is *gravity*. Similarly, during welding operations, the worker may be exposed to temperature hazards (sparks and hot surfaces), radiation hazards (high intensity light), chemical hazards (smoke and fumes), etc. Detailed information on the energy sources is available in Hallowell *et al.* (2013) and is also presented in Figure 3.

Proactive and real-time hazard identification

Most construction hazard identification techniques focus on predicting hazards that may possibly be encountered on the job. For example, as mentioned above, when pre-task safety planning and job hazard analyses (JHAs) are undertaken, work tasks are examined to identify associated hazards that are to be managed (Sacks *et al.*, 2009). These techniques heavily rely on cognitive and intuitive shortcuts called 'heuristics' to make useful judgments under uncertainty (Kahneman *et al.*, 1982). For example, workers will rely on past experience and the similarity of the undertaken tasks with previously encountered scenarios to project hazardous outcomes and predictions (Tversky and Kahneman, 1974). While this method is helpful, there are serious pitfalls in such an approach (Clemen, 1996). In a dynamic, complex, and rapidly changing environment (such as a construction site) although workers may perceive two situations to be similar, generalizing across different settings is often invalid. Workers also rely on the availability heuristics, which is the ease with which instances or situations can be recalled from memory (Tversky and Kahneman, 1974). Such reliance on availability can also result in biased and incorrect predictions. For example, workers may more easily recall recently witnessed accidents or relatively extreme incidents. Further, because regular safety training programmes focus more on high frequency and/or high severity injuries, other latent and subtle hazards often remain unrecognized. Our examination of JHAs, for example, revealed that gravity hazards (e.g. fall, trip, slip) were regularly mentioned, but radiation hazards (e.g. welding arc, microwaves) and biological hazards (e.g. bacteria, viruses, contaminated water), which are also more health than safety related, were rarely reported and communicated. In fact some studies demonstrate that such less frequently mentioned hazards may lead to very costly long-term effects including muscular-skeletal disorder (MSD), silicosis, radiation-induced cancers, etc. (National Academy of Sciences, 2008). Moreover, these long-term predictions that are made during the planning phase, although important, may fail to identify emerging and latent hazards because of any gap that exists between work as planned and work as executed (Borys, 2012).

In practice, emerging and latent hazards can be reliably identified using short-term predictions with progress in work as uncertainty reduces. In fact, the human cognitive framework naturally identifies hazard patterns as events unfold based on past experience and acquired knowledge. In other words, the human brain can assess tasks and conditions throughout the work period and refine the list of potential hazards based on real-time information. This real-time hazard recognition process involves repeated steps in which workers identify hazards as they are developing and adjust their hazard management model to reflect these changes. Unfortunately, current hazard recognition methods do not allow for the capture and communication of hazards that are identified during the work process. Our goal was to provide workers with a new strategy that captures potential hazards proactively using recall cues, existing knowledge, and past experience by using the hazard identification and transmission board. We aimed to use the hazard identification and transmission board to identify and communicate hazards during the pre-task planning phase; and to identify additional hazards that become more obvious as the work is executed.

Figure 2 conceptually illustrates how individuals recognize events in dynamic, complex and rapidly changing construction environments to identify hazards. Individuals use their cognitive framework that they have developed through past experiences and acquired knowledge (Baron, 2006) to discern patterns that signify the presence of hazards. Alertness and active search for hazard patterns within the construction environment lead to improved situational

