# ABSTRACT

JEELANI, IDRIS. Personalized Hazard Recognition Training for Construction Workers.
(Under the direction of Dr. Alex Albert).

Proper hazard recognition is an essential element in the safety management process. When safety hazards remain unrecognized or unmanaged, construction workers are more likely to experience occupational injuries and illnesses. However, recent research has demonstrated that a large proportion of safety hazards remain unrecognized in construction environments.

To improve hazard recognition levels, employers adopt a variety of safety and hazard recognition training programs. Despite these efforts, desirable levels of hazard recognition have not been achieved. This is partly because of weaknesses in traditional hazard recognition methods and ineffective training practices. In fact, current hazard recognition method and training programs are designed without a concrete understanding of why construction hazards remain unrecognized in dynamic work environments.

To advance theory and practice, the objective of this study was twofold: (1) identify downstream factors that impede thorough hazard recognition at the work interface, and (2) develop and evaluate the first personalized training strategy targeted at improving hazard recognition levels in construction.

The first objective was accomplished through an exploratory study where workers were tasked with recognizing construction hazards in work-representative environments, and follow-up brainstorming sessions were conducted to assess why certain hazards remained unrecognized. The initial findings results were supplemented with input from an expert panel consisting of 10 construction professionals and 4 academic researchers. The research processes yielded 13 factors that impede thorough hazard recognition within construction. The most commonly observed factors were: (1) selective attention or inattention to certain hazard types, (2) unexpected and unknown potential hazard set, and (3) the perception that certain hazards impose low levels of safety risk.

The second objective was accomplished by developing a personalized hazard recognition training strategy by incorporating training techniques known to improve stimuli and threat detection in other domains such as medicine, the military, and aviation. The techniques included: (1) visual cues to aid systematic hazard search, (2) personalized hazard recognition performance feedback, (4) personalized eye-tracking visual attention feedback, and (4) metacognitive prompts that trigger the adoption of remedial measures.

Following the development, the effectiveness of the training strategy in improving hazard recognition was empirically evaluated using the non-concurrent multiple baseline testing approach. The findings of the study showed that the participating workers on average were able to identify only 42% of hazards prior to the introduction of the intervention, but were able to recognize 77% of hazards in the intervention phase. The findings of this study will be of interest to practicing professionals seeking to improve hazard recognition levels within construction.

# Personalized Hazard Recognition Training for Construction Workers

By

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# DEDICATION

Dedicated To my Mother

# BIOGRAPHY

I was born and raised in a beautiful valley of Kashmir in the shadows of mighty Himalaya. After high school, I joined the National Institute of Technology, Silchar, where I completed my under graduate studies in Civil Engineering in 2011. My four years at NIT, Silchar played a great role in shaping the person I am today. After completing my undergrad studies, I joined Shapoorji Pallonji Engineering and Construction, a construction company based in India and Middle East. I worked in the field for a year before being promoted to Sr. Engineer in contract administration department, where I worked for another one and a half years. There I strongly came to realize the acute need for well learned and informed individuals to manage the projects efficiently to ensure they are completed on time, within budget and most importantly without accidents and injuries. Hence, I decided to pursue a master's degree in Construction Engineering and Management and joined North Carolina State University, Raleigh in August 2014. During my masters, my research focus was on improving hazard recognition performance of construction workers and upon graduation, I intend to continue the research in the field of construction safety and obtain a Ph. D degree.

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I am thankful to my parents Mr. Khurshid Jeelani and Mrs. Masooda for their unconditional love, sacrifice and patience. I cannot thank them enough for the sacrifices they have made to give me a comfortable life and quality education. I am thankful to my brother Owais for his fatherly affection, my sisters Urooj and Shaifta for their love and support and to Monisa for being a caring elder sister to me. My Aunt Ghous-ul-Nisa, has always been an inspiration to me, I am grateful for that. I thank my grandparents for their selfless love and prayers and my nephews for the cheerful and joyous moments.

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# CHAPTER: 1 INTRODUCTION

## Observed Problem

Despite improvements in safety management practices, disproportionate injury rates continue to be a universal problem in the construction industry. Every year more than 60,000 fatal accidents are reported from construction projects around the world (Lingard 2013). Within the United States, construction accounted for 16% of fatalities in 2014, although employing only 5% of the workforce (BLS 2016).

Over the last 50 years, the construction industry has undergone profound changes in terms of safety enforcement, emphasis on safety training, and improvement in overall safety culture. However, a desirable level of safety performance has not been achieved; and construction workers continue to remain highly vulnerable to workplace injuries (Albert et al. 2014; Carter and Smith 2006). Apart from humanitarian concerns, the cost of these injuries exceed $48 billion every year (Ahmed et al. 2006), and adversely impacts profit-margins (Jaselskis 1996) and reputation. In fact, the staggering cost of construction injuries can threaten the survival of construction companies (Zou and Sunindijo 2015).

One of the reasons for poor safety performance within construction is the inability of workers to detect hazards in dynamic and rapidly changing work environments (Albert et al, 2013). In fact, Haslam et al. (2005) showed that up to 42% of safety incidents can be traced to poor hazard recognition and assessment performance.

Despite hazard recognition being one of the most essential steps in the safety management process, studies show that a large proportion of construction hazards remain unrecognized.

Carter and Smith (2006) found that between 10 and 33.5% of hazards remained unrecognized or inadequately assessed in projects in the U.K. Likewise, a study conducted by Bahn (2012) revealed that novice workers fail to detect over 57% of hazards in occupational environments. Recent studies in the United States suggest that over 40% of hazards remain unrecongized (Albert et al. 2014) in work environments. These unrecognized hazards expose construction workers to unanticpated safety risk that can potentially lead to catastrophic injuries and illness. (Albert *et* al 2014).

To improve hazard recognition levels, several hazard recognition techniques and training programs have been developed. Although beneficial, they have not completely addressed the issue of poor hazard recognition within construction (Haslam et al. 2005; Perlman et al. 2014). In fact, research has demonstrated that workers fail to recognize hazards despite having adopted traditional hazard recognition methods, and having received substantial safety training (Albert et al. 2014; Rozenfeld et al. 2010).

## Research Goals

To improve hazard recognition levels, the objectives of this research were to (1) identify underlying reasons why safety hazards remain unrecognized in construction workplaces, and (2) develop and empirically evaluate the effectiveness of a personalized hazard recognition training strategy designed to improve hazard recognition levels.

This study represents the first research effort to develop and test a personalized need-based hazard recognition training program in the context of the construction industry. This is also the first research effort to examine why construction hazards remain unrecognized.

The results of the study will inform safety training professionals and construction managers of effective training practices targeted at improving hazard recognition. Implementation of these training practices can dramatically improve hazard recognition performance of workers which is an important leading indicator of safety performance.

## Research Method Overview

The research was completed in two successive studies. Study 1 focused on identifying why construction hazards remain unrecognized, and study 2 focused on developing and evaluating a personalize hazard recognition training strategy. The complete study plan is schematically presented as Figure 3. The objective of study 1 was accomplished through observational studies where construction workers were tasked with recognizing safety hazards in construction case images captured from real projects in the United States. The results were supplemented by input from an expert panel of construction professionals and academic researchers.

The objective of study 2 was accomplished by developing an effective training strategy by incorporating several effective training practices that have found successful applications in other domains. Following development, the effectiveness of the training strategy in improving hazard recognition performance of workers was evaluated using the non-concurrent multiple baseline testing approach

## Study 1: Why Construction Hazards remain Unrecognized?

Study 1 was completed in three phases as depicted in figure 1

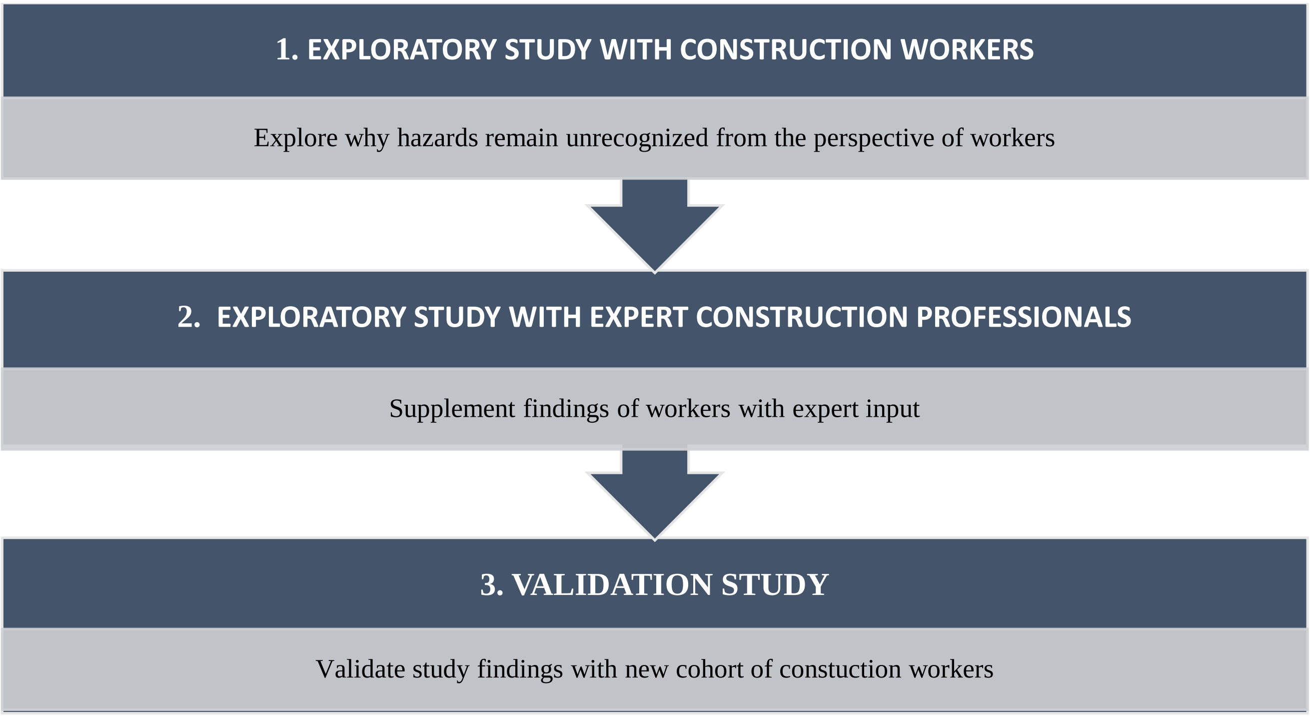

**Figure 1: Phases of Study 1**

### Exploratory Study with Construction Workers

Construction workers representing diverse specialty trades and construction projects were tasked with identifying hazards in construction case images captured from real projects in the United States. The data was collected and follow-up brainstorming sessions were conducted to understand why construction hazards remain unrecognized.

### Exploratory Study with Expert Construction Professionals

In the next phase, brain storming sessions were conducted with an expert panel consisting of construction safety professionals and academic researchers to gather supplementary data to augment finding from the first phase. A catalogue of factors impacting hazard recognition performance was developed.

### Validation Study

In the final phase, the findings of above two phases were validated with a new cohort of construction workers. The result from the participating workers was then combined and frequency tables were developed that examine the most common workplace impediments to thorough hazard recognition.

## Study 2: Development and evaluation of personalized Hazard recognition training Strategy

Study 2 was completed in four phases depicted in figure 2.

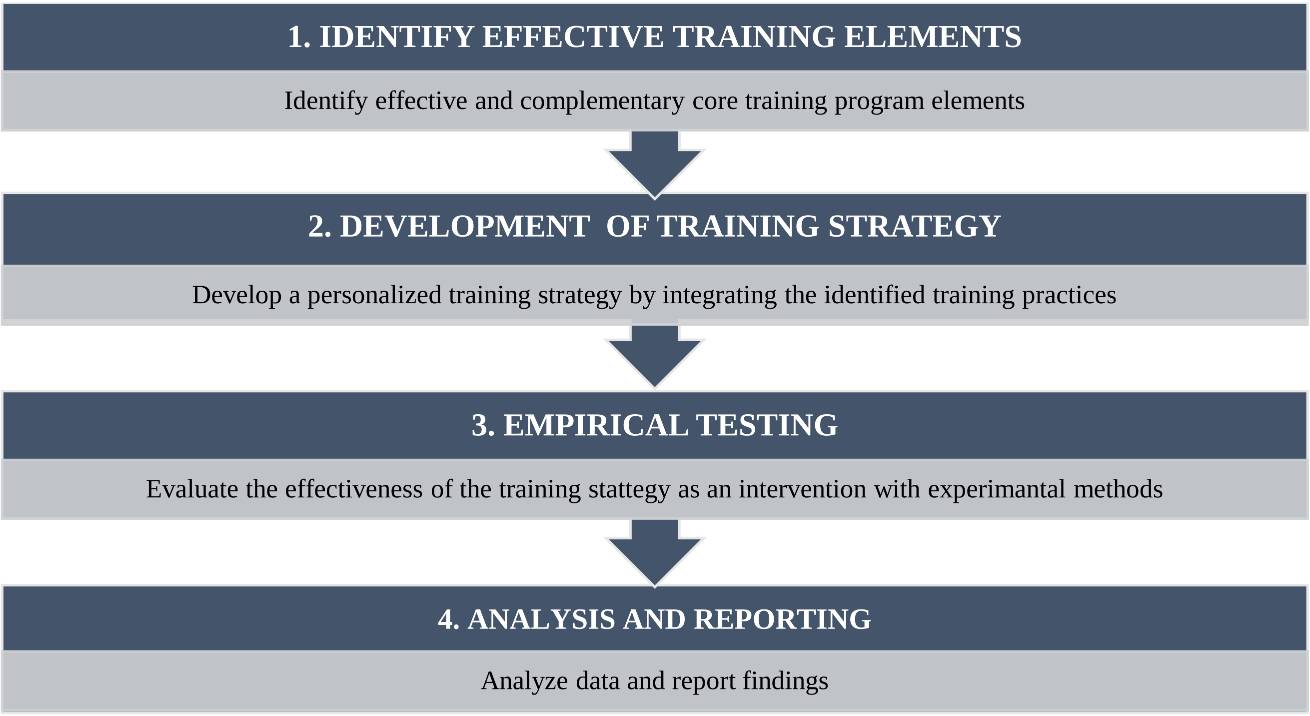

**Figure 2: Phases of Study 2**

### Identify Effective Training Elements

The objective of this phase was to identify individual core training elements that could potentially be integrated to develop an effective personalized hazard recognition training strategy. These core elements were identified through brainstorming sessions with an expert panel followed by literature review sessions to identify best practices for integration and implementation. The expert panel members asked to identify specific training elements to address the issue of hazard recognition within construction.

### Development of the Training Strategy

Following the identification of the training elements, the personalized training strategy was developed by integrating the core elements identified in the previous phase. A structured and repeatable training protocol was developed for the implementation of the training strategy.

### Empirical Testing

To test the effectiveness of the devised training program, the longitudinal, non-concurrent multiple baseline testing approach was used. Workers representing different trades and construction projects participated in the study and were tasked with recognizing safety hazards in construction case images, captured from construction projects across the United States. The criterion measure was the proportion of hazards identified and the treatment variable was the personalized hazard recognition training developed in the study.

### Analysis Phase

After collecting data from the experimental study, rigorous statistical analysis, using interrupted time-series analysis for non-concurrent multiple baseline experiment, was conducted.  The null hypothesis was that the training strategy will not lead to improvements in hazard recognition performance of workers.

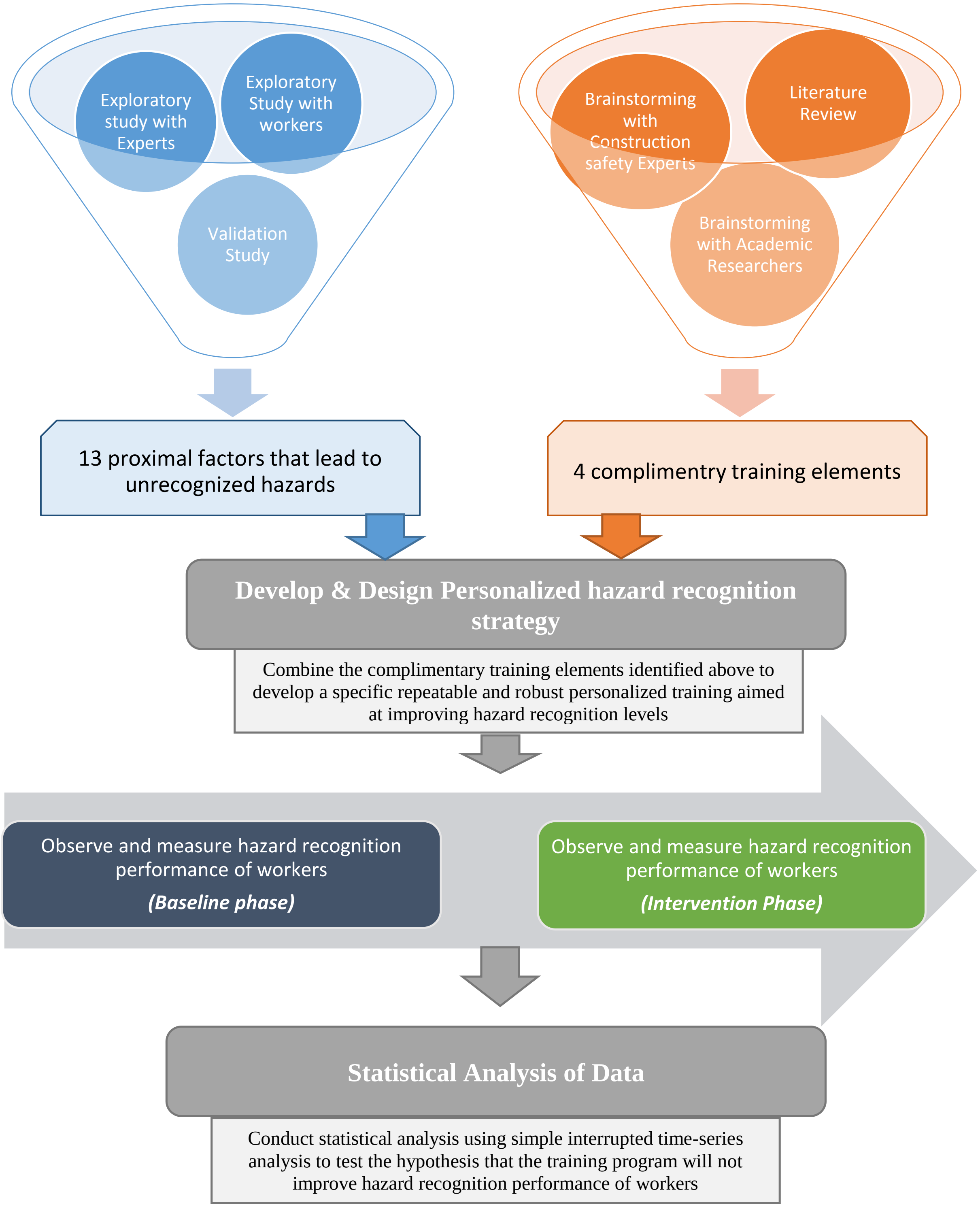

**Figure 3: Detailed research overview**

## Thesis Format

The thesis is organized in a two journal paper format.  Therefore, each of the subsequent chapters contains their own abstract, motivation and background, theoretical and practical contributions, research methods, conclusions, future research endeavors, and referenced articles.