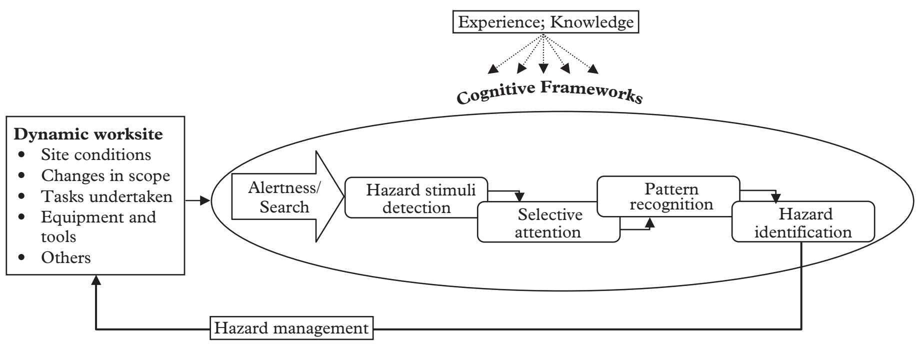

Figure 2 Hazard identification and management process

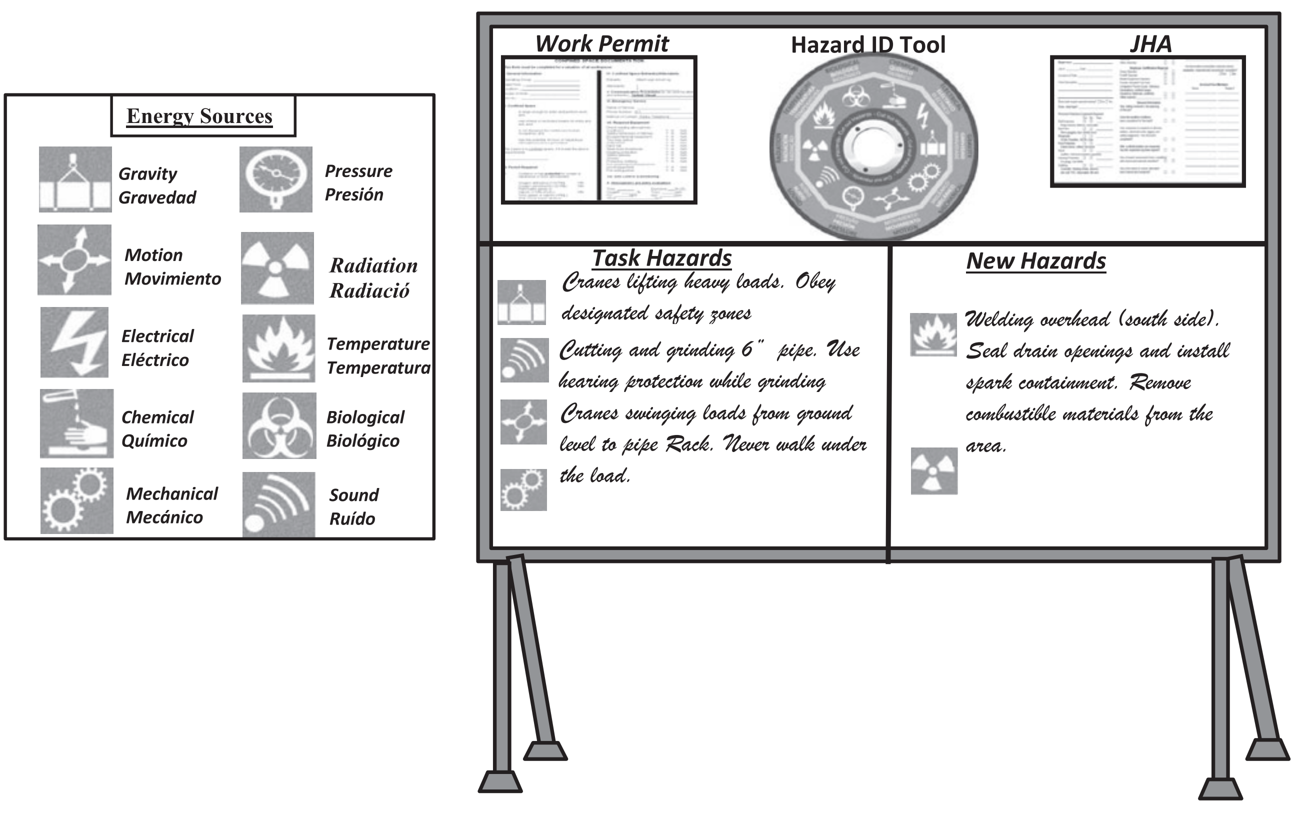

Figure 3 Hazard identification and transmission (HIT) board

awareness (SA) and facilitate the detection of hazard stimuli. This involves discriminating between actual hazard signals and irrelevant signals or noise (S/N) typical of these environments. Workers can then mentally relate observed patterns with experience and knowledge from the past to recognize hazards during execution (Kowalski-Trakofler and Barrett, 2003).

Design and implementation protocol of the HIT board

The hazard identification and transmission (HIT) board, shown in Figure 3, took the form of a 36 36 inch display board with magnetic recall-cue display components representing each of the energy sources. The board was supported by a rigid four-legged stand, and was provided with a transparent waterproof screen. The board was intended to facilitate the pre-task safety planning process during which workers review each energy source to identify potential hazards that may be encountered during work. Unlike traditional strategies, the HIT board also permits workers to identify and communicate additional hazards that become evident as the work progresses. Disruptions to work only include the identification of new hazards associated with unexpected changes to the work environment or task. Thus, this method effectively and proactively promotes hazard recognition and hazard communication while also drastically reducing challenges associated with precisely predicting work tasks and associated hazards.

In order to effectively use the HIT board, the following protocol was developed through questionnaire survey instruments and with input from the expert panel through brainstorming sessions:

(1) **Identify the job**: The tasks for the day should be adequately identified and divided into sub-activities, discussing the sequential order of operations.
(2) **Tools and environmental conditions**: Tools/equipment required to accomplish the sub-tasks must be identified and listed on the HIT board. Workplace conditions should also be noted.
(3) **Hazard identification and mitigation**: Relevant energy sources should be listed to facilitate the identification of specific hazards associated with each sub-activity. Subsequent plans to eliminate or control hazards should be discussed.
(4) **Permits and JHA**: As the meeting proceeds, the JHA should be prepared and displayed on the HIT board. Permits associated with the day's tasks are also presented.
(5) **Discussion location**: The hazard identification board is placed adjacent to the area where the job is conducted and hazards that become evident as the job progresses are also recorded on the board to improve hazard awareness of the working crew.
(6) **Supervisor and crew actions**: The supervisor facilitates the discussions and engages the crew members in the hazard identification process. Crew members actively participate, providing input and writing or drawing hazards associated with the work tasks, tools and environmental conditions near the relevant energy symbol, circling the most dangerous hazards.

The expert panellists expected that the HIT board would significantly improve the proportion of hazards identified and communicated because it (1) provides energy-based recall cues to assist with recognizing and communicating hazards; (2) provides a visual reminder of hazards categories and hazards in the work environment; (3) facilitates proactive real-time hazard detection to identify additional hazards that were not predicted initially during planning; (4) provides for the comparison of crew performance with recommended description of implementation protocol. Additionally, the panellists believed that the intervention encouraged active worker engagement, is easily integrated with existing work practices, and is adaptable for diverse types of work.

Phase II: Empirical field testing

Our aim in designing and constructing the HIT board was twofold: to advance safety knowledge theory and develop hazard recognition best practices for the construction industry. Although the expert panel believed that these objectives were achieved in Phase I, we validated the efficacy of the HIT board as a transformative intervention through immersive field testing. Specifically, we attempted to test the null hypothesis that *use of the HIT board and underlying mnemonics does not increase the proportion of hazards identified and communicated.*

To enhance research rigour, we elected to conduct a longitudinal experiment that directly measured change in the response variable (hazard recognition and communication) over time (Willett, 1989; Singer and Willett, 2003). We selected a longitudinal approach and dismissed several common methods of experimental research based on inherent limitations. For example, cross-sectional, co-relation studies, where the response variable is measured only at a single static occasion, cannot be adequately used to measure within-subject or within-group changes (Diggle *et al.*, 2013). Such methods can only provide an estimate of the differences in response between individuals or groups. Further, comparative two-wave studies that involve measuring the response variable once at the pre-intervention and post-intervention phase are highly susceptible to measurement errors that are confounded with true changes, do not measure change over time, and cannot be used to distinguish delayed effects (Ployhart and Vandenberg, 2010). Longitudinal designs, however, allowed us to make reliable comparisons of the outcome variable before and after the treatment is introduced, thus eliminating between subjects or groups sources of variability. Additionally, the proportion of hazards identified and communicated is a dynamic variable that can assume different values over time and can be only observed over time.

Among longitudinal methods, the before and after (AB) design was dismissed because of its inherent weakness of confounding intervention effects with irrelevant nuisance variables. This form of threat to internal validity called 'history' occurs when changes in performance may have resulted due to unrelated factors that are of no interest to the researcher (Richards *et al.*, 1999; Dimitrov and Rumrill, 2003). A more sophisticated method, withdrawal design, was also rejected on the basis of ethical and methodical grounds because the use of such methods may require the withdrawal of an intervention that positively enhances worker health and safety (Baer *et al.*, 1968; Watson and Workman, 1981; Barlow *et al.*, 2009). After careful consideration, we decided to use the multiple baseline testing (MBT) approach because of its intrinsic capability to control confounding variables using within and between subject or group statistical comparisons (Hawkins *et al.*, 2007). Also, the positive intervention need not be withdrawn to reliably determine intervention effects.

The multiple baseline testing approach involves a series of replicated and simultaneously conducted AB (i.e. before-after) studies in which the intervention is introduced to each baseline in a staggered, or time-lagged fashion (McGuigan, 1997; Biglan *et al.*, 2000; Barlow *et al.*, 2009). Hence, when a given subject or group receives the intervention, the other groups serve as control. Simultaneous comparisons can be made within and between groups allowing us to reject any alternative or plausible explanations for the intervention effect. If similar patterns of changes are observed when, and only when, the intervention is introduced, then the observed effects can be confidently imputed to the intervention instead of other nuisance variables and causal inferences can be made (Bulté and Onghena, 2009).

To conduct field tests, we solicited large and stable projects in the US from industry forums and communities. Although our expert panel assisted with identifying case project sites, we ensured that they were not directly involved in managing the project to minimize bias. We selected two project sites and a two-week immersive case study was conducted on each project. The first MBT experiment was conducted in a food processing facility involving major maintenance work and the second study was conducted in a detergent manufacturing plant where construction, renovation and retrofit were being performed. In each of the two sites, three independent groups were identified to participate in the study. Hence, we included a total of six longitudinal baseline studies, which exceeds the minimum requirement of having two baselines for making meaningful inference suggested in literature (Kazdin and Kopel, 1975; Blount *et al.*, 1982; Barlow *et al.*, 2009).

Measuring hazard recognition and communication

To empirically evaluate the impacts of the intervention we developed a relevant metric and established a strict and repeatable field protocol for field measurement. The hazard recognition and communication (HRC) metric was computed as shown in Equation 1.

$$HRC_i = \frac{H_{crew_i}}{H_{crew_i} + H_{crew_r} + H_{crew_o}} \tag{1}$$

where H_{crew_i} represents the total number of hazards identified by the crew during the planning (i = p) and execution (i = e) phases for each work period, H_{crew_r} is the number of new hazards retrospectively recognized by the crew after completion of the work tasks, and H_{crew_o} represents the total number of hazards that the crew was exposed to during work that were not identified by the crew, but were identified by a site-based panel consisting of two safety professionals and one researcher. The denominator of the HRC index is referred to as H_{total} as it represented all identifiable hazards. To avoid double or triple counting of hazards, any overlaps between H_{crew_i}, H_{crew_r} and H_{crew_o} were accounted for only once. Also, this metric places considerable emphasis on the skill of the workers to identify hazards before, during, and after work.

Two forms of the HRC index were measured. The first was based on the hazards identified and discussed during the pre-task meeting (HRC_p) and the second included additional hazards identified and communicated during the execution phase before exposure (HRC_e). Hence, H_{crew_p} was measured by recording the hazards that were identified and discussed in the pre-task meeting and H_{crew_e} included all hazards that were identified before exposure by the individual work crews, including those identified and communicated *during* construction.

Measuring H_{total} was more challenging because our goal was to identify *all* hazards to which the workers were exposed during the work period, including those not identified by the crew. To achieve this goal we established an oversight group of one researcher and two safety professionals from the host organization. This group observed the work process and recorded all hazardous exposures that were not recognized by the crew. To operationalize the process and ensure internal consistency, the group created a catalogue of hazards from previous task-specific hazard assessments, injuries, and training materials. The catalogue also included a list of all previously identified hazards for all work periods by the workers. As new discrete observations were made by the workers and the observers they were added, along with a definition, to the catalogue. In the definitions we used the fundamental nature of the hazard (e.g. slippery floor surface) rather than slang, informal, or vague terms sometimes used (e.g. slick).