Chapter 2 of this thesis presents the research focusing on why construction hazards remain unrecognized. Chapter 3 presents the development and testing of a personalized training strategy designed to improve the hazard recognition performance of workers. The thesis concludes with chapter 4 that presents the summarized findings, contributions, limitations and recommendations for future research.

The thesis also includes 3 Appendices. They contain results of intervention experiments conducted with workers during study 1 & 2 and sample data form and calculations.

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# CHAPTER 2: WHY CONSTRUCTION HAZARDS REMAIN UNRECOGNIZED AT THE WORK INTERFACE

# Abstract

Recognizing and managing construction hazards is the central focus of all safety management initiatives. When safety hazards remain unrecognized, the likelihood of occupational injuries and illnesses increase substantially. Therefore, proper hazard recognition is an essential prerequisite to effective safety management. However, recent research findings have demonstrated that a large proportion of construction hazards remain unrecognized and unmanaged in complex and dynamic work environments. Despite the importance of hazard recognition, there is a dearth of research examining why construction hazards remain unrecognized in work environments. While past studies have identified upstream factors such as management support and experience that may indirectly impact hazard recognition; no study has focused on downstream factors that directly influence performance when workers examine the work environment. The objective of this exploratory research was to address this knowledge gap by identifying downstream factors that impede thorough hazard recognition at the work interface. The objectives of this research effort were accomplished in two complementary phases. The first phase involved a hazard recognition activity where 8 workers were tasked with identifying hazards in case images captured from real projects within the United States. This was followed by an interview session where the workers were asked to identify possible reasons why specific hazards remained unrecognized in the hazard recognition activity. In the second phase, additional factors that impact hazard recognition and relevant examples were catalogued by interviewing an expert panel of construction professionals and academic researchers. Further, the experts examined the hazard recognition results from the first phase and brainstorming sessions were held to determine possible reasons why hazards remain unrecognized. The experts were also asked to provide relevant examples for each identified factor. The research process yielded 13 factors that impact hazard recognition. A follow-up validation study with construction workers revealed that the most common reasons for not recognizing construction hazards at the work interface include: (1) selective attention or inattention to certain hazard types, (2) unexpected and unknown potential hazard set, and (3) the perception that certain hazards impose low levels of safety risk. The findings of the study will be useful to researchers and practitioners seeking to develop improved interventions for hazard recognition (e.g. training) that are cognizant of field-based impediments to thorough hazard recognition.

**Keywords:** Construction Safety, Hazard recognition, Hazard identification, Safety management, Safety interventions, Safety training

## Introduction

More than 60,000 fatal injuries are reported each year from construction projects around the world (Lingard 2013). In the United States, the number of fatal construction injuries increased by 16% from 781 in 2011 to 908 in 2014 (Bureau of Labor Statistics 2015). Non-fatal injury rates resulting in days away from work increased by 5% in 2013 compared to 2012; although significant reductions were observed in the preceding years (Center for Construction Research and Training 2016). Undoubtedly, construction workers are highly susceptible to being injured in the workplace; despite significant advancements is safety research and practice. These injuries inflict emotional and physical distress on workers and their families, and the annual cost of such incidents exceed $48 billion in the United States (Ahmed et al. 2006). The cost of construction injuries significant impinge on profit margins, and adversely impact project success; and in some cases threaten the survival of construction companies (Zou and Sunindijo 2015).

To improve construction safety, researchers have devoted much effort to identifying and understanding antecedent factors of construction incidents (Abdelhamid and Everett 2000; Mitropoulos et al. 2005; Rajendran and Gambatese 2009). Among others, recent studies have emphasized the issue of poor hazard recognition within construction. For example, Carter and Smith (2006) argued that the likelihood of injuries dramatically increase when hazards remain unrecognized in the workplace. Further, proper hazard recognition is a necessary prerequisite to adopting effective safety interventions (Albert et al. 2014a). In fact, Haslam et al. (2005) found that more than 42% of accidents within construction involve worker related factors such as inadequate hazard recognition and appraisal skills.

To improve hazard recognition levels, employers adopt diverse hazard recognition techniques and safety training programs. Although beneficial, hazard recognition methods and training have not completely addressed the problem of poor hazard recognition within construction (Carter and Smith 2006). In fact, research has demonstrated that workers fail to recognize hazards despite having adopted traditional hazard recognition methods, and having received substantial safety training (Haslam et al. 2005; Perlman et al. 2014).

While researchers and practitioners have grappled with these challenges, injury investigation reports have generally recommended more training to improve hazard recognition and management skills among workers (NIOSH 2016). These recommendations are generally based on the assumption that inadequate safety knowledge is the primary causal factor leading to poor hazard recognition and management within construction.

Although safety knowledge is essential, recent advances in the field of human factors have demonstrated that a diverse array (i.e. apart from knowledge) of psychological, environmental, and technical factors can influence human performance (Garrett and Teizer 2009). In other words, apart from safety knowledge, several factors that are both external and internal to human workers can influence hazard recognition performance.

Some of these factors are more distant or upstream in its causal link with hazard recognition performance, and some others are more proximal. Upstream factors such as experience and training can indirectly influence hazard recognition through more proximal factors such as safety knowledge (i.e. knowledge gained through experience or training) (Perlman et al. 2014). Although few studies have focused on examining such upstream factors, there is a dearth of research on downstream field level challenges that directly influence hazard recognition performance.

A better understanding of why hazards remain unrecognized at the work interface can facilitate the design and adaption of more efficient upstream interventions (e.g. training) that facilitate field-level hazard recognition. For example, interventions that are cognizant of the limitations of humans, and those that support their strengths, can be designed to improve hazard recognition performance. Accordingly, the objective of this exploratory research was to identify specific field-level challenges and issues that impede thorough hazard recognition. The study represents the first effort to identify and examine proximal downstream factors that directly impact hazard recognition.

## Background

### Construction Hazard Recognition

Hazard recognition is generally regarded as the first step in the safety management process as shown in Figure 1.When hazards are recognized, workers can adopt effective safety measures to control hazard exposure and reduce injury potential. On the other hand, when hazards remain unrecognized, the likelihood of injuries increase substantially (Albert et al. 2014a).

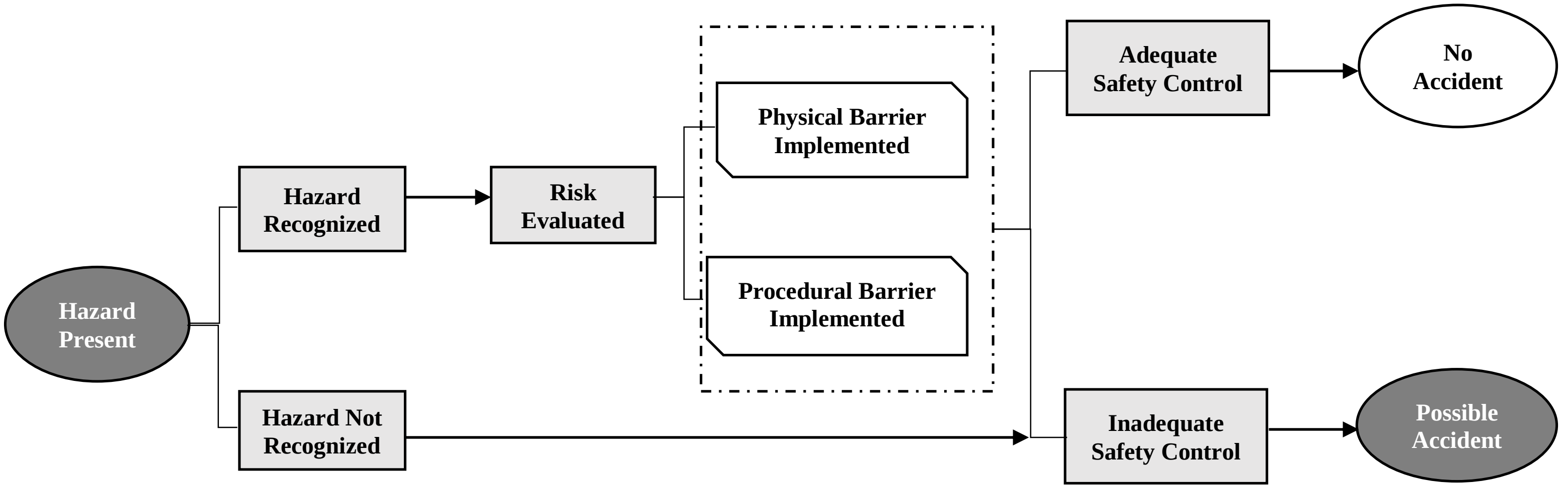

Figure 1: Role of hazard recognition in safety management

Because of the importance of hazard recognition, employers adopt several methods to improve hazard recognition levels. These methods can generally be classified into two types; namely predictive and retrospective hazard recognition methods. Predictive methods such as Job hazard Analysis (JHA) focus on visualizing construction tasks that will be undertaken in the near future and predicting expected hazards that may be encountered (Rozenfeld et al. 2010). Methods such as pre-task safety planning and task demand analysis are also predictive in nature (Mitropoulos and Namboodiri 2011).

While predictive methods are useful, these methods are associated with important limitations that prevent thorough hazard recognition. The most significant limitation of these methods is the assumption that workers are inherently skillful at predicting future work conditions and expected hazards (Fleming 2009). However, past research has revealed that these assumptions do not hold true in practice. For example, past research has shown that the dynamic nature of construction projects make task visualization and prediction incredibly challenging for workers (Mitropoulos et al. 2005). Further, task as imagined or planned is often very different from how tasks are ultimately performed at the work interface (Borys 2012). Apart from these primary limitations, predictive methods also do not generally support the recognition of hazards unassociated with the primary tasks, hazards imposed by adjacent construction crews, and those introduced by changes in scope and conditions (Albert et al. 2014a; Rozenfeld et al. 2010).

Retrospective hazard recognition methods such as lessons learned focus on extrapolating knowledge gained from past safety incidents to new situations and projects (Behm and Schneller 2012; Goh and Chua 2009). However, like predicative hazard recognition methods, retrospective methods are also associated with important limitations. For example, past injury reports generally do not capture detailed information for effective future learning. In addition, useful information remains uncaptured from near misses and unreported safety incidents (Dong et al. 2011). Also, the generalizability of lessons learned from projects and project types is questionable.

Partly because of such limitations, a large proportion of construction hazards remains unrecognized in construction projects irrespective of project type and project location. For example, studies conducted in the United States in diverse projects revealed that more than 50% of construction hazards remained unidentified (Albert et al. 2013). In the U.K, Carter and Smith (2006) revealed that up to 33% of hazards remained unrecognized in work method statements. More shockingly, novice workers from Australia were unable to recognize 53% of hazards in work representative environments (Bahn 2013). These unrecognized hazards expose workers to unexpected safety risk that can result in catastrophic accidents and injuries. A comprehensive understanding of why hazards remain unrecognized within construction can inform efforts to develop more effective hazard recognition methods and practices.

## Safety and Hazard Recognition Training

Field-level hazard recognition performance largely depends on the ability of workers to detect hazard stimuli amidst irrelevant distractors. Therefore, a large proportion of safety training efforts is devoted to equipping workers with the skill-sets necessary to recognize and manage hazards in dynamic environments. However, recent research suggests that workers lack essential safety skills despite having received substantial training (Perlman et al. 2014). Not surprisingly, a large number of injury investigations reveal deficits in worker ability to recognize and manage hazards, and recommend more training to prevent injury reoccurrence (Haslam et al. 2005). Such observations have triggered a stream of research articles examining why training efforts fail.

Among other reasons for training failure, several studies have investigated industry barriers to effective training. For example, Goldenhar et al. (2001) argued that the transient nature of the workforce and the temporal nature of projects discourages some employers from adopting more effective and resource intensive training methods. Others have alluded to the assumption held by certain employers that the additional cost of resource-intensive training methods may increase construction cost; which in turn can impact the competitiveness during project bidding. Apart from these primary industry barriers, other challenges include the scarcity of resources and experienced training personnel, schedule constraining in fast-pace projects, and language barriers among construction workers (Wang et al. 2010).

In addition to industry barriers, few studies have focused on design flaws inherent in training delivery within construction. For example, Wilkins (2011) found that most training programs adopt passive classroom-type instructional methods to meet regulatory requirements; but are often ineffective for adult learners. Likewise, Burke et al. (2006) found that traditional training methods fail to sufficiently engage workers, thereby limiting the transfer of safety knowledge. In fact, Haslam et al. (2005) argue that that the adoption of ineffective and unengaging training methods can instigate negative attitudes among workers to safety issues, and can have dire consequences. Other reasons for training failure in construction identified in past research include the use of ineffective instructional material and inexperienced trainers (Demirkesen and Arditi 2015).

While past research has focused on addressing these issues, training interventions largely ignore specific challenges workers experience during the hazard recognition process. Training interventions built upon a better understanding of why construction hazards remain unrecognized in the workplace can potentially improve hazard recognition and safety performance within construction.

## Point of Departure and Research Objectives

As discussed above, desirable levels of hazard recognition have not been achieved in construction (Albert et al. 2013; Bahn 2013; Carter and Smith 2006). Prior research has generally attributed such poor hazard recognition performance to ineffective training practices and shortcomings with traditional hazard recognition methods (Perlman et al. 2014; Wilkins 2011). To overcome these issues, studies have focused on developing more effective training interventions and hazard recognition methods (Albert et al. 2014c; Rozenfeld et al. 2010).

However, much of these efforts have been performed without a concrete understanding of why hazards remain unrecognized in the workplace.

For example, training interventions assume that hazards remain unrecognized primarily because workers lack adequate safety knowledge (Haslam et al. 2005). Accordingly training interventions focus on transferring safety knowledge efficiently. However, from a human factors or systems perspective, a diverse array of factors that include psychological, environmental, and technical factors can impact human performance (Garrett and Teizer 2009). In other words, factors that are both internal and external to workers can impact whether hazards are recognized. Therefore, designing and adopting hazard recognition techniques and training interventions that are cognizant of weaknesses and strengths of workers can potentially improve hazard recognition and safety performance.

To facilitate the development of such interventions, the objective of this study was to answer the question: Why construction hazards remain unrecognized at the work interface? Because several upstream and downstream factors may impact hazard recognition, the researchers decided to limit the scope of the study to downstream factors and challenges that occur at the work interface. Specifically, the focus is only limited to factors that impact hazard recognition while workers examine the work environment to recognize safety hazards.

For example, the study does not focus on organization factors such as leadership support or supervisor involvement which are more upstream in the causal link with field-level hazard recognition (Hallowell and Gambatese 2009); nor does the study focus on social influences of peers or supervisors that can indirectly impact whether hazards remain unrecognized (Williams et al. 2010). Also, the study does not focus on personal or situational factors such as experience, fatigue or emotional state (Tixier et al. 2014). The study also does not focus on factors that may impact the accuracy of hazard recognition during the planning stage when conditions may be relatively unpredictable with potential for scope changes. Rather, the study focused on specific factors and challenges that impact hazard recognition when workers examine or scan the workplace to identify safety hazards.

The findings of this study can be used by researchers and practitioners to develop improved methods for field-level hazard recognition. In addition, the findings can be used to optimize training interventions to specifically target hazard recognition skills based on a better understanding of why construction hazards remain unrecognized at the workplace.

## Research Methods

The objectives of the research were accomplished in two complementary phases where data were gathered from 8 construction workers, 10 construction safety professionals, and 4 academic researchers. The following sections describe the research process in detail.

### Phase I: Exploratory Study with Construction Workers

The first phase of the study focused on assessing why hazards remained unrecognized from the perspective of workers. To gather this data, the researchers first recruited 8 construction workers representing diverse specialty trades including 3 electricians, 2 plumbers, 2 maintenance workers, and 1 iron worker. The workers were employed in 4 construction projects within the Southeastern United States.

After gathering worker demographic information, the workers were asked to participate in a hazard recognition activity. The hazard recognition activity involved identifying hazards in a pre-selected set of construction case images that were captured from real projects within the United States. The construction case images were gathered during a previous research effort by an expert panel of construction professionals representing Construction Industry Institute (CII) member organizations (Albert et al. 2013). From over 100 captured case images, the expert panel selected 16 case images that represented diverse construction operations with a variety of hazards. After the case images were selected, the expert panel pre-identified hazards present in each of the case images through brainstorming sessions. An example case images with pre-identified hazards can be found at Albert et al. (2013). The case images included diverse work scenarios including welding, cutting, grinding, drilling, excavation, pipe laying, crane rigging and lifting, and others. The number of hazards in each case image ranged from between 8 to 17.

In the current study, the hazard recognition activity required that the workers identify hazards from a random sample of 4 construction case images from the initial set of 16. As the workers identified hazards verbally from each case image, the researchers cataloged the information. At the end of the hazard recognition activity, the workers were presented with the catalogue that contained information regarding the hazards that were successfully identified, and others that remained unidentified. After the information was shared, brainstorming sessions were conducted with the workers to determine why specific hazards remained unrecognized. The results of the brainstorming sessions were recorded. The workers were also asked to identify additional reasons why hazards may remain unrecognized apart from those that were relevant to their hazard recognition activity.