Members of the observation group independently conducted observations and, at the end of the work period, shared all the observations. Feedback was also elicited from the crew. Each work period was defined as the four-hour period before or after lunch. Therefore, H_{total} was computed as the total number of hazards identified by the safety professionals, researcher, and the workers before, during, and after each work period. Although it is highly unlikely that the three observers and workers would comprehensively identify all hazards for every work period, we maintained a strict protocol that enhanced consistency and repeatability. For each crew, the observers computed two HRC indices for 16 work periods in both projects (192 observations in total). As stated above, each work period was typically the four-hour work periods before and after the lunch break.

When administrating such studies, one primary concern is the 'observer effect' which occurs when research subjects alter their behaviour because they are being watched by external researchers. To control such bias, several methods have been suggested in literature. For example, Desai (2002) argued that hidden surveillance cameras and remote recording devices should be used to make observations. For this study, however, it was impossible to implement such methods due to disclosure and confidentiality requirements that were imposed by the host organizations. Instead, we adapted other methods that have been discussed in the literature to control observer effects. First, we collaborated with in-house safety managers who frequently conducted field observation and were very familiar with the work crews. Second, the researcher became accustomed to the work crews before the study was initiated and the intervention was provided only after several baseline periods during which the researcher frequently visited the site. According to Chandler and Owen (2002) longitudinal studies reduce the impact of the observer effect with time lapse. Also, both sites that participated in the study were frequently visited by external audit and planning teams so it was customary for the workers to be observed. Lastly and perhaps most validating, we included an objective hazard identification skill and knowledge pre-/post-test in addition to the MBT.

Multiple baseline testing protocol and analysis procedure

As mentioned earlier, the intervention was introduced on a staggered basis through training sessions that were provided by the safety managers and researchers. In the training session, each crew was independently introduced to the HIT board, its field integration protocol, and the retrieval mnemonics. In addition, the field implementation of the HIT board was demonstrated with several simulated work scenarios and visual construction photographs.

Interrupted time-series regression analyses were used to analyse the measured HRC indices and to make valid causal inferences. The HRC indices measured at the baseline phase provided an initial estimate of performance and associated variability in the absence of the intervention. This information can be used to forecast performance in the future for a situation where the intervention was not introduced (Kirk, 2013). Our objective was to determine intervention effects using the difference between this projected performance in HRC indices and the actual performance that was observed after having introduced the intervention.

To accomplish this objective, we adopted and compared the time-series regression models proposed by Huitema and McKean (2000, 2007) to determine the most suitable mathematical model to conduct statistical analysis. These mathematical models are presented and described in Table 1. The first step involved fitting both model I and model II by regressing the HRC indices on

Table 1 Interrupted time-series regression models

Intervention parameters

Model I: Four-parameter (level change and slope change)

$Y_t = \beta_0 + \beta_1 T_t + \beta_2 D_t + \beta_3 SC_t + \varepsilon_t$

Model II: Two-parameter (level change only)

$Y_t = \beta_0 + \beta_2 D_t + \varepsilon_t$

where,

Y_t is the dependent variable (hazard identification level) at time t;

β_0 is the intercept of the regression line at t = 0;

β_1 is the slope at the baseline phase;

β_2 is the level change measured at time $n_1 + 1$;

β_3 is the change in slope from the baseline phase to the intervention phase;

T_t is the value of the time variable T at time t;

Dt is the value of the level-change dummy variable D (0 for the baseline phase and 1 for the intervention phase) at time t;

SC_t is the value of the slope-change variable SC defined as [Tt -(n1 + 1)]D;

ε_t is the error of the process at time t;

the respective predictor variables. This was followed by a model comparison test to identify the appropriate mathematical model. This was accomplished by testing the null hypothesis, using Equation 2, where the slope in the baseline phase and the slope change in the intervention phase is equal to zero ($\beta_1 = \beta_3 = 0$). If the null hypothesis is accepted there is an absence of a slope in both phases. In this case β_1 and β_3 in model I are redundant, the model indicates that only level change was observed and the relationship can be modelled using the model II equation. In other words, when model II is more appropriate, eliminating the redundant parameters (β_1 and β_3) better represents the underlying data with higher power for statistical inference. On the other hand if a slope is present in either of the phases, then model II may provide a skewed estimate of level change.

$$F = \frac{(SS_{Reg\,ModelI} - SS_{Reg\,ModelII})/2}{MS_{Reg\,ModelI}} \qquad (2)$$

where $SS_{Reg\,ModelI}$ is the regression sum of squares based on model I; $SS_{Reg\,ModelII}$ is the regression sum of squares based on model II; and $MS_{Reg\,ModelI}$ is the residual mean squares based on model I.

After comparing model I and model II, the assumption of independent errors (autocorrelation) was tested. When repeated measures are gathered, observations are assumed to be autocorrelated if the measured error at time t can be systematically used to predict subsequent errors (e.g. $t + 1$) in the time series. For this purpose, we used the Durbin-Watson test to test the null hypothesis that the lag-1 autocorrelation among the observations were equal to zero ($\rho = 0$). If the null hypothesis is accepted, the previously selected model I or II can be used appropriately to represent the data. But if the null hypothesis is rejected, alternative models that account for autocorrelation must be adopted.

The estimated coefficients of the regression equation indicate the intervention effects, either positive or negative in terms of the level-change and the slope-change coefficient. The coefficients from independent crews were then used to compute the overall level-change test statistic using the reciprocal of error variance as shown in Equation 3.

$$LC_{overall} = \frac{\sum_{j=1}^{J} \frac{1}{\sigma_j^2} b_{LC_j}}{\sum_{j=1}^{J} \frac{1}{\sigma_j^2}} \qquad (3)$$

where j is the number of crews; b_{LC_j} is the level-change coefficient estimated for the jth crew; σ_j^2 is the estimated standard error for the jth level-change coefficient.

Independent validation using construction images

To validate the findings of the multiple baseline studies and to provide corroborative evidence, we conducted independent pre-/post-tests using images from real construction projects. Here, we focused on measuring the proportion of hazards identified and communicated in a random sample of construction photographs.

To accomplish this, we selected a random sample of 16 photographs from a database of more than 100 photographs that were gathered by the expert panellists. In brainstorming sessions the expert panellists pre-identified a comprehensive list of observable hazards. Then, the photographs were randomly assigned for the pre-test and the post-test. The pre-test was instituted just prior to receiving the intervention and the post-test was administered after the last work period for all crews. Similar to the MBT study, we developed a relevant metric to measure the proportion of hazards identified and communicated as shown in Equation 4. We then conducted two-sample comparative tests to determine the impact of the intervention.

$$HRC = \frac{H_{crew}}{H_{crew} + H_{panel}} \qquad (4)$$

where H_{crew} is the number of hazards identified by the crew, and $H_{crew} + H_{panel}$ is the total number of hazards identified by the crew and the research expert panel.

Results

Case 1 description: major maintenance work at a food processing facility

The first study was conducted at a food processing facility involving major maintenance located in the Southeastern United States. The annual revenue of this facility surpassed \$13 million and the number of worker-hours exceeded 278 370. At the time of our visit, 12 crews representing diverse trades were actively involved in the project. For the purposes of this study, three crews (mechanical, electrical and civil) were selected to participate from a stratified population. The upper management identified two highly experienced safety managers with a total of 46 years of practical experience to facilitate data collection and coordinate the integration of the HIT strategy. The size of the selected natural work crews ranged between nine and 12 workers.

Case 1 results, analysis and discussions

The proportion of hazards identified and communicated (HRC index) across work periods are shown in Figure 4 and the analysis results are presented in Table 2. Models I and II were estimated using conventional regression. Model I was estimated by regressing