### Phase II: Exploratory Study with expert construction professionals

To gain a holistic perspective, the second phase focused on gathering supplementary data on why construction hazards remain unrecognized from the perspective of construction safety professionals and academic researchers. The data gathered in this phase was useful because hazard recognition is a complex cognitive activity involving both conscious and unconscious mental processes which may often be difficult to recognize, comprehend, and verbalize. Apart from identifying why hazards remain unrecognized, this phase also focused on gathering industry relevant examples of hazards that generally remain unrecognized for each underlying reason.

In this phase, potential expert safety professionals were identified from the Associated General Contractors (AGC) database and local construction projects within the Raleigh area. For the purposes of this study, an expert was defined as a safety professional with over 10 years of experience within construction with extensive knowledge in safety topics. Overall 10 safety professionals accepted participation, and their accumulated experience in construction exceeded 230 years. At the time of participation, all the expert participants were involved in projects located in the Southeast or Northeast United States.

Apart from the industry experts, participation was also sought from academic researchers with expertise in the area of construction safety. Overall 4 academic researchers whose research focus was construction safety participated in the study.

The data were gathered from each expert participant in two stages. The first stage involved in-depth interviews where the participants were asked to identify why construction hazards remained unrecognized at the work interface. Specifically, the expert participants were asked to imagine workers visually examining the work environment for construction hazards. Following this, they were asked to identify possible reasons why certain hazards may remain unrecognized during the examination process.

In the second stage, the results of the hazard recognition activity from one random worker gathered in the first phase was shared with each of the expert participants. This was followed by brainstorming sessions where the experts were asked to examine the results and identify possible reasons why specific hazards remained unrecognized.

For each identified reason, the experts were asked to share additional industry-relevant examples of hazards that may remain unrecognized because of the same phenomena. Overall, 13 factors that impact hazard recognition at the work interface were identified along with relevant examples in the first two phases of this study.

## Research Findings

The research process yielded 13 factors that can impede through hazard recognition at the workplace. The findings are summarized below with relevant examples:

## Operational Unfamiliarity with construction tools and equipment

A large number of construction operations require the use of diverse equipment such as dozers, forklifts, and cranes; and hand tool such as grinders, mechanical saws, and drills. These equipment and tools expose workers to different hazards based on their application and operational features. The research findings suggested that workers may not be familiar with the operation and operational features of certain construction equipment and tools, and, therefore, may not recognize associated safety hazards.

Two construction professionals pointed out that certain tools may be used for the same purpose, however, they may have operational and feature differences. For example, chainsaws that may be used to cut lumber, concrete, or pipes may be either operated using gas or electricity. Accordingly, workers may be exposed to hazards such as an electric source or proximity to flammable substances while operating such equipment. Failure to understand such differences in operational features can lead to hazards that remain unrecognized. In fact, the data gathered from phase I revealed that a participating worker mistook a gas operated saw as being operated using electricity.

Another example brought up by the expert participants included hazards associated with hydraulic equipment and tools that workers may not be aware of due to operational unfamiliarity. Specifically, workers may not recognize significant safety hazards associated with hydraulic fluids in equipment that are under high pressure, the flammable nature of hydraulic fluids, and the potential for burns from hydraulic systems and fluids operating in high temperatures.

### Hazards that are secondary or unassociated with the primary task

Phase I findings suggested that a number of hazards that were unassociated with the primary task being performed remained unrecognized. These hazards were within the work environment but were either secondary or unrelated to the primary task being performed. Follow-up brainstorming sessions with the workers and construction experts revealed that workers tend to focus attention on hazards associated with the primary task, while devoting less attention to other hazards in the work vicinity.

For example, in a case image where excavation was on-going, several workers did not recognize overhead powerlines. In another example, where the primary task was pipe-laying in a trench, workers did not identify a propane gas tank beside the trench. Other examples included not identifying the possibility of falling objects from overhead adjacent work, trip hazards that were within the worksite but not proximate to the primary task, and the possibility of struck by incidents while work is performed adjacent to a site-based traffic route. One of the experts also indicated that inexperienced workers may not recognize vehicular traffic as a potential hazard when the primary task is undertaken adjacent to roadways.

### Hazards perceived to impose low levels of safety risk

Although industry experts from the previous study believed that certain hazards were relevant to safe construction operations, a number of hazards were not identified by the workers during the hazards recognition activity. The follow-up brainstorming sessions with workers revealed that some of these hazards were believed by workers to impose only minimal levels of safety risk. In other words, the workers did not report certain hazards during the hazard recognition activity that they deemed to be within their safety risk tolerance threshold. Previous studies have alluded to such differences in safety risk tolerances between workers and the management.

### Premature termination of hazard recognition

Construction environments generally contain numerous safety hazards. To ensure workplace safety, workers are tasked with recognizing and managing all potential safety hazards. However, workers tend to prematurely terminate the hazard recognition activity when they believe an adequate number of hazards have been recognized.

One expert participant indicated that workers feel a sense "that the job is done" after a few hazards are recognized.  Another safety professional indicated that workers often begin with recognizing the most mundane hazards such as trips, falls, pinch points, etc.; however, they often stop prematurely without evaluating all potential hazards.  He further added that, in most cases, the mundane easily identifiable hazards are not the ones that hurt workers. The ones that hurt them are often the ones they did not expect will hurt them.

In our examination of worker data, the workers on average stopped their hazard recognition search process after they had identified 4 hazards. Several other hazards that were recognized by the expert panel from the previous study remained unrecognized.

### Low prevalence and unexpected hazards

Construction environments are dynamic, and no two construction projects are alike in all aspects. Therefore, workers may be exposed to hazards that they rarely encounter in typical projects, or they may encounter hazards that were unexpected. For example, an expert participant pointed out that snake bites or attack by animals are relatively rare within the U.S. construction industry, and, therefore, such hazards are unexpected and often remain unrecognized. The same expert also pointed out that poisonous plants and insects rarely show up on JSAs although they may be relevant.

Another participant mentioned that hydraulic failure of construction equipment are typically rare, and such hazards often remain unrecognized until failure occurs. Others alluded to the diverse array of chemical and biological hazards that workers may be exposed to in an industrial setting, and in sanitary infrastructure projects which in many cases are unpredictable and rare.

### Visually unperceivable / obscure hazards

Workers largely depend on their visual perception of the work environment to recognize workplace hazards. Hazards that are visually not perceivable are more likely to remain unrecognized. For example, gases (e.g. CO, $H_2S$), vapors (e.g. gasoline), and fumes (e.g. fumes from hot work) that may be colorless and sometimes odorless are more difficult to recognize. High temperature and high pressure pipelines are also generally difficult to recognize because they may not be visually perceivable.

The expert participants mentioned that high temperatures that may be generated from boilers and industrial plants may remain unrecognized because of visual unpercievability. Another participant mentioned that the presence of underground utilities and electrical lines can remain unperceived until contact is made in minor digging and trenching operations.

Apart from visually unperceivable hazards, certain hazards may be obscure within the construction environment although they can be visually perceived. These include hidden hazards such as electrical cables on the floor of a cluttered worksite, hand tools left among other construction material, protruding nails within used or reusable formwork material and others.

### Unexpected and unknown potential hazard set

A typical construction environment contains numerous construction hazards. Workers are tasked with recognizing and managing all potential hazards that can result in undesirable hazard exposure. Even if a single serious hazard remains unrecognized, the consequence can potentially be catastrophic. However, workers may not have precise knowledge of what hazards to expect, what to look for, and how many of them to anticipated. When such knowledge is absent, workers often are unaware of what to look for and how many hazards can be expected.

To illustrate this phenomenon, consider a worker looking for his safety gloves. He has precise information that he will need two of them (i.e. a pair) for both his hands. Therefore, it is unlikely that he will be satisfied after finding only one of them. This would be the case because the worker has prior knowledge of the total number of gloves he would need to work safety and efficiently. However, this is not the case with typical hazard recognition within construction. While workers participate in hazard recognition, no prior knowledge is available regarding the number of hazards they will need to look for. Further, there is no knowledge of what to look for like in the case of specifically looking for the pair of safety gloves.

Because of the absence of such prior knowledge, workers may not know what hazards to particularly look for, and how many of them can be anticipated at the work interface. Subsequently, a number of hazards may remain unrecognized in the workplace.

### Selective attention or Inattention

Although diverse construction operations are associated with numerous hazards, workers often do not recognize certain hazards either due to selective attention or inattention. For example, three workers selectively recognized "gravity" hazards such as trip, slip, and fall potential and other hazards that may lead to stuck-by incidents; however, chemical, biological, and radiation related hazards remained unrecognized. Some workers did not recognize electrical hazards at all despite the presence of electrical cables and electrical equipment in several case images. Another worker only recognized hazards that were in close proximity to workers depicted in the case images, while ignoring other hazards. Further, as indicated previously, few workers only devoted attention to hazards associated with the primary task.

Apart from the findings from the case images, one expert participant indicated that workers may pay close attention to hazards associated with their work task, but may not focus on hazards that adjacent crews may impose on them. Another expert participant indicated that workers while performing their own work tasks, may be oblivious to other hazards in their vicinity.

### Multiple hazards associated with single source or task

Certain hazard sources and activities may be associated with multiple hazards. For example, an electric cable on the floor may be associated with a trip hazard and an electric hazard. In these cases, workers often recognized only one of the hazards (e.g. potential for trip). In several of these instances, workers claimed that they did not recognize other related hazards because they through the hazard(s) associated with the source was already recognized. In another example, workers recognized the sparks generated from a metal cutting operation as a potential ignition source, but did not recognize the harmful fumes generated as a potential hazard.

Other expert participants pointed out that a large variety of construction tools and equipment are associated with multiple hazards that may not all be recognized. For example, tools such as welding machines, circular saws, drills, jack hammers and all construction equipment can be associated with multiple hazards. Workers may assume that all hazards are recognized, even if few hazards remain unrecognized.

### Task Unfamiliarity

Similar to operational unfamiliarity with construction equipment and tools that was discussed earlier, workers may be unfamiliar with certain tasks and their associated safety hazards. This may be because of a lack of experience with certain work tasks or being relatively new to the construction industry. This may also be the case when certain workers may not be aware of task procedures generally undertaken by specialty contractors such as utility work, mechanical work, and demolition.

Although workers representing specific work trades may not be familiar with specialized work tasks and their associated safety hazards, they may still be susceptible to exposure while working in projects involving multiple contractors and crews.

Several of the expert participants pointed out that this was a major reason why certain hazards remained unrecognized in the work environment. Another expert participant mentioned that JSA cannot be accurate if workers are not aware of task procedures. A number of the participants mentioned that several injuries are the result of hazard exposure when multiple crews work in close proximity and workers are unaware of all potential hazards associated with work tasks.

Task unfamiliarity and its association with hazard recognition was also noticed during the hazard recognition activity with the participating workers. For example, when a case image depicting a group of workers preparing to initiate an arc stud welding operation was presented, the participating worker indicated that he was not aware of the operation being undertaken. As a result, he did not recognize several hazards including the fact that sparks will be generated which can become a potential ignition source.

### Latent and stored energy hazards

Construction environments contain several dormant hazards that are not expected or perceived as imposing any imminent danger. Such hazards often remain in work environments as latent or stored energy for extended time periods without causing any harm. However, the unexpected release or trigger of these latent sources of stored energy can result in dramatic injury and illnesses. The dormant nature of such hazards often causes them to remain unrecognized in construction environments.

The study participants mentioned several examples of latent and stored energy hazards. For example, one participant mentioned that the unexpected rupture of high-pressure pipelines, vessels, and hydraulic lines are fairly common within construction and is a leading cause of fatal incidents. Other relevant examples included the potential for cave-ins during excavation and trenching operations, the possibility of arc flash incidents while working on energized equipment, the release of mechanical energy from compressed springs, and unexpected chemical reactions and explosions at the workplace. Several of these types of hazards also remained unrecognized during the hazard recognition activity with workers.

## Hazard Source Detection Failure

Construction environments contain a variety of building materials, equipment, tools, chemicals and environmental features that can cause harm, injury, or illnesses. However, workers may experience challenges detecting every hazardous source within a construction environment.

For example, one expert participant pointed out that a worker may inadvertently contact a certain irritant or chemical in an industrial setting. But the worker may not be able to identify what the source or irritant was despite experiencing the outcome (i.e. irritation). Another example cited by an expert participant was the presence of small patches of mold in structural lumber. The worker may see the patches, but may not recognize that the patches indicate the presence of mold that can cause undesirable health outcomes.

Another expert participant pointed out that workers in rehabilitation and maintenance projects must be cautious of the presence of lead-based paints and asbestos. However, recognizing these hazard sources among other workplace elements may be challenging.

Within the construction case images, some workers expressed their inability to detect certain hazard sources. For example, certain containers contained industrial wastes and flammable material. Although most workers indicated that the containers may contain hazardous material, they were unsure of what the material precisely were. Most of these workers were also not aware of the potential harm that may result from exposure to the elements.

In several instances, the participating workers were not able to recognize certain construction equipment which were potential hazard sources. For example, some workers were unable to recognize that an equipment depicted in the case image was an arc stud welding device. Such challenges with recognizing hazard sources may lead to poor hazard recognition levels.

### Hazards without immediate outcome onset

Hazards that may not cause an immediate undesirable outcome often remain unrecognized in workplaces. One expert participant claimed that hazards where the cause and effect relationship is much more uncertain or not immediately observable often may not receive the attention of workers. One example cited was the effect of exposure to sunlight. The expert participant pointed out that that the exposure to UV radiations in sunlight can result in sunburns. He added that sustained exposure to these radiations can also lead to skin cancer. However, because the impacts are not immediate they often remain unrecognized.

Several participating participants alluded to other hazards of this type such as hazards associated with manual lifting and the adoption of unsafe lifting techniques, and the effect of adopting tools and equipment that induce body vibrations in workers where the effects are not immediate.

Such instances were also prevalent in the hazard recognition activity with construction workers. For example, work requiring improper body postures as depicted in the case images remained unrecognized in many instances; although actions such as bending, kneeling, crouching, and overhead work were present. In addition, hazards such as exposure to concrete dust, silica, welding fumes, and others that do not manifest as immediate effects remained unrecognized in many cases.

## Validation Study

To validate the research findings, a new cohort of 8 workers were recruited to participate in a second hazard recognition activity study. The participating workers represented 4 different trades including civil, electrical, mechanical, and an equipment operator. The workers were employed in 5 different projects in the Southeastern United States during participation.

Similar to the initial study, the workers were tasked with identifying hazards from a random set of 6 construction case images. After the hazard recognition activity, the hazards that were successfully identified and those that remained unidentified were presented to each worker. The workers were then presented with a checklist in the format shown in Figure 2, and each of the factors was briefly explained to the workers. The workers were then asked to indicate on the checklist all factors that were relevant to why specific hazards remained unrecognized during the hazard recognition activity. The workers were allowed to select more than one factor for each hazard if they believed they were relevant to what they experienced.

*Directions:* In your opinion, why did you not recognize specific safety hazards during the hazard recognition activity?

| | ← **Hazard 1 to Hazard n** → | | | |
|---|---|---|---|---|
| | Hazard 1 | Hazard 2 | ………. | Hazard n |
| **1. Operational unfamiliarity with construction tools and equipment**: I was not familiar with the operations and the operational features of the equipment or tool to recognize the associated safety hazard | | | | |
| **2. Hazard that are secondary or unassociated with the primary task**: The hazard was not relevant to the primary task being carried out which I focused on. So, I missed this hazard. | | | | |
| **3. Hazards perceived to impose low levels of safety risk:** The risk associated with the hazard was very low to be regarded as dangerous. So, I disregarded this as being a hazard | | | | |
| **4. Premature termination of hazard recognition:** After identifying several hazards, I thought I identified all of them, so stopped looking for more. | | | | |
| **5. Low prevalence or unexpected hazards:** This hazard is quite rare for the work tasks being carried out and the workplace conditions. So, I missed this | | | | |
| **6. Visually unperceivable / Obscure hazards:** The hazard was not visually perceivable (e.g. hot surfaces, gasses) or was obscure within the workplace for me to recognize | | | | |
| **7. Unexpected and unknown potential hazard set:** I was not sure what hazards I could expect or I needed to look for. So, I missed this hazard | | | | |
| **8. Selective attention or Inattention:** I did not pay attention to this type or category of hazard or I just did not pay attention to this hazard | | | | |
| **9. Multiple hazards associated with single source or task:** I thought I had already identified the hazard(s) associated with this source or task. But it turns out that the source or task was associated with other hazards as well | | | | |
| **10. Task unfamiliarity:** I wasn't aware of the potential hazards associated with the ongoing tasks or operations | | | | |
| **11. Latent or stored energy hazards** The construction hazard was latent or did not impose any immediate danger. However, it is true that a trigger or unexpected release of the stored energy can cause potential injury or illness | | | | |
| **12. Hazard source detection failure:** I wasn't able to identify the source of the hazard (e.g. material, tool, equipment, task, object, etc.). So I wasn't sure what the associated hazard was in this case. | | | | |
| **13. Hazards without immediate outcome onset:** This hazard can cause injury or illness in the long term. But the outcome onset is not immediate. So I did not recognize this hazard | | | | |

**Figure 2: Validation Study Checklist**

The results of the validation study are presented in Table 1. The results indicate that the workers believed that all factors identified in the research study contributed to why certain hazards remained unrecognized in the validation study. Among all factors, the workers indicated that selective attention or inattention was the most common cause of unrecognized hazards. In fact, selective attention and inattention was associated with more than 28% of unrecognized safety hazards. It was followed by "*unexpected* & *unknown potential hazard set"* and perception of workers that certain hazards imposed low levels of safety risk with 16% and 11 % of unrecognized hazards associated with these factors respectively. About 10% of unrecognized hazards were attributed to *Visually unperceivable or obscure hazards*. The findings suggest that the least common factor associated with unrecognized hazards was low prevalence and unexpected safety hazards that accounted for less than 1% of hazards. This is not surprising because these hazards by definition are rare and unexpected within construction environments.