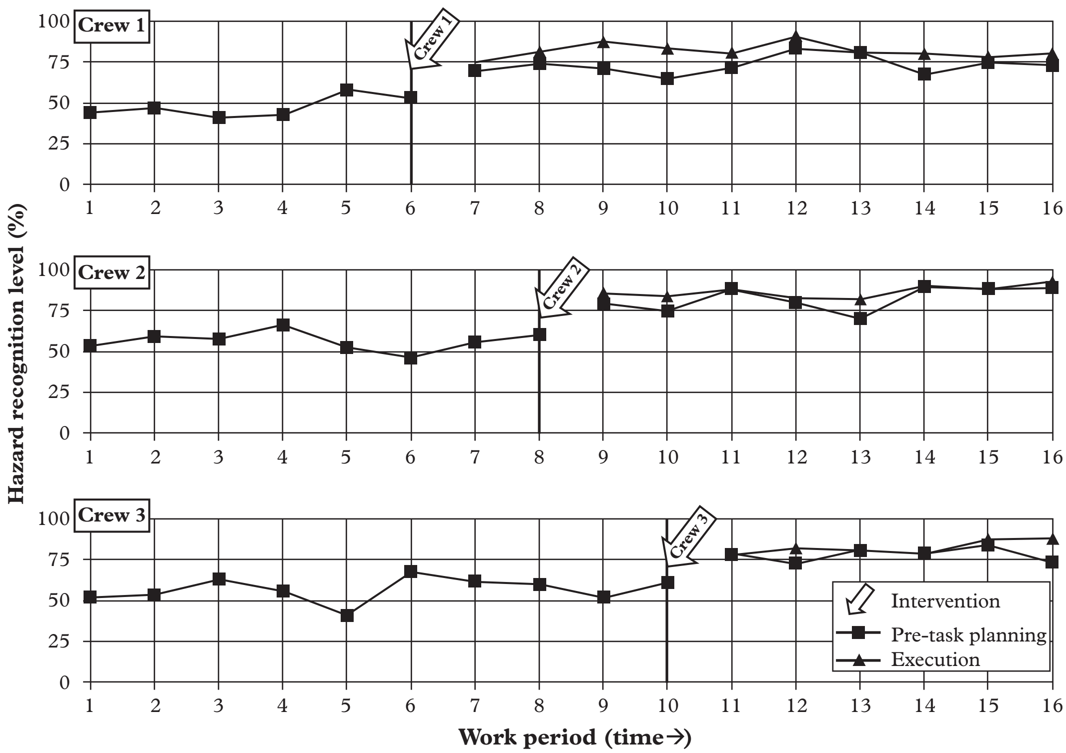

Figure 4 Results of Case 1: multiple baseline study on food processing facility

Table 2 Results of Case 1: multiple baseline study on food processing facility

	Predictor	Coefficient	Std. error	t value	p value	Model test (Fcritical = 3.885)	r^2	D-W test	$p_{Levene's}$ ($\alpha = 0.05$)	$p_{A\text{-}D}$ ($\alpha = 0.05$)
Planning phase	*Crew 1: Mechanical*									
	Constant	47.788	2.422	19.735	0.000	*Model II*	0.867	1.711	0.540	0.278
	D	25.423	3.063	8.300	0.000	$F_{obt} = 1.6588$				
	Crew 2: Electrical									
	Constant	56.598	2.414	23.444	0.000	*Model II*	0.807	1.941	0.251	0.688
	D	26.095	3.414	7.643	0.000	$F_{obt} = 1.2090$				
	Crew 3:Civil									
	Constant	56.789	2.093	27.133	0.000	*Model II*	0.736	2.514	0.212	0.414
	D	21.363	3.418	6.250	0.000	$F_{obt} = 0.34249$				
Execution phase	*Crew 1: Mechanical*									
	Constant	47.788	2.160	22.125	0.000	*Model II*	0.912	1.927	0.216	0.142
	D	34.101	2.732	12.481	0.000	$F_{obt} = 1.0992$				
	Crew 2: Electrical									
	Constant	56.598	1.781	31.787	0.000	*Model II*	0.906	1.764	0.367	0.856
	D	30.325	2.518	12.043	0.000	$F_{obt} = 0.6013$				
	Crew 3:Civil									
	Constant	56.789	2.085	27.232	0.000	*Model II*	0.804	2.381	0.237	0.197
	D	25.781	3.405	7.571	0.000	$F_{obt} = 1.054$				

the HRC index on the three predictor variables (T, D, and SC) and model II was estimated similarly by regressing the HRC index on only the level-change dummy variable (D) as shown in Table 2. Following the estimation of the parameters of both models, the model comparison test (see Equation 2) was used to select the preferred mathematical model. Comparing the obtained F value ($F_{obt} = 1.659$) with the critical value ($F_{critical} = 3.682$) using an alpha level of 0.05 and the degree of freedom ($df = 2, 12$), model II was selected as the preferred model. For Crews 2 and 3, the same approach was followed and model II was determined to be appropriate in each case. Therefore, according to the results, each crew demonstrated only a level-change improvement.

The Levene's test for the homogeneity of the error variance and the Anderson-Darling test for the normality of errors, in each case, yielded a p-value above 0.05. Hence, it was reasonable to accept homoscedasticity of error variance and the normality for errors. The Durbin-Watson test statistics revealed no evidence of autocorrelation, implying the adequacy of the selected mathematical model presented in Table 1. Thus, additional parameters that account for autocorrelation were unnecessary for further analysis.

From Table 2, the results indicate that Crew 1 demonstrated a level-change improvement of 25% ($p < 0.005$) in the planning phase (48% to 73%) immediately after receiving the intervention. This value represents the difference between the projected baseline performance in the absence of the intervention and the actual observed performance for the seventh work period (T = 7). The projected baseline performance is 48% ($\beta_0 + \beta_2$ D), where D assumes the value zero in the baseline phase, whereas the performance in the intervention phase is 73% (D = 1). The difference between the two phases is equal to the level-change coefficient of 25% ($p < 0.005$) as indicated in Table 1. Similarly, the analysis results for Crews 2 and 3 demonstrated a level-change improvement of 26% ($p < 0.005$) and 21% ($p < 0.005$), respectively.

In addition to the hazards identified in the planning phase, the crews identified hazards as the work was being executed. Following the same analysis procedure, Crews 1, 2 and 3 revealed a level-change improvement of 34% ($p < 0.005$), 30% ($p < 0.005$), and 26% ($p < 0.005$), indicative of a net improvement of 9%, 4% and 4% in the execution phase, respectively. The overall level-change statistic (see Equation 3) demonstrated a level-change improvement of 24% ($p < 0.005$) in the planning phase and 31% ($p < 0.005$) in the execution phase. Therefore, the net improvement in hazard recognition in the planning phase was 24% and an additional 5% of hazards were identified during field execution.

The independent corroborative test using construction images to cross-validate the MBT findings revealed similar trends. Two sample t-tests for independent measures were used to test the null hypothesis that the HRC index remained constant before and after the intervention. Before receiving the intervention, Crews 1, 2 and 3 identified only 53%, 46% and 55% of hazards respectively, whereas they identified 92%, 78% and 79% of the hazards after the intervention. In other words, a statistically significant improvement in hazard recognition and communication for Crews 1, 2 and 3 of 39% ($p < 0.005$), 32% ($p < 0.005$) and 24% ($p < 0.005$), respectively was observed.

Case 2 description: construction, renovation and retrofit in a manufacturing plant

The second study was conducted in a manufacturing plant involved in the production of household detergent located in the Mid-Western United States. The long-term contract on average generated $18 million annually and required an average of 342 250 worker-hours every year. During our visit, eight crews were actively involved in the project. Two millwright crews and one piping crew were selected to participate in the study. Similar to Case 1, two highly experienced safety managers with more than 32 total years of safety experience worked along with the researchers in data collection and intervention integration. The size of the selected crews ranged between six and 11.

Case 2 results, analysis and discussions

The results of Case 2 are presented in Figure 5 and Table 3. As indicated, similar to Case 1, the measured HRC index over time for each crew were mathematically represented appropriately using model II. This suggests that the intervention introduced a level-change improvement in the proportion of hazards identified and communicated. Further, all necessary assumptions of homoscedasticity and normality of error variance required to perform ordinary least squares (OLS) regression procedures were satisfied, indicating robustness of the mathematical model to make valid inferences. The Durbin-Watson test statistic implied that the relationship among the error estimates was equal to zero, eliminating the need for additional autocorrelation parameters. Comparing performance at the baseline and intervention phase, Crew 1 revealed a level-change improvement of 29% ($p < 0.005$) during pre-task planning. An additional 5% of hazards were identified as the tasks were carried out during the execution phase. Similarly Crews 2 and 3 exhibited a level-change improvement of 19% ($p < 0.005$) and

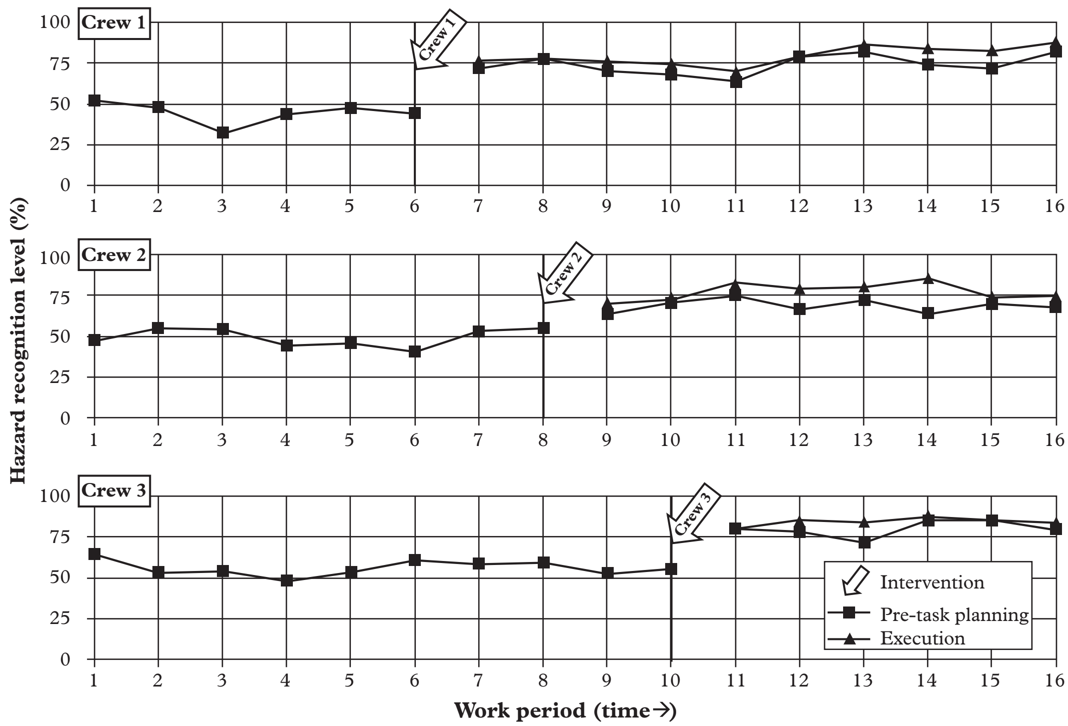

Figure 5 Results of Case 2: multiple baseline study on manufacturing plant

Table 3 Results of Case 2: multiple baseline study on manufacturing plant

	Predictor	Coefficient	Std. error	t value	p value	Model test (Fcritical = 3.885)	r^2	D-W test	$p_{Levene's}$ (α = 0.05)	$p_{A\text{-}D}$ (α = 0.05)
Planning phase	*Crew 1: Millwright*									
	Constant	44.745	2.584	17.315	0.000	*Model II*	0.870	1.680	0.886	0.681
	D	29.474	3.269	9.017	0.000	F_{obt} = *0.78385*				
	Crew 2: Electrical									
	Constant	49.733	1.696	29.318	0.000	*ModelI II*	0.825	2.199	0.115	0.397
	D	19.461	2.399	8.112	0.000	F_{obt} = *0.00421*				
	Crew 3: Millwright									
	Constant	55.996	1.531	36.750	0.000	*Model II*	0.867	1.713	0.936	0.622
	D	23.929	2.500	9.570	0.000	F_{obt} = *0.26747*				
Execution phase	*Crew 1: Millwright*									
	Constant	44.745	2.432	18.399	0.000	*Model II*	0.901	1.207	0.945	0.698
	D	34.758	3.076	1.299	0.000	F_{obt} = *2.6557*				
	Crew 2: Electrical									
	Constant	49.732	1.939	25.648	0.000	*Model II*	0.883	1.903	0.812	0.217
	D	28.145	2.742	10.263	0.000	F_{obt} = *0.6013*				
	Crew 3: Millwright									
	Constant	55.996	1.599	35.028	0.000	*Model II*	0.867	1.657	0.084	0.901
	D	24.927	2.610	9.549	0.000	F_{obt} = *1.054*				

23% ($p < 0.005$) in the planning phase. An additional improvement of 9% was observed for Crew 2 and 1% was observed for Crew 3 during execution. In total, Crews 1, 2 and 3 exhibited a level-change improvement of 15% ($p < 0.005$), 28% ($p < 0.005$) and 25% ($p < 0.005$) before any exposure. The weighted overall level change computed using Equation 3 was 23% ($p < 0.005$) for the planning phase and 29% ($p < 0.005$) for the execution phase.

In the corroborative test with construction photograph images similar to Case 1 results, the two sample *t*-tests revealed that Crews 1, 2 and 3 were able to identify and communicate only 49%, 54%, and 52% of hazards respectively. But after the intervention, Crews 1, 2, and 3 were able to identify and communicate 84%, 77%, and 87% of hazards. That is, Crews 1, 2 and 3 revealed a statistically significant improvement of 35% ($p < 0.005$), 23% ($p < 0.005$), and 35% ($p < 0.005$), respectively.