**Table 3: Factors affecting hazard recognition**

| Factors | Frequency | Hazards Associated with this Factor |
|---|---|---|
| 1. Operational unfamiliarity with construction tools and equipment | 27 | 2.9% |
| 2. Hazard that are secondary or unassociated with the primary task | 39 | 4.1% |
| 3. Hazards perceived to impose low levels of safety risk | 103 | 10.9% |
| 4. Premature termination of hazard recognition | 60 | 6.3% |
| 5. Low prevalence or unexpected hazards | 9 | 1.0% |
| 6. Unexpected and unknown potential hazard set | 148 | 15.6% |
| 7. Visually unperceivable / Obscure hazards | 93 | 9.8% |
| 8. Selective attention or Inattention | 273 | 28.8% |
| 9. Task unfamiliarity | 62 | 6.5% |
| 10. Hazard source detection failure | 79 | 8.3% |
| 11. Multiple hazards associated with single source or task | 20 | 2.1% |
| 12. Hazards without immediate outcome onset | 19 | 2.0% |
| 13. Latent or stored energy hazards | 15 | 1.6% |

The findings suggest that the least common factor associated with unrecognized hazards was low prevalence and unexpected safety hazards that accounted for less than 1% of hazards. This is not surprising because these hazards by definition are rare and unexpected within construction environments.

## Theoretical and Practical Implications

The finding of this study advances theoretical knowledge in the area of hazard recognition and construction safety, and has practical implications for industry success. The current study represents the first effort focusing on understanding why construction hazards remain unrecognized at the workplace. The theoretical and practical implications of the study findings are discussed below:

First, the results of the study question the adequacy of traditional safety training practices that solely focus on safety knowledge transfer. The findings suggest that a number of additional factors, apart from safety knowledge, impact hazard recognition performance. For example, human factors such as inattention and selective attention, the nature of hazards such as the visual perceivability, and the inherent nature of the hazard recognition process can all influence performance. Training interventions that are cognizant of these factors may substantially improve both hazard recognition and safety performance.

Second, the findings of the study can be used to improve traditional hazard recognition methods. For example, Job hazard analyses (JHA) tools may be customized to provide workers with mental cues that call to attention potential hazards that may be visually unperceivable. The tools may also be used to alert workers that a single hazard source may be associated with multiple safety hazards, and that workers may be exposed to hazards that are unassociated with the primary tasks.

Finally, researchers and practicing professionals may use the findings of this study to develop new policies, practices, and interventions to improve hazard recognition and safety performance within construction.

## Study Limitations

Despite the strengths of the study, the study has important limitations that must be addressed in future research. First, because of the exploratory nature of the study and the complex mental processes involved in the hazard recognition process, it is possible that additional factors, not identified in this study, may be relevant to why construction hazards remain unrecognized. This is partly because hazard recognition is a complex activity involving mental processes that are both consciously and unconsciously undertaken. While conscious efforts may be easier to recognize, more complex mechanisms are challenging to recognize and verbalize.

Second, the current study heavily relied on construction case images to assess whether specific hazards remained unrecognized. The case images do not capture the reality of construction sites that are more dynamic and uncontrolled. Although additional examples and factors were identified using expert opinion, future efforts may focus on supplementing the current effort by focusing on hazard recognition in actual work environments.

Finally, the scope of this research was limited to capture only downstream factors that impact hazard recognition when workers physically examine the work environment. Future efforts must focus on a more holistic approach by examining both upstream, downstream, and the interaction between these factors impact hazard recognition.

## Conclusion

Hazard recognition is a fundamental component of the safety management program. When safety hazards remain unrecognized, workers are more likely to be injured on-the-job (Albert et al. 2014b). However, past research has demonstrated that a large proportion of construction hazards remain unrecognized in construction projects (Albert et al. 2013; Bahn 2013; Carter and Smith 2006). Consequently, workers are exposed to unanticipated and undesirable safety risk.

To improve hazard recognition levels and reduce injury likelihood, employers adopt diverse hazard recognition methods and training interventions. However, important limitations of these methods and common industry barriers impede through hazard recognition within construction. These findings have encouraged researchers to develop more robust hazard recognition methods and better training practices (Albert et al. 2014c; Wilkins 2011). However, much of this research has progressed without a sufficient understanding of why workplace hazards remain unrecognized

In this study, 13 downstream factors that impact hazard recognition performance were identified. Specifically, these factors were found to be relevant when workers examined the work environment to identify safety hazards. This research represents the first effort to better understand why certain hazards remain unrecognized.

The findings of the study have important implications for the industry. Specifically, the findings challenge the common assumption that knowledge transfer alone is adequate to maximize hazard recognition performance. The results of the study suggest that employers must also focus on human factors such an inattention and selective attention, the nature of hazards such as the visual percievability, and inherent challenges with the hazard recognition processes (e.g. unknown potential hazard set). The findings of this study can be incorporated in future research efforts to develop novel hazard recognition techniques and more robust training interventions.

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# CHAPTER 3: DEVELOPMENT OF PERSONALIZED HAZARD RECOGNITION TRAINING STRATEGY

## Abstract

Recognizing and managing construction hazards is the central focus of all safety management initiatives. Hazards that remain unrecognized or unmanaged can expose workers to unanticipated safety risk, and can potentially result in catastrophic safety incidents. Unfortunately, recent research has demonstrated that a large proportion of safety hazards remain unrecognized in construction workplaces. To improve hazard recognition levels, employers adopt a variety of safety and hazard recognition training programs. However, desirable levels of hazard recognition have not been achieved, and the expected benefits from training have not been attained. Such failure in training efforts has generally been attributed to the adoption of poor and ineffective training practices. While efforts are being undertaken to address these issues, construction research has not focused on developing or evaluating personalized training solutions that are customized to the learning needs of individual workers. To advance theory and practice, the objective of this study was to develop the first personalized training strategy targeted at improving hazard recognition levels. The objective was accomplished by a collaborative effort involving two industry experts and three academic researchers, along with guidance from training literature. The training strategy incorporates important elements known to improve stimuli or threat detection in domains including medicine, the military, and aviation. The elements include (1) visual cues to aid systematic hazard search, (2) personalized hazard recognition performance feedback, (4) personalized eye-tracking visual attention feedback, and (4) metacognitive prompts that trigger the adoption of remedial measures. After development, the effectiveness of the training strategy in improving hazard recognition was empirically evaluated using the non-concurrent multiple baseline testing approach. The findings of the study showed that the participating workers on average were able to identify only 42% of hazards prior to the introduction of the intervention, but were able to recognize 77% of hazards in the intervention phase. The findings of this study will be of interest to practicing professionals seeking to improve hazard recognition levels within construction.

**Keywords:** Construction Safety, Hazard recognition, Hazard identification, Safety management, Safety interventions, Safety training

## Introduction

Alarming injury rates continue to be a worldwide issue within the construction industry. Estimates reveal that more than 60,000 fatal injuries occur every year in construction projects around the world (Lingard 2013). In the United States, the 2014 Bureau of Labor Statistics (2015) reported more than 900 fatal and 200,000 non-fatal construction injuries. Apart from physical and emotional distress, the annual cost of these injuries exceed $48 billion; resulting in significant loss in revenue, profitability, and reputation (Ahmed et al. 2006; Zou and Sunindijo 2015).

Because of such dire consequences, construction safety researchers and practitioners have devoted much effort towards understanding accident and injury precursors (Abdelhamid and Everett 2000; Mitropoulos et al. 2005; Rajendran and Gambatese 2009). Among others, poor hazard recognition levels within construction have received much attention. For example, studies have shown that unrecognized hazards can lead to unexpected and catastrophic injuries (Albert et al. 2014a). Moreover, recent findings have demonstrated that a disproportionate number of construction hazards remain unrecognized in dynamic construction environments (Bahn 2013; Carter and Smith 2006). In fact, Haslam et al. (2005) found that more than 42% of construction injuries are associated with poor hazard recognition and assessment.

To improve hazard recognition levels, construction employers invest millions of dollars towards developing and delivering hazard recognition and safety training interventions. The purpose of these training interventions is to equip workers with the necessary skills to effectively recognize and manage construction hazards. However, despite such efforts, desirable levels of hazard recognition have not been achieved (Albert et al. 2014b; Carter and Smith 2006). In fact, studies have shown that only 10-15% of training investments translate into desirable outcomes in the workplace (Baldwin and Ford 1994; Cromwell and Kolb 2004). Not surprisingly, past studies have not found a positive correlation between the adoption of traditional training methods and safety performance (Li et al. 2012).

Such failure in training efforts within construction is generally attributed to the adoption of poor training practices and methods (Demirkesen and Arditi 2015). Most training programs are delivered using passive instructional or lecture-based techniques that do not sufficiently engage workers (Namian et al. 2016). Wilkins et al. (2011) recommend replacing such unengaging training methods with more engaging methods to achieve desirable safety outcomes. In fact, Haslam et al. (2005) argued that the use of unengaging training methods can instill negative attitudes among workers to safety issues, which in turn can negatively impact safety performance.

To address these issues, recent efforts have focused on developing more engaging and interactive training solutions (Albert et al. 2014b; Li et al. 2012). However, one area that largely remains unexplored in construction is the adoption of personalized training solutions that are tailored to the learning needs of individual workers. Such training methods have gained considerable popularity in other domains, and is quickly replacing the traditional one-size-fits-all training approach (Lin et al. 2014). Personalized training solutions offer several advantages including improved trainee satisfaction, higher return on investments, and the optimal use of time and resources (Dorobat and Nastase 2010). The objective of this research effort is to develop and empirically evaluate the first personalized training intervention for construction hazard recognition.

## Background

### Hazard Recognition in Construction

Hazard recognition is arguably the most important step in the safety management process. Hazards that remain unrecognized are more likely to remain unmanaged, and can result in catastrophic accidents and injuries (Albert et al. 2014a). To prevent such safety incidents, workers adopt a number of hazard recognition methods at the workplace. These methods can broadly be classified as being either predictive or retrospective in nature.

Predictive hazard recognition methods, such as job hazard analyses (JHA), rely on the ability of workers to visualize future work tasks and identify associated safety hazards (Rozenfeld et al. 2010). Examples of other predictive methods include pre-task safety planning sessions and task demand analysis (Mitropoulos and Namboodiri 2011). Despite their usefulness, these methods are associated with important limitations that impede thorough hazard recognition. For example, predictive methods assume that workers are innately able to recognize hazards and predict the sequence of work tasks. However, past research has demonstrated that even experienced workers and supervisors fail to recognize a substantial number of hazards in dynamic work environments (Fleming 2009). Further, tasks, as visualized or planned, is often significantly different from how they are actually performed in the field (Borys 2012). Other secondary limitations associated with such methods (e.g. JHAs) include its inability to capture hazards associated with changes in work scope, and hazards imposed by other crews working in close proximity (Rozenfeld et al. 2010).

Retrospective methods, unlike predictive methods, rely on generalizing knowledge gained from past injuries to prevent future safety incidents (Behm and Schneller 2012; Goh and Chua 2009). Examples of retrospective methods include lessons learned and the use of safety checklists developed using past experience and injury data (Fang et al. 2004). Like predictive hazard recognition methods, retrospective methods have important weaknesses. For example, injury reports and near misses rarely capture detailed information for effective future learning (Dong et al. 2011). Further, the extrapolation of past experience to systematically different projects may not be viable or reasonable.

Because of such limitations and the complex nature of construction activities, desirable levels of hazard recognition have not been achieved within construction. For example, Bahn (2013) showed that novice Australian workers failed to recognize 57% of hazards in work representative environments. Likewise, Carter and Smith (2006) found that up to 33.5% of hazards remained unrecognized in U.K. based projects. More recently, research in the United States found that construction crews on average recognized less than 50% of workplace hazards in diverse projects (Albert et al. 2013). These unrecognized workplace hazards can potentially result in unexpected workplace accidents and injuries.

## Safety Training in Construction

Safety training is one among the most common interventions to improve hazard recognition and workplace safety. The benefits of safety training are widely accepted within the construction community; and its importance has been emphasized in decades of construction research (Haslam et al. 2005; Jaselskis et al. 1996; Toole 2002). Construction employers invest millions of dollars in training their workforce on safety issues including hazard recognition, hazard management, and the adoption of effective injury prevention methods. Despite such efforts, research has demonstrated that construction workers lack essential safety knowledge and skill. In fact, Haslam et al.'s (2005) found that over 70% of construction injuries are linked with inadequate safety knowledge or skill.

Much of these deficits in safety knowledge has been attributed to common industry barriers to effective training. For example, Goldenhar et al. (2001) found that the transient nature of the construction workforce discourages some employers from adopting innovative and resource-intensive training methods. Similarly, Wang et al. (2010) found that productivity pressures and limited training resources at the project level impede training efforts.

Apart from these industry-relevant barriers, training efforts also fail due to the adoption of ineffective, unengaging, and poorly designed training methods. In fact, past research has shown that only 10-15% of training investments translate to true benefits (Baldwin and Ford 1994; Cromwell and Kolb 2004). For example, Haslam et al. (2005) argued that the adoption of classroom type lecture-based training methods do not sufficiently engage workers. Moreover, such unengaging training methods that do not capture the interest of workers can instill negative attitudes among workers to safety-related issues (Haslam et al. 2005). Other researchers have argued that pedagogical instructional approaches must be replaced with andragogical methods that are more appropriate for adult learners (Wilkins 2011). Likewise, Albert e al. (2016) found that high engagement training methods that facilitate dialogue, feedback, and action are associated with higher learning gains. Therefore, it is necessary for research efforts to focus on developing engaging and learner-centric training programs.

## Research Objectives and Point Of Departure

Although recent research has focused on improving training practices, the use of personalized training solutions in construction remains unexplored. Personalized training solutions are customized training programs that are tailored to the needs of individual trainees or learners (Dorobat and Nastase 2010). Generally, such methods first seek to understand what a trainee already knows, and then attempt to customize learning experiences accordingly (Lewis et al. 2011). Personalized training practices have gained increased popularity in diverse domains including healthcare, education, and aviation; and is quickly replacing the traditional *one-size-fits-all* training approach (Lin et al. 2014; Sampson and Karagiannidis 2010). According to Hannun (2009), personalized training solutions eliminate repetition and redundant instruction that has increasingly been shown to be associated with frustration, boredom, and inattention.

This study attempted to develop and empirically test the first personalized training solution for constitution hazard recognition. Accordingly, the research objectives were to (1) identify effective and complementary training practices that can lead to improvements in hazard recognition, (2) integrate the identified training practices to develop a robust personalized training strategy, and (3) empirically evaluate the effectiveness of the developed training strategy as an intervention using experimental methods. The study seeks to advance theoretical and practical knowledge to improve hazard recognition levels within construction.

## Research Methods

The objectives of the study were accomplished in three complementary stages. The first two phases focused on developing the personalized training strategy, and the third phase focused on testing the effectiveness of the strategy in improving hazard recognition levels.

To guide the research process, and to ensure theoretical and practical relevance, a research team comprising of two highly experienced industry professionals and three academic researchers were formed. The industry professionals had accumulated over 56 years of construction experience, and the researcher’s primary area of expertise was in construction safety and intelligent learning systems. The following sections describe the research methods in detail.

### Phase I: Identify core training program elements targeted at improving hazard recognition

This phase focused on identifying core training program elements that could potentially be integrated to develop the personalized hazard recognition training strategy. These core elements were identified through brainstorming sessions among the research team members followed by literature review sessions to identify best practices for integration and implementation. The elements that were identified to be included in the design of the training program included (1) visual cues for systematic hazard recognition, (2) personalized hazard recognition performance feedback, (3) personalized eye-tracking visual attention feedback and self-reflection, and (4) metacognitive prompts to encourage self-diagnosis and correction. The following section briefly describes each of these elements and discusses the rational for including them as part of the training strategy.

### *Visual Cues for systematic hazard recognition*

Hazard recognition involves identifying hazard stimuli amidst numerous irrelevant distractors. However, workers may not have precise knowledge on what hazard stimuli to expect or look for in dynamic environments (Fleming 2009). For example, workers may not have precise knowledge that an underground powerline should be expected during trenching operations, or that an exposure to a certain chemical may occur during demolition operations.

Because workers are often unaware of what hazards to expect, they may randomly examine the work environment, often in a haphazard manner, hoping to detect all hazards. However, these unsystematic hazard search processes often result in suboptimal hazard recognition performance (Nickles et al. 2003) .

When random and less structured approaches to hazard recognition are adopted, workers largely rely on cognitive shortcuts called ‘heuristics’ to make decisions (Albert et al. 2014a). For example, workers may rely on the availability heuristics which is the ease with which past experiences or incidents can be recalled (Kahneman et al. 1982). Although useful, the reliance on such methods can be dangerous for hazard recognition as they can result in biased and incorrect expectations (Albert et al. 2014a). For example, past studies have demonstrated that workers can more easily recall recently witnessed injuries and associated safety hazards (Hallowell and Gambatese 2009). Consequently, workers may detect certain hazard types, while the rest may remain unrecognized. Not surprisingly, JHAs are replete with generic hazards such as slips, trips, falls and pinch points that can be recalled with relative ease; but often do not include radiation and biological hazards even when relevant (Fleming 2009).

Compared to haphazard or random search methods, systematic search methods have resulted in a superior performance in diverse domains including the military, security screening, and construction (Albert et al. 2014a; Nickles et al. 2003; Wang et al. 1997) . For example, when workers follow a systematic procedure such as first inspecting equipment and tools, followed by identifying task-related, and work-environment related hazards, a larger proportion of hazards can be expected to be recognized. This is because systematic search methods provide mental schemas to guide workers through the hazard recognition process unlike random unplanned search operations (Nickles et al. 2003). Despite the superiority of systematic and guided hazard recognition methods, they are rarely used in practice within construction.

For the purpose of this research, it was decided to provide workers with mental schemas based on the Haddon's energy release theory (Haddon 1973). According to this theory, any undesirable exposure to an energy source can potentially result in an injury. Based on this approach, workers were provided with a taxonomy of energy sources that can cause harm to guide the hazard recognition process. This procedure for detecting hazards in construction environment was proposed in previous research conducted by Albert et al. (2013) Table 1 reproduces the energy sources and a few examples that were used as part of the training intervention in this study. Workers can systematically examine the work environment for each of the possible energy sources that can lead to injuries or illnesses.