Apart from the results of the multiple baseline study and the independent validation studies, quantitative feedback was received from site personnel. According to one safety manager: 'Identifying additional hazards as the work progress using the cues is a great idea'. According to a crew supervisor: 'The board with the energy visuals engages the crew. The discussions were much better than usual.' The challenges identified by the workers while using the HIT board included transporting the board within the site premises during job location changes and difficulty in accessing the HIT board during work at height and in space restricted areas.

Study limitations

The most important limitation of this study pertains to the computation of the HRC index. Because hazards were identified by the site-based panel, we were unable to verify whether all hazards were comprehensively catalogued. Despite the existence of literature that questions the ability of safety professionals to identify all hazards, we followed a strict and consistent protocol and engaged multiple, experienced observers in both studies to make meaningful and reliable comparisons. We expected that the aggregate hazards identified by the safety managers, the researcher and the workers would yield nearly all identifiable hazards. The consistency in the results among the cases, despite the differences in work, location, observers, training programmes, and management strategies, is a strong indicator that the operationalized method was effective.

Another limitation of this study pertains to the long-term impacts of the intervention. Despite using a longitudinal research effort, we are unable to comment on the impact of the intervention once the research team departed from the site. Despite follow-up efforts, it was impossible for us to determine the long-term effects because several of the crews were disbanded, dispersed, or merged for new tasks. Large-scale studies conducted at the project level involving all workers in a site run by the principal contractor may help determine long-term effects. However, resource constraints required this study to be conducted at the crew level.

Finally, both cases were conducted in large and stable projects with a strong safety culture as a foundation. Because the successful implementation of the strategy requires a strong safety culture and climate, the results of the studies may not apply across project and management types.

Conclusions

Hazard recognition and communication are critical elements for improved safety performance (Carter and Smith, 2006). Several researchers have expressed concerns with current hazard recognition methods and the proportion of hazards that remain unidentified and unmanaged (Rozenfeld *et al.*, 2010; Pinto *et al.*, 2011). Unidentified hazards can result in unanticipated risk exposure with dire consequences such as: preventable injuries, emotional distress, productivity losses, wasted resources, and others. This study developed a new hazard recognition strategy called the hazard identification and transmission (HIT) board that integrated concepts of retrieval mnemonics for cued hazard recognition during pre-task planning and work execution. Implementation of the HIT board resulted in an overall level-change improvement in hazard recognition of 24% in the planning phase, and an overall level-change improvement of 29% in the execution phase for all six crews studied. In other words, hazard recognition improved 23% during pre-task planning and an additional 5% of hazards were identified while the tasks were being executed. The findings support previous literature that illustrate the difference between work as imagined and work as performed. The HIT board and associated protocol are highly beneficial for large commercial, industrial and heavy sector projects where the identified diverse energy sources are predominant. The inexpensive, efficient and effective characteristics of the HIT board present a real possibility for use in residential and small-scale projects as well. However, the HIT board has only been tested on large projects and large contractors and is therefore not generalizable to small projects or small contractors.

This study also challenges the current hazard recognition paradigm that defines standard methods such as job hazard analyses and pre-task plans. These methods typically involve forecasting work scenarios and brainstorming hazardous conditions. The limitation of this method is that workers and managers are often unable to forecast work scenarios and associated hazards, especially when the subsequent work is dynamic and involves multiple crews. Here, we challenge the current hazard recognition paradigm by presenting a new conceptualization of hazard recognition. First, the HIT board is a platform for hazard recognition that is designed around the premise that hazard recognition activities should take place prior to work, during work, and after work is completed. In this way, hazard recognition becomes an integral component through multiple crew activities rather than being ancillary to task performance. Also, this method of hazard recognition helps to improve adjustment to change, learning, and continuous improvement, which is supported by the data presented.

Second, the HIT board method is also designed to facilitate the use of the Haddon energy mnemonic, which this research has shown, for the first time, to *cause* improvement in hazard recognition skill. We believe that the energy mnemonic has the potential to drastically improve hazard recognition because of the results presented here and those presented in Albert *et al*. (2014a, 2014b). The HIT board and associated multi-phase hazard recognition method are thought to be effective for delivering and operationalizing the mnemonic.

Third, the research methods used to test the hypothesis involved a new method of hazard recognition and communication measurement. The HRC index was invented to improve upon current methods by including direct observations made by a three-person research team and post-work-period assessments of hazards encountered. Although this measurement technique is time consuming and resource intensive, the data are much more reliable and valid.

Finally, this is the first known attempt to empirically evaluate the impacts of a proactive and real-time hazard recognition strategy using rigorous experimental approaches. Specifically, we employed the underutilized, but rigorous multiple baseline testing approach along with interrupted time-series regression models to quantify intervention effects. In fact, it is one of the first uses of MBT in the construction engineering and management domain. The longitudinal nature of the study reduced systemic errors, common in cross-sectional research studies, and improved the reliability and validity of research findings.

Other complementary studies that explore the designer's ability in hazard recognition during the design phase and comparative studies of the worker's ability in identifying specific hazard types (by energy sources) as mentioned in this research are ongoing. We suggest future research undertakings to develop additional transformative and proactive hazard recognition strategies to improve construction safety performance. We recommend using a multi-layered approach for hazard detection and management to ensure hazards are adequately addressed. Despite the logical connection between hazard recognition and safety performance, the degree of association between the two variables needs to be further explored. Finally, current hazard recognition safety training programmes are not designed particularly for effective adult learning; andragogy principles need to be incorporated and evaluated for improved results (Wilkins, 2011).

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