## Table 1: Energy sources for hazard identification process

| Energy Sources | Definitions and Examples |
|---|---|
| **Gravity** | The force caused by the attraction of all masses to the mass of the earth<br>*Examples: falling objects, collapsing roof, and a body tripping or falling* |
| **Motion** | The change in position of objects or substances.<br>*Examples: vehicle, vessel or equipment movement, flowing water, wind, body positioning: lifting, straining, or bending* |
| **Mechanical** | The energy of the components of a mechanical system, i.e. rotation, vibration, motion, etc. within otherwise stationary piece of equipment/machinery.<br>*Examples: rotating equipment, compressed springs, drive belts, conveyors, motors* |
| **Electrical** | The presence and flow of an electric charge.<br>*Examples: power line, transformers, static charge, lightning, energized equipment, wiring, batteries* |
| **Pressure** | Energy applied by a liquid or gas which has been compressed or is under a vacuum.<br>*Examples: pressure piping, compressed gas cylinders, control lines, vessels, tanks, hoses, pneumatic and hydraulic equipment* |
| **Temperature** | The measurement of differences in the thermal energy of objects or the environment, which the human body senses as either heat or cold.<br>*Examples: open flame and ignition sources, hot or cold surface, liquids or gases, hot work, friction, general environmental conditions, steam, extreme and changing weather conditions* |
| **Chemical** | The energy present in chemicals that inherently, or through reaction, has the potential to create a physical or health hazards to people, equipment, or the environment.<br>*Examples: flammable vapors, reactive hazards, carcinogens or other toxic compounds, corrosives, pyrophorics, combustibles, inert gas, welding fumes, dusts* |
| **Biological** | Living organisms that can present a hazard.<br>*Examples: animals, bacteria, viruses, insects, blood-borne pathogens, improperly handled food, contaminated water* |
| **Radiation** | The energy emitted from radioactive elements, or sources, and naturally occurring radioactive materials.<br>*Examples: lighting issues, welding arc, X-rays, solar rays, microwaves, naturally occurring radioactive material (NORM) scale, or other non-ionizing sources* |
| **Sound** | Sound is produced when a force causes an object or substance to vibrate—the energy is transferred through the substance in waves.<br>*Examples: impact noise, vibration, high-pressure relief, equipment noise* |

### ***Personalized hazard recognition performance feedback***

Personalized performance feedback has played a powerful role in education, training, and knowledge acquisition literature; and has become a proven technique to improving learning, motivation, and performance (Linderbaum and Levy 2010; London 2003). For example, feedback clarifies performance expectations, and can exemplar what good performance looks like. In addition, they can motivate individuals to reduce ineffective practices and focus on areas needing improvement (Mory 2004). For example, Locke et al. (1970) illustrated that when individuals are satisfied with their past performance, their satisfaction triggers a desire to maintain high performance levels. However, when they are dissatisfied with their previous performance, their dissatisfaction triggers a desire to change and improve performance. Similar findings have been reported in construction safety literature (Cameron and Duff 2007).

As part of the training strategy, the research team decided that the hazard recognition performance of workers will be assessed in construction representative environments, and feedback will be provided regarding (1) hazards that were successfully recognized, and (2) hazards that were not recognized. The performance goal for each worker is to identify all hazards present in the work environment.

### ***Personalized eye-tracking visual attention feedback and self-reflection***

The hazard recognition and search process adopted by workers largely depends on hidden mental processes and stored tacit schemas that vary across individuals. These mental processes are largely inaccessible to trainers and often to workers themselves that are involved in the hazard recognition activity (Bojko 2013). However, novel technologies such as eye-tracking have substantially enhanced our ability to acquire and understand otherwise inaccessible cognitive processes using eye movement data. Eye-tracking can provide an objective measure of stimuli that received attention during visual search activities and has found application in aviation, medicine, transportation, and education (Sarter et al. 2007; Tien et al. 2014). For example, eye tracking technology has been used to assess if radiologist focus attention on specific abnormalities during cancer screening (Drew et al. 2013); and if drivers devote attention to roadway signage and hazardous conditions (Konstantopoulos et al. 2012).

For construction hazard recognition, similar to other domains, eye-tracking data can provide information on hazard stimuli that received attention and other that did not receive attention (Dzeng et al. 2016). Further, this information, can be provided as feedback to workers to communicate search process deficiency, trigger self-reflection processes, and improve subsequent hazard search performance (Tien et al. 2014). Although promising, eye-tracking data has not been using for training applications within construction.

To test the feasibility of using eye-tracking for construction hazard recognition training, a pilot study was conducted with a construction worker. Specifically, three construction case image (i.e. photographs) captured from real projects were presented, and the worker was tasked with identifying hazards while using an eyetech VT3 remote eye-tracker. Figure 1 presents an example case image and the resulting visual attention-map that schematically represents specific stimuli that received attention and others that did not receive attention. As can be seen, most of the worker’s attention was on the individual in the excavation. Subsequently, the worker identified the following hazards: (1) possible cave-in of soil, (2) worker on the smooth pipe can potentially fall, and (3) equipment close to the edge of the excavation. However, several other hazards including (1) the unattended gasoline cylinder, (2) electrocution possibility from cables, (3) potential for trips (4) stability of unsecured pipe, (5) awkward body position of the individual leaning on the pipe, and (6) pinch-points from handling pipes did not receive attention; and as a result were not identified. Furthermore, the worker did not notice other issues such as OSHA requirements for ladder clearance and access that were violated.

**Figure 1: Pilot study participant's visual attention-map**

Using the attention-maps and the scan gaze the researchers triggered self-reflection activity by asking the worker to evaluate his own performance. Specifically, the researchers prompted the worker to examine the photograph and assess (1) hazard stimuli that received attention and were subsequently identified (i.e. recognized), (2) hazard stimuli that did not receive attention and were not subsequently identified (search error), and (3) hazard stimuli that appeared to have receive attention (i.e. fixated) but were not identified (detection error). This assessment and feedback process was continued with two additional case images that constituted the pilot study training. In subsequent tests, the worker demonstrated an improvement of over 20% in hazard recognition performance. Based on the findings of the pilot test, the research team decided to include the eye-tracking procedure as part of that training strategy.

#### ***Metacognitive prompts to facilitate self-diagnosis and correction.***

Metacognition has recently received much attention in education and training literature, and has been identified as one of the most influential predictors of quality learning (Karaali 2015; Tomlinson and McTighe 2006). Simply put, metacognition is the process of reflective introspection of one's own cognitive process to identify performance weaknesses and strengths (Flavell 1979). Such an understanding can trigger the adoption of remedial or self-regulatory measures to overcome observed weaknesses if any (Berthold et al. 2007).

For example, a student that is unsatisfied with his grade in an undergraduate math exam may decide to diagnose his weaknesses. Specifically, he may ask himself: "Why have I performed poorly?" and "How may I improve?" Through introspection, he may realize that he has trouble with calculus concepts but not with algebra related topics. Having determined his weakness, he may change his learning strategy or devote additional effort to improve his performance in calculus.

While such metacognitive practices are useful to improve performance, novice learners may struggle with adopting effective metacognitive strategies. To facilitate effective metacognition, Berthold et al. (2007) recommend that instructors use metacognitive prompt to trigger introspection, self-diagnosis, and correction in learners. For example, a student may be prompted by the instructor to diagnose weaknesses by encouraging him to ask questions such as: “What topics do I completely not understand?”, “How can I improve my future performance”, or “what learning strategies can I adopt to improve performance?”

In construction, if a worker does not identify specific hazards associated with a work scenario, metacognition activity may be prompted. For example, trainers may prompt metacognition by asking workers to introspect their hazard recognition performance by answering the following questions:

- Why did I not recognize this specific hazard?
- Did I not recognize this hazard because it was unassociated with the primary task?
- Did I not recognize this hazard because I was unfamiliar with the equipment or task being performed?
- Did I not recognize this hazard simply because I did not expect it to be present in the work scenario?
- How can I improve my performance next time?

For the purposes of this study, the researchers decided to prompt trainee metacognition by asking workers to self-diagnose underlying reasons why specific hazards remained unrecognized. To guide the self-diagnosis, workers shall be presented with a catalogue enlisting underlying reasons why hazards generally remain unrecognized in construction. This catalogue was developed based on recent research findings as presented in Figure 2.

*Directions:* In your opinion, why did you not recognize specific safety hazards during the hazard recognition activity?

| | ← **Hazard 1 to Hazard n** → | | | |
|---|---|---|---|---|
| | Hazard 1 | Hazard 2 | ……… | Hazard n |
| **1. Operational unfamiliarity with construction tools and equipmen**t: I was not familiar with the operations and the operational features of the equipment or tool to recognize the associated safety hazard | | | | |
| **2. Hazard that are secondary or unassociated with the primary task**: The hazard was not relevant to the primary task being carried out which I focused on. So, I missed this hazard. | | | | |
| **3. Hazards perceived to impose low levels of safety risk:** The risk associated with the hazard was very low to be regarded as dangerous. So, I disregarded this as being a hazard | | | | |
| **4. Premature termination of hazard recognition:** After identifying several hazards, I thought I identified all of them, so stopped looking for more. | | | | |
| **5. Low prevalence or unexpected hazards:** This hazard is quite rare for the work tasks being carried out and the workplace conditions. So, I missed this | | | | |
| **6. Visually unperceivable / Obscure hazards:** The hazard was not visually perceivable (e.g. hot surfaces, gasses) or was obscure within the workplace for me to recognize | | | | |
| **7. Unexpected and unknown potential hazard set:** I was not sure what hazards I could expect or I needed to look for. So, I missed this hazard | | | | |
| **8. Selective attention or Inattention:** I did not pay attention to this type or category of hazard or I just did not pay attention to this hazard | | | | |
| **9. Multiple hazards associated with single source or task:** I thought I had already identified the hazard(s) associated with this source or task. But it turns out that the source or task was associated with other hazards as well | | | | |
| **10. Task unfamiliarity:** I wasn't aware of the potential hazards associated with the ongoing tasks or operations | | | | |
| **11. Latent or stored energy hazards** The construction hazard was latent or did not impose any immediate danger. However, it is true that a trigger or unexpected release of the stored energy can cause potential injury or illness | | | | |
| **12. Hazard source detection failure:** I wasn't able to identify the source of the hazard (e.g. material, tool, equipment, task, object, etc.). So I wasn't sure what the associated hazard was in this case. | | | | |
| **13. Hazards without immediate outcome onset:** This hazard can cause injury or illness in the long term. But the outcome onset is not immediate. So I did not recognize this hazard | | | | |

**Figure 2: Metacognitive prompts for self-diagnosis and correction**

Following the diagnosis, workers are asked to reflect on strategies that they could adopt to improve hazard recognition performance. For example, in one of our trials in this study, a worker assessed that he did not identify multiple hazards that were unrelated to the primary task being performed. As a remedial measure, he decided to ensure he focuses on relevant hazards that may be unassociated with the primary task but within the work area.

## Phase II: Integration of core training elements to develop the personalized training strategy

The training strategy was developed by integrating the core training elements identified in Phase I. Based on brainstorming sessions, the researchers decided to adopt the training strategy as depicted in Figure 3.

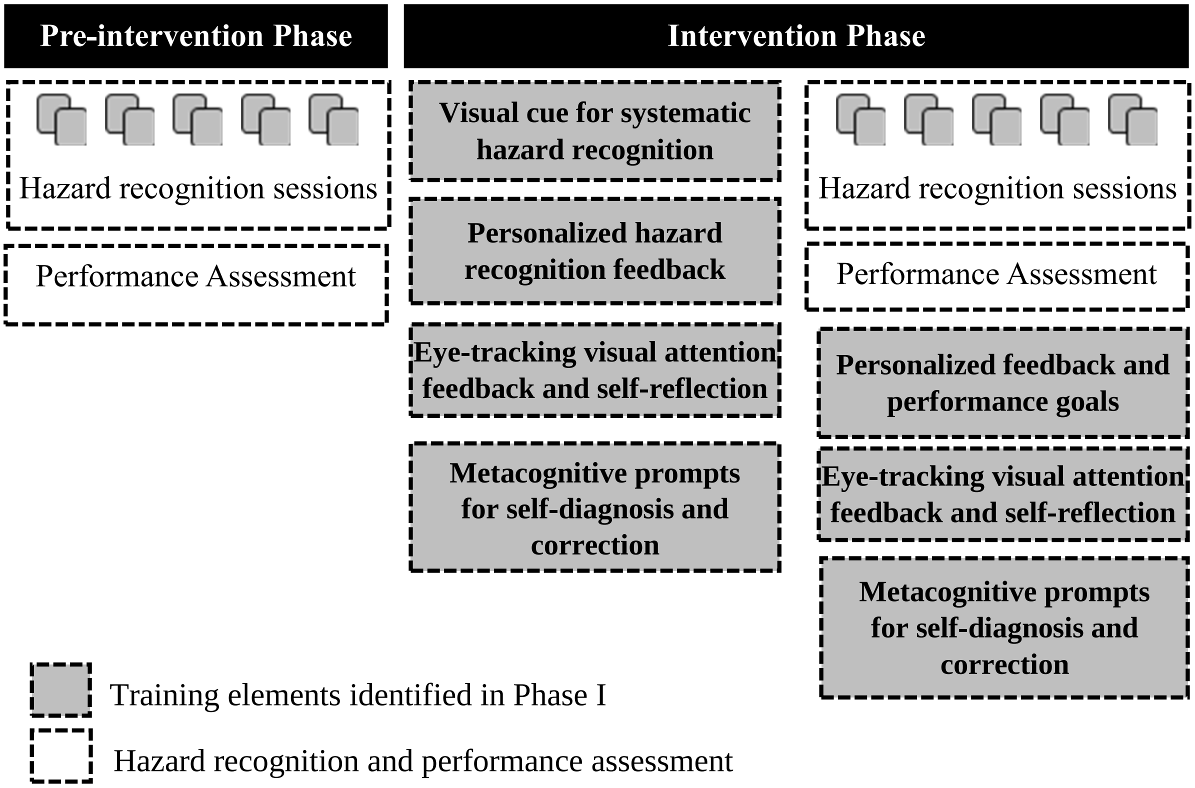


**Figure 3: Personalized training strategy**

As can be seen, the pre-intervention phase includes multiple hazard recognition sessions where baseline performance of individual workers is assessed. These sessions, based on the preference of the trainers, may be held in real workplaces, virtual environments, or using captured videos and photographs from real construction sites. The performance of workers with respect to hazards successfully recognized, and others that remain unrecognized shall be captured. In addition, the hazard recognition performance of workers shall be quantitatively computed as the ratio between the hazards successfully recognized and the total number of hazards.

The following intervention phase is sub-divided into two portions. In the first portion, the workers are introduced to the visual cues that facilitate systematic hazard recognition, and personalized feedback is provided in accordance to their performance in the pre-intervention phase. In addition, the personalized eye tracking attention-maps and the metacognition prompts are adopted as described in Phase I using the pre-intervention phase data.

The second portion of the intervention phase includes a new set of hazard recognition sessions where performance assessment similar to the pre-intervention phase is performance. After each individual session, the three training elements as shown in Figure 3 are adopted to facilitate additional practice and skill acquisition. Such repetitive practice, performance assessment, and feedback sessions have been shown to be related to higher learning gains than standard one-time training procedures (Nicol and Macfarlane-Dick 2006). Further, the trainer shall compare performance changes between the pre-intervention and intervention phase to assess learning gains and progress.

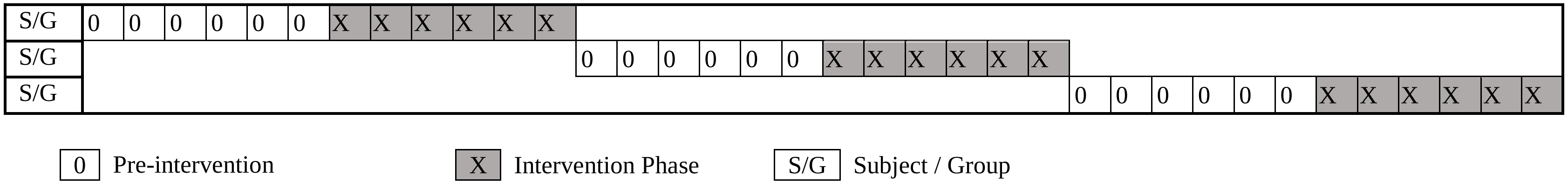
## Phase III: Empirical testing of training strategy using non-concurrent multiple baseline testing

### *Selection of Experimental design*

The objective of this phase was to test whether the introduction of the personalized training strategy would lead to improvements in hazard recognition performance among construction workers. To effectively test the hypothesis, the researchers decided to use longitudinal repeated measure-based experimental methods that directly measure change. Cross-sectional methods that measure the response variable at only one static occasion were dismissed as they are inadequate for capturing performance change or making causal claims (Diggle 2009). Likewise, two-wave studies that measure the response variable once during the pre-intervention and intervention phase were dismissed because such methods are more susceptible to measurement errors and cannot capture change over time (Ployhart and Vandenberg 2010). Given that the personalized training strategy provided additional learning opportunities across the intervention phase, longitudinal methods, that model change longitudinally, were preferable.

Among longitudinal experimental methods, standard before-after (AB) longitudinal methods were dismissed because of the method’s inherent weaknesses in differentiating intervention effects and the effects of confounding nuisance variables (Dimitrov and Rumrill 2003). Withdrawal designs were dismissed because the withdrawal of an effective safety intervention is unethical, and the reversal of interventions effects such as skill acquisition (e.g. hazard recognition ability) is impractical (Barlow et al. 2009).

After careful consideration, the research team decided to use the multiple baseline testing approach. Multiple baseline testing involves a series of longitudinal before-after (AB) studies replicated across subjects or groups within the same study (Hawkins et al. 2007). Each of these longitudinal studies may be conducted simultaneously (i.e. concurrent multiple baseline testing) or sequentially (i.e. non concurrent multiple baseline testing) (Christ 2007). Because of the personalized nature of the intervention, the researchers decided to use the non-concurrent multiple baseline testing approach that is schematically represented in Figure 4.



| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S/G | 0 | 0 | 0 | 0 | 0 | 0 | X | X | X | X | X | X | | | | | | | | | | | | | | | | | | | | | | | | |
| S/G | | | | | | | | | | | | | 0 | 0 | 0 | 0 | 0 | 0 | X | X | X | X | X | X | | | | | | | | | | | | |
| S/G | | | | | | | | | | | | | | | | | | | | | | | | | 0 | 0 | 0 | 0 | 0 | 0 | X | X | X | X | X | X |

0 Pre-intervention

X Intervention Phase

S/G Subject / Group

Figure 4: Non-concurrent multiple baseline testing approach

A notable characteristic of multiple bassline studies is that the intervention is introduced in a staggered or time-lagged fashion. In other words, the intervention is not introduced to all subjects or groups at the same time. Rather they are introduced in sequence one after the other as shown in Figure 4. Evidence of causality is strong when similar patterns of change are observed for all the subjects or groups when the intervention is introduced (Christ 2007).

### Empirical testing and hazard recognition performance assessment

To test the effectiveness of the personalized training strategy, participation were sought from construction workers in the United States. Overall, 8 workers representing 4 different trades including civil, electrical, mechanical, and equipment operations accepted participation. The workers were employed in 5 different construction projects located in the Southeastern United States during participation.

After gathering demographic information for each worker, the experimental study followed the same procedure as depicted in Figure 3 and as discussed in Phase II. For the hazard recognition sessions and to assess performance in the pre-intervention and intervention phase, the researchers used construction case images captured from real projects in the United States. The construction case images were captured in a previous research effort by a panel of 17 construction professionals representing Construction Industry Institute (CII) member organizations (Albert et al. 2013). The case images included a wide range of construction operations including welding, grinding, excavation, pipe laying, stud welding and others. After the case images were gathered, the expert panel members pre-identified hazards in each of the case images through brainstorming sessions. The pre-identified hazards were useful in the current study to assess hazard recognition performance of each of the participating workers and to provide personalized feedback.

For the purposes of this study 24 construction case images were adopted and were randomly assigned into 12 sets. Six of these random sets were used to assess hazard recognition performance (i.e. during the hazard recognition sessions) of workers in the pre-intervention phase, and the other 6 were used in the intervention phase. Each set included two construction case images, rather than one, to reduce any bias that may result from performance variability in one case image. For example, an electrician may be able to recognize more hazards associated with electrical work, but his performance across multiple case images may be more reflective of this overall ability.

Throughout the hazard recognition sessions, for each case image, the workers verbally identified hazards. This was catalogued by a researcher who played the role of the trainer. In addition, the hazard recognition performance for each case image ($HR_i$) was calculated using Equation 1. The overall hazard recognition performance of each worker ($HR$), for each session, was computed as the average performance across the two case images in a set. The procedure yielded 6 data points during the pre-intervention phase, and 6 additional data points in the intervention phase for each worker.

$$HR_i = \frac{HR_{worker}}{HR_{total}} \quad (1)$$

Where $HR_{worker}$ represents the total number of hazards identified by the worker in a specific construction case image *i*; and $HR_{total}$ represents the total number of hazards identified by the expert panel and the worker for the same case image.

## Non-concurrent multiple baseline testing analysis strategy

In accordance with the non-concurrent multiple baseline testing procedure, the 8 workers sequentially – one after the other – participated in the study. The interventions for all workers were introduced after the sixth hazard recognition session.

The effectiveness of the intervention was estimated by comparing each workers' hazard recognition performance ($HR_i$) in the pre-intervention and intervention phase using interrupted longitudinal regression analysis. The pre-intervention data provided an estimate and variability of each worker's initial hazard recognition ability prior to the intervention. This data was then used to predict each worker's performance during the intervention phase in the hypothetical case that the intervention was not introduced. The difference between the hypothetically projected performance and the actual performance in the intervention phase provided a reliable measure of the intervention effects.

To achieve this objective, the multiple baseline testing procedure recommended by Albert et al. (2015) was followed. Accordingly, the mathematical regression models proposed by Huitema and McKean (2000, 2007) were estimated and compared to choose the most suitable statistical model. The mathematical models are presented as Equation 2 (Model I) and Equation 3 (Model II).

Model I $$HR = \beta_0 + \beta_1 T_t + \beta_2 D_t + \beta_3 SC_t + \varepsilon_t \quad (2)$$

Model II $$HR = \beta_0 + \beta_2 D_t + \varepsilon_t \quad (3)$$

> Where, *HR* is the performance of each worker in the hazard recognition sessions, $\beta_0$ is the intercept of the regression line, $\beta_1$ is the slope in hazard recognition performance in the pre-intervention phase; $\beta_2$ is the level (i.e. immediate) change measured at the seventh hazard recognition session (i.e. immediately after intervention is introduced), $\beta_3$ is the change in slope from the pre-intervention phase to the intervention phase; $T_t$ is the value of the hazard recognition session variable T at session *t* (analogous to time); $D_t$ is the value of the level-change dummy variable D (0 for the pre-intervention phase and 1 for the intervention phase) at session t; $SC_t$ is the value of the slope-change variable SC defined as $[T_t - (n_1 + 1)]D$; $\varepsilon_t$ is the error in performance at hazard recognition session t;

As can be seen, both models include the level change coefficient ($\beta_2$) which estimates the immediate change (e.g. improvement) after the intervention is introduced (i.e. seventh hazard recognition session). The slope change coefficient ($\beta_3$), on the other hand, estimates the change in the slope between the pre-intervention and intervention phase, which captures additional change (e.g. improvement) after the intervention is introduced beyond the seventh hazard recognition session. Both mathematical models are discussed in detail in Albert et al. (2015).

The first step in the analysis procedure involved the estimation of both mathematical models by regressing the response variable over the respective predictor variables. After both models were estimated, a model comparison test was conducted to test the null hypothesis that the slope in the pre-intervention and intervention phase is equal to zero (i.e. $\beta_1 = \beta_3 = 0$) using Equation 5. If the null hypothesis is accepted, then $\beta_1$ and $\beta_3$ in Model I can be assumed to be equivalent to zero, thereby reducing Model I to Model II. In this case, Model II is more appropriate to draw inferences, and provides stronger statistical power because of fewer model parameters. On the other hand, if the null hypothesis is rejected, then Model I that captures the slopes is more appropriate to capture additional performance beyond the seventh hazard recognition session.

$$F = \frac{(SS_{Reg\ ModelI} - SS_{Reg\ ModelII})/2}{MS_{Reg\ ModelI}} \qquad (5)$$

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 the selection of the appropriate model, the assumption of independent errors was (i.e. autocorrelation) tested. This test is important when repeated measures are gathered over several sessions, and there is a possibility that errors between subsequent hazard recognition sessions may be correlated. To test for the presence of autocorrelation, the null hypothesis that the lag-1 autocorrelation between observations is equal to zero (i.e. ($\rho = 0$) was tested using the Durbin-Watson test and the Huitema-McKean test. If the null hypothesis is accepted, the previously selected models (i.e. Model I and Model II) adequately represent the data. But, if rejected, alternate models that account for autocorrelation as discussed in Albert et al. (2015) must be adopted.

After the selection of the suitable mathematical model, the obtained regression coefficients provide the measure of change – either positive or negative – in terms of the level change and the slope change. The aggregate overall change for all the eight participants was computed using the reciprocal of error variance as shown Equation 6.

$$LC_{overall} = \frac{\sum_{j=1}^{J} \frac{1}{\sigma_j^2} b_{LC_j}}{\sum_{j=1}^{J} \frac{1}{\sigma_j^2}} \qquad (6)$$

Where J is the number of workers (i.e. 8); $b_{LC_j}$ is the level change coefficent estimated for the jth crew; $\sigma_j^2$ is the estimated standard error for the jth level change coefficient

# Results and Discussions

Figure 5 schematically presents the hazard recognition performance of two example workers (i.e. worker 1 ad worker 7) across all hazard recognition sessions, and Table 2 presents the analysis results for all workers.

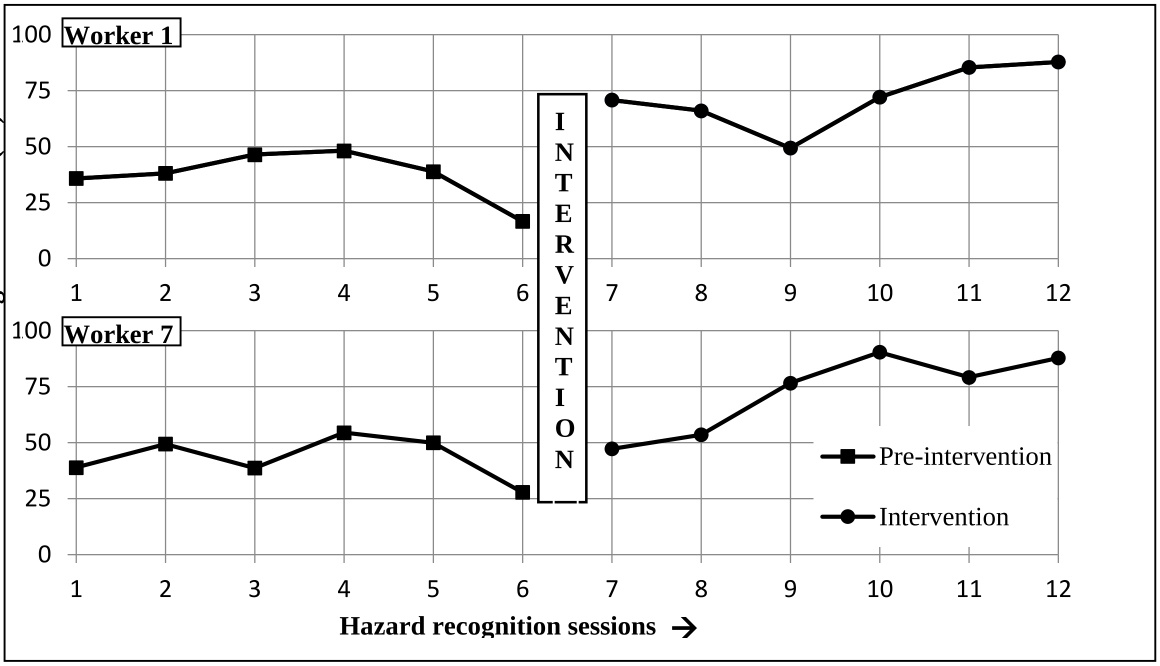


Figure 5: Hazard recognition performance of worker 1 and worker 7

## Table 4: Results of non-concurrent multiple baseline experiment

| Predictor | Coefficient | Std. Error | *t*-value | *p*-value | Model test ($F_{critical} = 4.459$) | $r^2$ | D-W test | $p_{H\text{-}M\ test}$ ($\alpha = 0.05$) | $p_{Levene's}$ ($\alpha = 0.05$) | $p_{A\text{-}D}$ ($\alpha = 0.05$) |
|---|---|---|---|---|---|---|---|---|---|---|
| *Worker 1* | | | | | | | | | | |
| Constant | 37.355 | 5.184 | 7.206 | 0.000 | *Model II*<br>$F_{obt} = 1.869$ | 0.690 | 1.266 | 0.070 | 0.623 | 0.202 |
| D | 34.602 | 7.331 | 4.720 | 0.001 | | | | | | |
| *Worker 2* | | | | | | | | | | |
| Constant | 37.208 | 4.564 | 8.153 | 0.000 | *Model II*<br>$F_{obt} = 0.945$ | 0.452 | 2.469 | 0.634 | 0.242 | 0.498 |
| D | 18.533 | 6.454 | 2.871 | 0.017 | | | | | | |
| *Worker 3* | | | | | | | | | | |
| Constant | 38.347 | 4.656 | 8.235 | 0.000 | *Model II*<br>$F_{obt} = 0.618$ | 0.747 | 1.484 | 0.126 | 0.796 | 0.443 |
| D | 38.073 | 6.585 | 5.782 | 0.000 | | | | | | |
| *Worker 4* | | | | | | | | | | |
| Constant | 32.992 | 4.721 | 6.988 | 0.000 | *Model II*<br>$F_{obt} = 0.009$ | 0.773 | 2.397 | 0.772 | 0.858 | 0.639 |
| D | 38.922 | 6.677 | 5.829 | 0.000 | | | | | | |
| *Worker 5* | | | | | | | | | | |
| Constant | 56.485 | 4.252 | 13.285 | 0.000 | *Model II*<br>$F_{obt} = 1.241$ | 0.622 | 2.412 | 0.603 | 0.752 | 0.053 |
| D | 24.403 | 6.013 | 4.059 | 0.002 | | | | | | |
| *Worker 6* | | | | | | | | | | |
| Constant | 60.585 | 4.755 | 12.742 | 0.000 | *Model II*<br>$F_{obt} = 0.0.824$ | 0.392 | 2.519 | 0.407 | 0.919 | 0.311 |
| D | 17.070 | 6.724 | 2.539 | 0.029 | | | | | | |
| *Worker 7* | | | | | | | | | | |
| Constant | 36.158 | 6.742 | 5.363 | 0.001 | *Model I*<br>$F_{obt} = 5.040$ | 0.898 | 2.258 | 0.434 | 0.592 | 0.374 |
| Time | 0.198 | 1.731 | 0.114 | 0.912 | | | | | | |
| D | 13.005 | 8.540 | 1.523 | 0.166 | | | | | | |
| SC | 6.669 | 2.448 | 2.724 | 0.026 | | | | | | |
| *Worker 8* | | | | | | | | | | |
| Constant | 44.817 | 10.351 | 4.330 | 0.003 | *Model I*<br>$F_{obt} = 7.873$ | 0.804 | 2.259 | 0.487 | 0.276 | 0.057 |
| Time | -0.851 | 2.658 | -0.320 | 0.757 | | | | | | |
| D | 12.634 | 13.111 | 0.964 | 0.363 | | | | | | |
| SC | 9.246 | 3.759 | 2.460 | 0.039 | | | | | | |

For worker 1, both Model I and Model II were estimated, and the model comparison test was performed. The obtained value of F ($F_{obj}$ = 1.87) computed using Equation 2 was compared with the critical value of F ($F_{critical}$= 4.45) which was calculated using an alpha level of 0.05 and the degree of freedom (*df = 2,8*). The model comparison test suggested that Model II was preferable for worker 1 over Model I.

The Durbin-Watson test and the Huitema-McKean test did not reveal any evidence of autocorrelation for any of the workers. Therefore, the selected models were appropriate, and alternate models that account for autocorrelation were not necessary. The Levene's test for the homogeneity of error variance and the Anderson-Darling test for normality of errors returned a p-value greater than the alpha value of 0.05. Therefore, the assumption of equal error variance and the normality of errors were reasonable to infer.

As shown in Table 3, worker 1 demonstrated a level change improvement of 34.60% in hazard recognition immediately after receiving the intervention. This value represents the difference between the projected performance in the absence of the intervention and actual performance in the seventh hazard recognition session. The projected performance for the seventh hazard recognition session was 37.35% ($\beta_0 + \beta_2$ D), where D assumes the value zero for the prediction in the pre-intervention phase. Whereas, the actual estimated performance using the intervention data was 72.96% (D=1). The difference in performance between the two phases, as shown in Table 3, is 34.60%; and the difference is statistically significant (*p-value* < 0.05). Similarly, workers 2 through worker 6 demonstrated only level change improvements in performance (i.e. Model II); and in each case, the observed improvement was statistically significant (*p-value* $< 0.05$).

Worker 7 demonstrated a level change improvement of 13%. In this case, the projected performance using the pre-intervention data was 37.54% ($\beta_0 + \beta_2$ T + $\beta_3$ D + $\beta_4$ SC); where T=7, D=0, and SC=0. The estimated performance based on the intervention data was 50.55%; where T=7, D=1, and SC=0. The difference between the two values is 13% which represents the immediate change in performance in the seventh hazard recognition session. However, the associated *p*-value suggested that the level change was not statistically significant. Similar trends were demonstrated by worker 8.

The slope change coefficient of 6.67% for worker 7 represents the change in slope between the pre-intervention and intervention phase performance. The slope change captures any additional improvements in performance beyond the seventh hazard recognition session. Based on the results in Table 3, the slope in the intervention phase is 6.87% (6.67+0.20) which is the sum of the pre-intervention phase slope and the slope change coefficient. Therefore, as the worker progressed through each hazard recognition session in the intervention phase, an improvement of 6.87% in hazard recognition was observed. Overall, the worker was able to recognize over 84% of hazards at the end of the experiment. The *p*-value associated with the slope change suggests that the change is statistically significant. Likewise, worker 8 also demonstrated a significant slope change as presented in Table 3.

Finally, the overall level-change summarizing the net improvement across all the 8 workers was computed using Equation 5. The weighted average indicated that the workers demonstrated a level change improvement of 26.33% (*p-value* < 0.05). Similarly, the overall slope change for the two workers that demonstrated slope change (worker 7 and 8) was 5.34 (*p-value* < 0.05). The cumulative evidence, therefore, suggests that the intervention was effective in improving the hazard recognition performance of all the workers.

## Contributions and Study Implications

The study findings have practical implications for worker safety, and significantly contributes to the training literature within construction. The current effort represents the first formal attempt to develop a personalized training solution for construction hazard recognition. Unlike traditional training methods, the personalized training strategy facilitates proactive performance assessment and feedback to improve hazard recognition performance of workers. The strategy also equips workers with visual cues that enable systematic hazard search as opposed to haphazard methods that are traditionally adopted by workers.

Apart from personalized feedback and visual cues, the current strategy represents the first effort to incorporate eye-tracking technology for construction hazard recognition training. Eye-tracking technology has been successfully used for training purposes in diverse domains including aviation, emergency response, and the military (e.g. Sarter et al. 2007; Tien et al. 2014); and offers breakthrough opportunities for construction safety training. The current effort also represents the first attempt in incorporating metacognitive strategies that facilitate introspection, self-diagnosis, and correction for hazard recognition training.

Overall, the study findings suggests that the developed training strategy is effective in improving the hazard recognition ability of workers. In fact, each participating worker demonstrated a significant improvement in performance in the intervention phase. The improvements ranged from 17% for worker 6 to over 50% for worker 8. On average, the workers identified 42% of hazards in the pre-intervention phase; but were able to identify 76.6% of hazards at the end of the intervention phase.

Finally, the pre-intervention hazard recognition data confirms recent findings that a large number of construction hazards remain unrecognized in work-representative environments (Albert et al. 2013; Bahn 2013; Carter and Smith 2006). The findings reinforce the need for research that focuses on developing effective interventions that target hazard recognition performance.

## Study Limitations and Future Research Recommendations

Although the current study has its strengths, there are few limitations that may be addressed in future research. The most significant limitation is the use of construction case images to capture hazard recognition performance of workers. While the case images depicted real construction operations from projects within the United States, they do not capture the true dynamic nature of construction operations. Nonetheless, the use of construction case images provided a standardized approach to measure hazard recognition and provide feedback to workers. In addition, past research has demonstrated a strong correlation between the performances of workers in case images and real construction environments (Albert et al. 2013). Future efforts may extend the current research by conducing personalized training sessions in real workplaces.

Another typical concern in such observational studies is the observer effect, in which subjects may modify behavior because of the presence of an observer. In the current study, despite the presence of a researcher, hazard recognition performance was lower in the pre-intervention phase; and substantially increased in the intervention phase. Further, while research subjects may alter behavior while being observed, changes in skills such as those required for hazard recognition is unlikely to occur as a result of observer effects. Like most effective training methods, the current training strategy required significant levels of interaction between the trainee and the trainer throughout the training process. Future studies will focus on developing a computer-based automated personalized training strategy that excludes the need for a dedicated observer or trainer.

Finally, despite the longitudinal nature of the current study, the long term impacts of the intervention beyond the study period remain unknown. Specifically, it is unknown if the improvements in hazard recognition performance will sustain in the long term. Follow-up evaluation of hazard recognition performance was not possible due to the difficulty in keeping track of worker as they transitioned to different projects and locations. While the researchers believe that the intervention effects will sustain as long as employers reinforce learning through continuous training, future efforts must focus on evaluating the long-term impacts of personalized training solutions.

Apart from addressing the study limitations, future efforts must also focus on evaluating the relative effectiveness of each of the training elements incorporated in the current training strategy. Future research must also focus on assessing the impact of improved hazard recognition on recordable injury rates and safety performance.

## Conclusion

Proper hazard recognition is one of the most essential steps in the safety management process. When hazards remain unrecognized or unmanaged, the likelihood of construction injuries dramatically increases (Albert et al. 2014a). Unfortunately, past research has demonstrated that an unacceptable proportion of construction hazards remain unrecognized in typical projects, thereby exposing workers to unanticipated safety risk (Carter and Smith 2006).

To improve hazard recognition levels, construction employers adopt a wide variety of hazard recognition methods and training procedures. However, desirable levels of hazard recognition have not been achieved due to inherent limitations in traditional hazard recognition methods and training practices.

To address the issue of low hazard recognition levels within construction, the objective of this research was to develop the first personalized hazard recognition training strategy for workers. Unlike traditional training methods, the personalized training facilitates proactive assessment of hazard recognition performance of workers to facilitate tailored feedback. Moreover, the strategy promotes systematic hazard recognition using visual cues, uses eye-tracking technology to facilitate search process feedback, and uses metacognitive prompts to encourage the adoption of remedial measures.

To empirically evaluate the effectiveness of the training strategy, experimental non-concurrent multiple baseline studies were conducted with 8 construction workers. The results indicated that workers on average recognized only 42% of hazards prior to receiving the intervention, but were able to recognize over 76% of hazards in the intervention phase.

The study represents the first attempt to develop and empirically test the effectiveness of a personalized hazard recognition training strategy. The results of the study would be of interest to practicing professionals that are interested in adopting effective training methods targeted at improving hazard recognition performance within construction.

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# CHAPTER 4: CONCLUSIONS AND RECOMMENDATIONS

# Introduction

Unacceptable injury rates within construction is a global issue. Despite efforts to pursue zero incident projects, a large number of injuries are reported from construction projects around the world (Lingard 2013). In the United States, more than 900 fatal and 200,000 non-fatal construction injuries have been recorded in 2014 (BLS 2015).. Apart from physical pain and emotional distress, the staggering cost of safety incidents adversely impact project success, profit-margins, and reputation (Ahmed et al., 2006; Jaselskis 1996).

Among injury causal factors, inadequate hazard recognition has been identified as a leading cause of construction injuries. In fact, according to Haslam et al. (2005) over 42% of construction injuries are associated with inadequate hazard recognition or assessment.

Despite the importance of hazard recognition in the safety management process (Mitropoulos et al. 2005, Albert et al, 2013), past studies have shown that a large number of construction hazards remain unrecognized (Carter & smith 2006, Bahn 2013, Albert et al 2013). Such unrecognized hazards expose construction workers to unanticipated safety risk and injury potential (Albert et al, 2013).

Although employers adopt a wide variety of hazard recognition methods and training programs to improve hazard recognition, desirable levels of hazard recognition have not been achieved (Albert et al. 2014; Carter and Smith 2006). This is partly because traditional hazard recognition methods and training programs are developed without a concrete understanding of why construction hazards remain unrecognized. In fact, no previous research effort has focused on why construction hazards remain unrecognized at the work interface.

To advance knowledge and practice, the objective of this research was to identify why construction hazards remain unrecognized, and develop a personalized hazard recognition training strategy to improve hazard recognition levels.

## Theoretical and Practical Research Contributions

The first contribution of the study is the identification of field-level challenges that impede thorough hazard recognition in construction. Table 1 lists the 13 factors identified in this study.

**Table 1: Factors that impede thorough hazard recognition**

| Factors identified in the study |
|---|
| 1. Operational unfamiliarity with construction tools and equipment |
| 2. Hazard that are secondary or unassociated with the primary task |
| 3. Hazards perceived to impose low levels of safety risk |
| 4. Premature termination of hazard recognition |
| 5. Low prevalence or unexpected hazards |
| 6. Unexpected and unknown potential hazard set |
| 7. Visually unperceivable / Obscure hazards |
| 8. Selective attention or Inattention |
| 9. Task unfamiliarity |
| 10. Hazard source detection failure |
| 11. Multiple hazards associated with single source or task |
| 12. Hazards without immediate outcome onset |
| 13. Latent or stored energy hazards |

These findings challenge traditionally held assumptions that deficits in safety knowledge is the sole reason why construction hazards remain unrecognized. The findings suggest that additional factors such as selective attention and inattention, and the nature of hazards can impact whether hazards remain unrecognized. The findings of this study will be useful to practicing professionals and safety researchers interested in developing new methods to improve hazard recognition levels within construction. Further, current hazard recognition methods and training programs can be customized to draw the attention of workers to such hazards that generally remain unrecognized.

The second contribution of the study was the development of the personalized training strategy to improve the hazard recognition performance of workers. The strategy incorporated training elements that have been successfully used to improve stimuli and threat detection including:

(1) Visual cues for systematic hazard recognition,
(2) Personalized hazard recognition performance feedback,
(3) Personalized eye-tracking visual attention feedback and self-reflection, and
(4) Metacognitive prompts to encourage self-diagnosis and correction.

After development, the usefulness of the personalized training strategy was evaluated using the non-concurrent multiple baseline testing approach. The results of the testing indicated that the adoption of the strategy can lead to substantial improvements in hazard recognition performance. In fact, the study participants, on average, only recognized 42% of hazards in the pre-intervention phase, but were able to recognize over 76% in the intervention phase.

The developed personalized training strategy will be useful to practicing professionals seeking to improve hazard recognition levels within construction. Most importantly, with improvements in hazard recognition, the likelihood of injuries can dramatically decrease.

## Future Research

As discussed in the earlier chapters, future efforts will be undertaken to address the limitations of the current study. The scope of this study was limited to downstream factors and challenges that occur at the work interface. Future efforts will focus on a more holistic approach by examining both upstream and downstream factors. Further, the interaction between factors will be evaluated. For example, upstream factors such as management support and supervisor involvement, may influence downstream factors, which in turn may impact hazard recognition levels. An understanding of the interactions between these factors is important to maximize hazard recognition and safety performance. Fig 2 represents 13 proximal factors identified in this study along with other intermediate, distal and originating factors that may directly or indirectly affect hazard recognition. Future efforts will focus on exploring the interrelationship between the factors.

Future efforts will also focus on developing novel hazard recognition methods and training processes that contribute to higher levels of hazard recognition. For example, the visual cues used in the personalized training strategy can also be incorporated into Job Hazard Analysis (JHA) and pre-task planning tools to improve hazard recognition levels. Further, as demonstrated in this research, training methods that focus on other areas – apart from safety knowledge transfer – must be developed to maximize hazard recognition performance. Efforts will also focus on developing automated personalized training solutions where a dedicated trainer or instructor is not necessary. Such automated solutions can dramatically reduce the cost of training the workforce, but also reduce repetitive and redundant instruction.

Future efforts will also focus on the long-term impacts of personalized training solutions, and whether improvements observed during the training translate to performance in the field. Studies will also focus on assessing the relationship between hazard recognition performance and injury rates within construction.

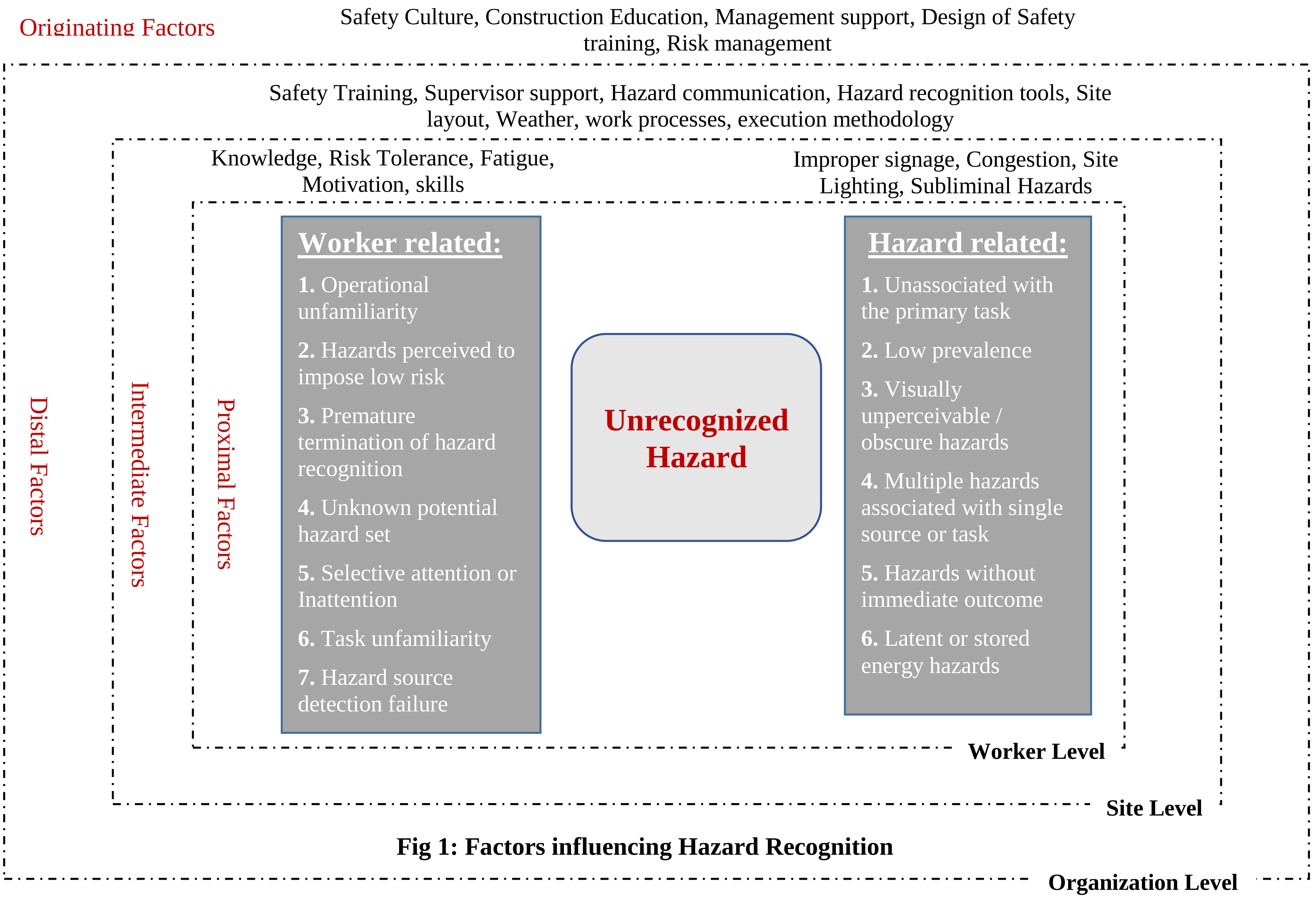

**Fig 1: Factors influencing Hazard Recognition**

Finally, eye-tracking technology can be used to understand how scan-paths of workers impact hazard recognition and safety risk perception. Eye tracking data can also provide in-depth understanding into the hazard search process adopted by individual workers. Future efforts will also focus on comparing scan paths and fixations of expert professionals with novice workers to advance knowledge in the hazard recognition process.

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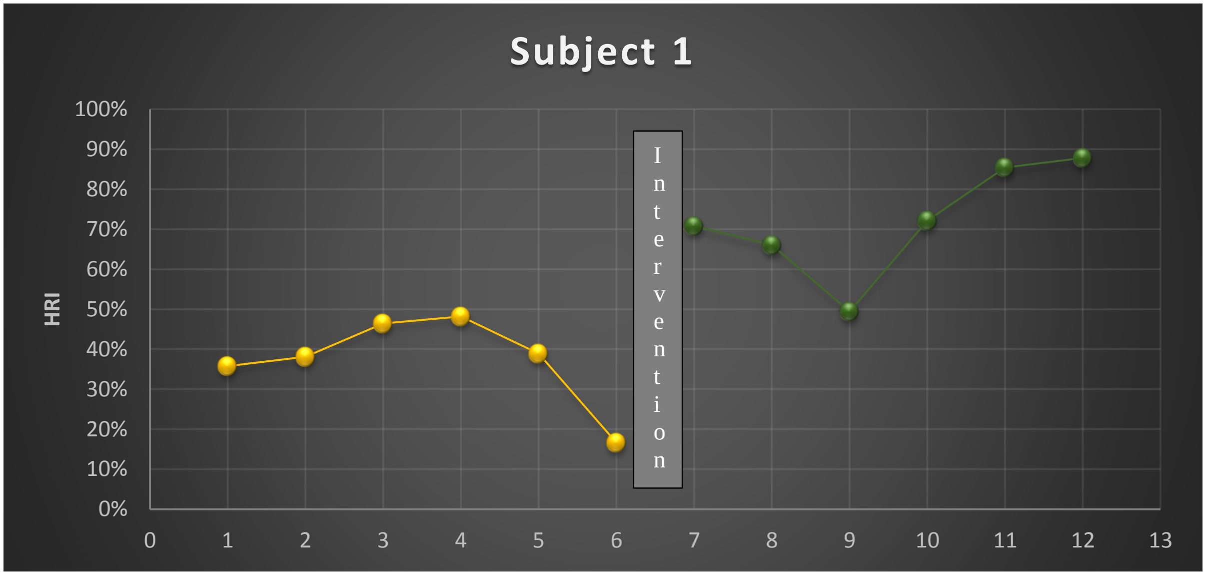
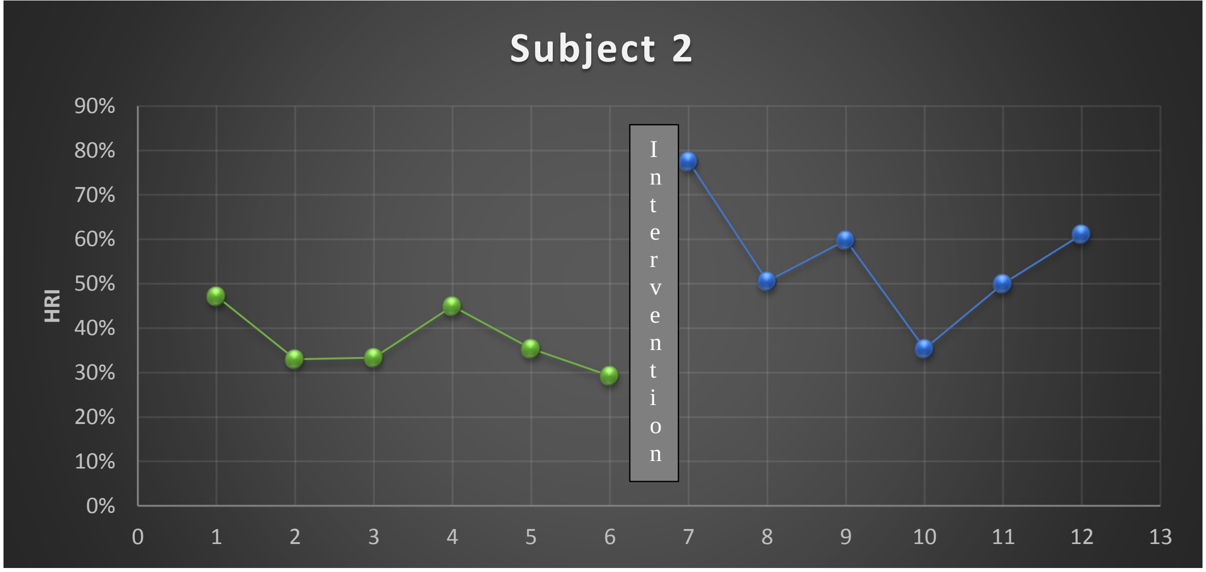
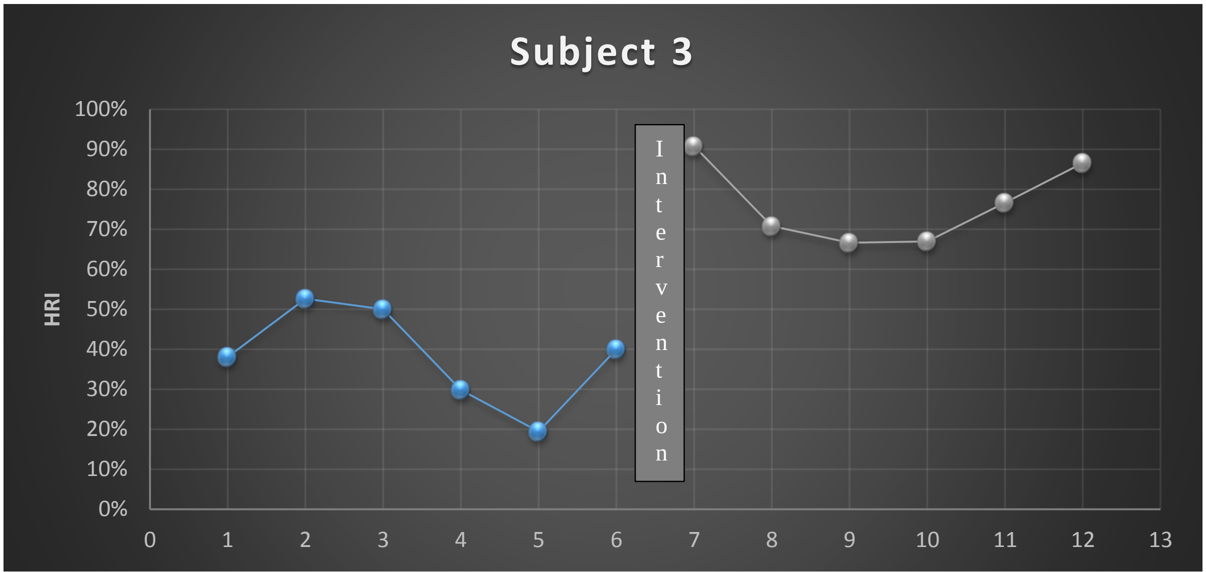
# APPENDICES

# Appendix 1: Results from Hazard Recognition Exercise with Workers



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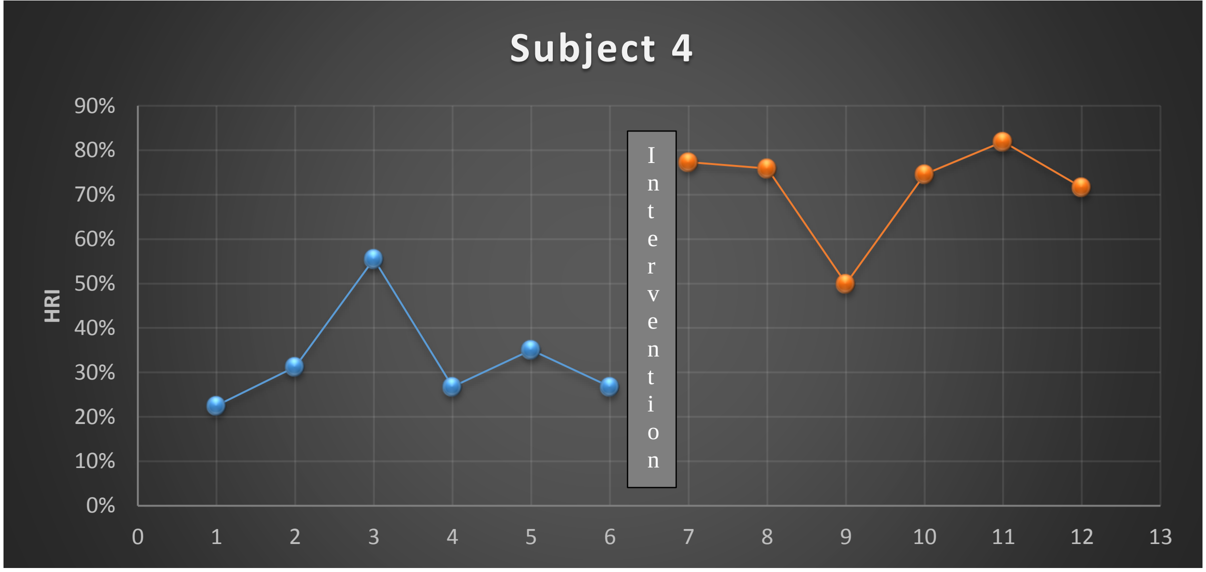
Intervention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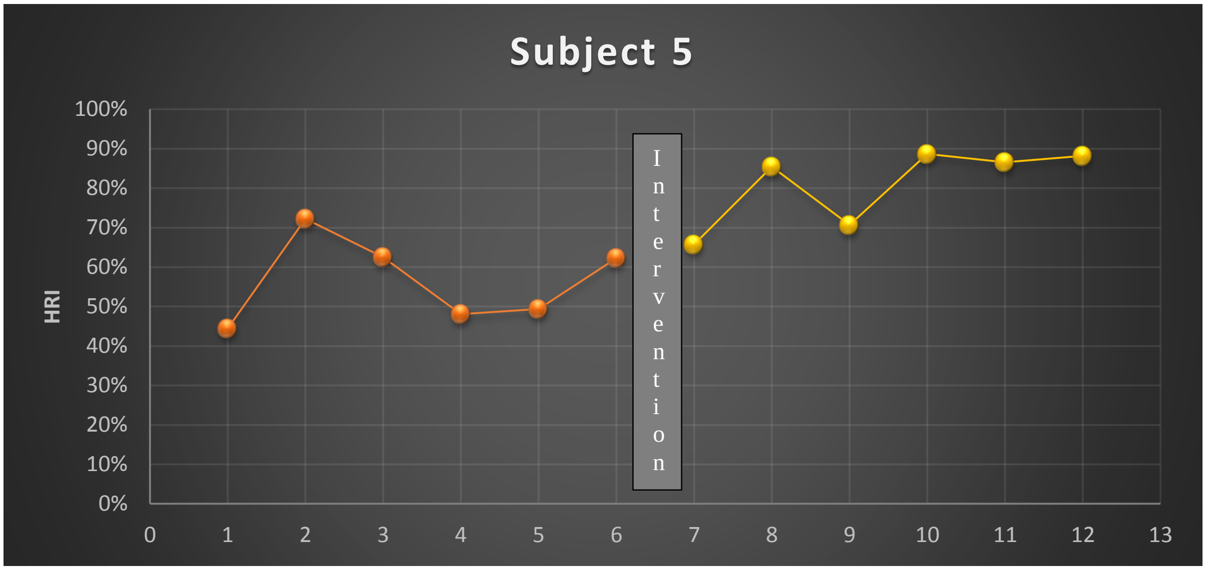
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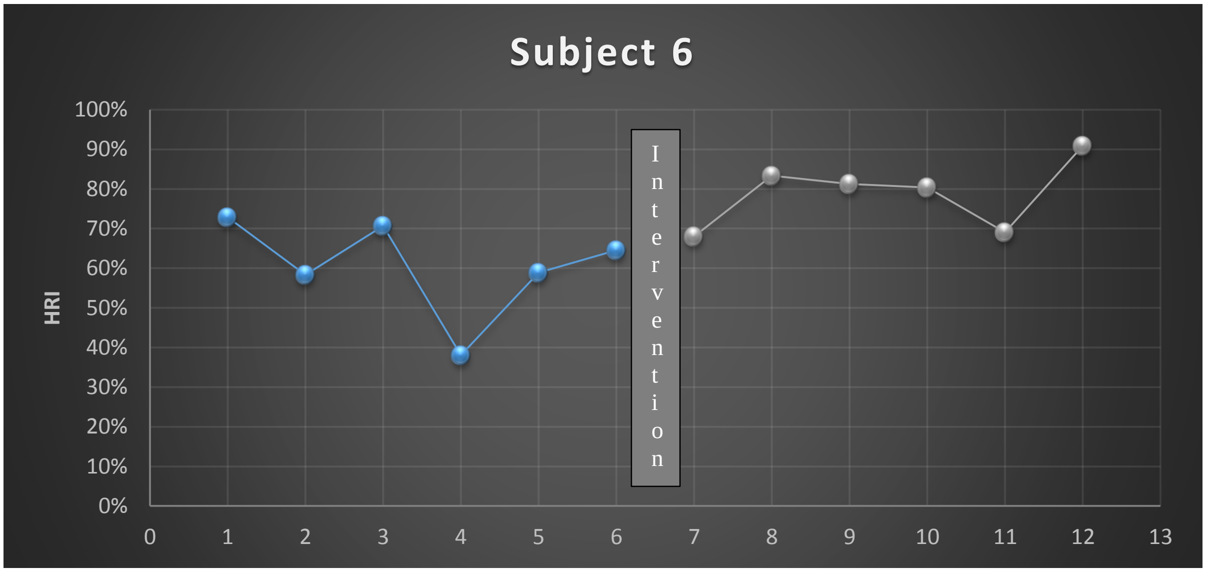
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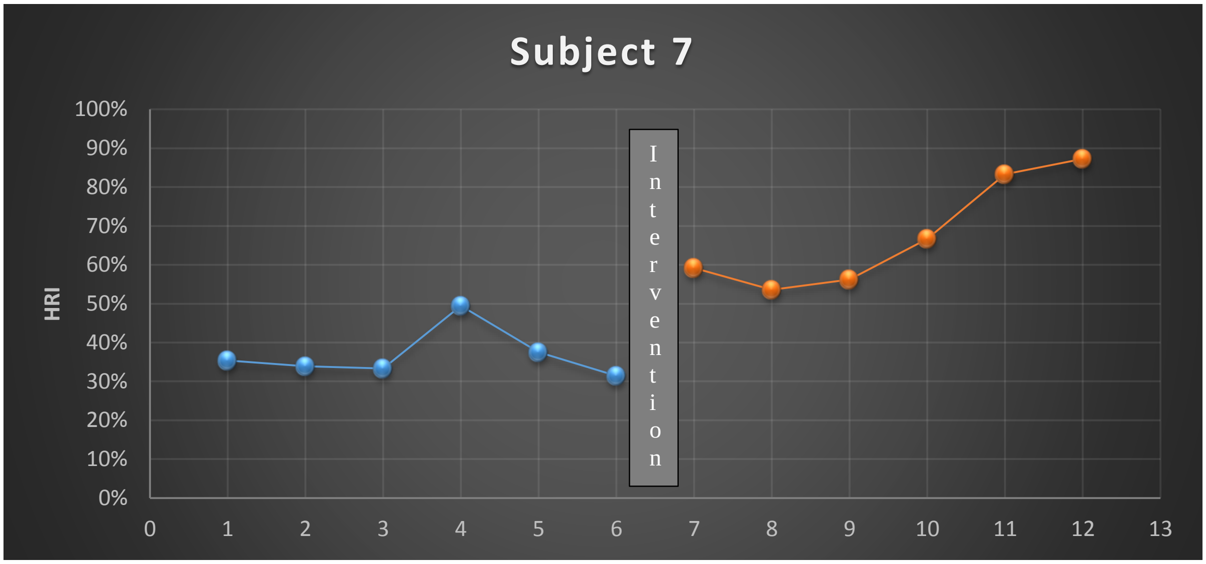
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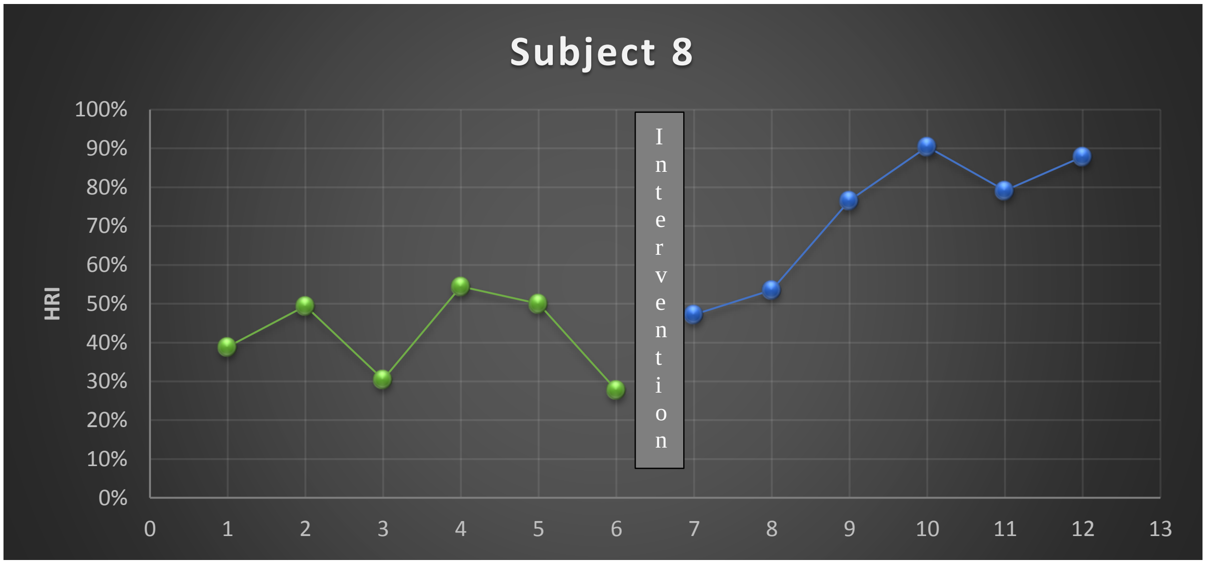
Intervention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Intervention

# Appendix 2: Sample Data form

| **Subject No: 1; Image No 5** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | **Frequency** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Identified (1=Yes, 0=No)** | **1** | **1** | **1** | | **1** | | **1** | **1** | | | | | | | **6** |
| | | | | | | | | | | | | | | | |
| **1. Operational unfamiliarity with construction tools and equipmen**t: I was not familiar with the operations and the operational features of the equipment or tool to recognize the associated safety hazard | | | | | | | | | | | 1 | 1 | | | **2** |
| **2. Hazard that are secondary or unassociated with the primary task**: The hazard was not relevant to the primary task being carried out which I focused on. So, I missed this hazard. | | | | | | 1 | | | | | | | | | **1** |
| **3. Hazards perceived to impose low levels of safety risk:** The risk associated with the hazard was very low to be regarded as dangerous. So, I disregarded this as being a hazard | | | | 1 | | | | | | | | | | | **1** |
| **4. Premature termination of hazard recognition:** After identifying several hazards, I thought I identified all of them, so stopped looking for more. | | | | | | | | | | | | 1 | 1 | 1 | **3** |
| **5. Low prevalence or unexpected hazards:** This hazard is quite rare for the work tasks being carried out and the workplace conditions. So, I missed this | | | | | | | | | | | | | | | **0** |
| **6. Unexpected and unknown potential hazard set:** I was not sure what hazards I could expect or I needed to look for. So, I missed this hazard | | | | | | | | | | 1 | | | 1 | 1 | **3** |
| **7. Visually unperceivable / Obscure hazards:** The hazard was not visually perceivable (e.g. hot surfaces, gasses) or was obscure within the workplace for me to recognize | | | | | | | | | | | | | | | **0** |
| **8. Selective attention or Inattention:** I did not pay attention to this type or category of hazard or I just did not pay attention to this hazard | | | | 1 | | 1 | | | 1 | 1 | | | | | **4** |
| **9. Task unfamiliarity:** I wasn't aware of the potential hazards associated with the ongoing tasks or operations | | | | | | | | | | | | | | | **0** |
| **10. Hazard source detection failure:** I wasn't able to identify the source of the hazard (e.g. material, tool, equipment, task, object, etc.). So I wasn't sure what the associated hazard was in this case. | | | | | | | | | | | | | | | **0** |
| **11. Multiple hazards associated with single source or task:** I thought I had already identified the hazard(s) associated with this source or task. But it turns out that the source or task was associated with other hazards as well | | | | | | | | | | | | | | | **0** |
| **12. Hazards without immediate outcome onset:** This hazard can cause injury or illness in the long term. But the outcome onset is not immediate. So I did not recognize this hazard | | | | | | | | | | | | | | | **0** |
| **13. Latent or stored energy hazards** The construction hazard was latent or did not impose any immediate danger. However, it is true that a trigger or unexpected release of the stored energy can cause potential injury or illness | | | | | | | | | | | | | | | **0** |
| **Total Hazards** | **14** | | | | | | | | | | | | | | |
| **Hazards Identified** | **6** | | | | | | | | | | | | | | |
| **H.R Index** | **0.428571** | | | | | | | | | | | | | | |

# Appendix 3: Sample Calculations

| Subject | SS Model1 | SS Model 2 | MS Model 1 | F* | F (critical) | Selected Model** |
|---|---|---|---|---|---|---|
| 1 | 0.41 | 0.36 | 0.01 | 1.86 | 4.45 | Model 2 |
| 2 | 0.13 | 0.10 | 0.01 | 0.92 | 4.45 | Model 2 |
| 3 | 0.45 | 0.44 | 0.01 | 0.61 | 4.45 | Model 2 |
| 4 | 0.46 | 0.45 | 0.02 | 0.00 | 4.45 | Model 2 |
| 5 | 0.20 | 0.18 | 0.01 | 1.25 | 4.45 | Model 2 |
| 6 | 0.11 | 0.09 | 0.01 | 0.86 | 4.45 | Model 2 |
| 7 | 0.37 | 0.29 | 0.01 | 8.20 | 4.45 | Model 1 |
| 8 | 0.41 | 0.28 | 0.01 | 5.17 | 4.45 | Model 1 |

*

$$F = \frac{(SS_{Reg\ ModelI} - SS_{Reg\ ModelII})/2}{MS_{Reg\ ModelI}} \qquad (5)$$

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

**

*Model I* $HR = \beta_0 + \beta_1 T_t + \beta_2 D_t + \beta_3 SC_t + \varepsilon_t$ *(2)*
*Model II* $HR = \beta_0 + \beta_2 D_t + \varepsilon_t$ *(3)*

Where, *HR* is the performance of each worker in the hazard recognition sessions, $\beta_0$ is the intercept of the regression line, $\beta_1$ is the slope in hazard recognition performance in the pre-intervention phase; $\beta_2$ is the level (i.e. immediate) change measured at the seventh hazard recognition session (i.e. immediately after intervention is introduced), $\beta_3$ is the change in slope from the pre-intervention phase to the intervention phase; $T_t$ is the value of the hazard recognition session variable T at session *t* (analogous to time); $D_t$ is the value of the level-change dummy variable D (0 for the pre-intervention phase and 1 for the intervention phase) at session t; $SC_t$ is the value of the slope-change variable SC defined as $[T_t - (n_1 + 1)]D$; $\varepsilon_t$ is the error in performance at hazard recognition session t;