Construction Industry Institute®

Strategies for Improving Hazard Recognition

Research Summary 293-1

Version 1.1

Construction Industry Institute

Strategies for Improving Hazard Recognition

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Contents

Executive Summary

Although injury rates in the construction industry have declined significantly in the last 40 years, the rate of safety improvement has recently slowed substantially. Organizations that hold safety as a core value have expressed a strong desire for new methods that accelerate safety improvement. One of the current weaknesses revealed by recent research is the lack of adequate hazard recognition skills among construction personnel on diverse and dynamic projects (Carter and Smith 2006; Center for Disease Control and Prevention 2012). To address this problem, Construction Industry Institute (CII) Research Team (RT) 293 set out to develop transformative strategies and practical hands-on tools that directly improve workers' skills for recognizing and communicating hazards. Hazard recognition is a core competency upon which all other safety processes are built. Without strong hazard recognition skills, even safety planning activities that are potentially highly effective (e.g., job hazard analyses and site audits) will not achieve their objectives.

The first phase of the study involved developing a comprehensive list of hazard recognition strategies from safety literature used in a diverse range of industries, including aerospace, the military, manufacturing, mining, construction, and many others. The research team identified more than 100 hazard recognition techniques that were either new to construction or not used specifically as hazard recognition improvement tools. The team used the nominal group technique—a research technique that capitalizes on the expertise of a group—to select the three with the greatest potential for step-change improvement. The three strategies include the following: 1) a pre-job safety meeting quality measurement (SMQM) maturity model that facilitates continuous improvement of the pre-job hazard identification and communication process; 2) a hyper-realistic augmented training environment—called the System for Augmented Virtuality Safety (SAVES)—that immerses workers in a jobsite simulation; and 3) a visual-cue-based Hazard Identification and Transmission (HIT) Board that records hazards during task evaluation and in real time as the job progresses.

Because the three strategies were new to construction and were completely conceptual, the research team developed prototype versions of each tool in the second phase of the study. After completing these prototypes, the team conducted empirical field tests in the third phase to verify the strategies' effectiveness with active work crews. Specifically, the team used the multiple-baseline testing (MBT) approach for experimental field testing because it would allow for the establishment of a cause-and-effect relationship between the strategies and hazard recognition improvement. This empirical data collection and analysis method provides a more objective measurement than the more subjective survey method of assessment.

The results of the team's experimental field testing indicate that workers identify less than half of hazards in their immediate work environment before work begins. Alarmingly, this logically means that more than half of hazards are not identified and discussed prior to work. Fortunately, the field tests reveal that the SMQM model, SAVES system, and HIT Board caused net weighted overall improvements in hazard recognition skill of 31 percent, 27 percent, and 30 percent, respectively. To validate these results, the research team used skill tests with high-resolution photographs of diverse construction settings both before and after the application of the three strategies.

The implications of these findings are that this suite of new hazard recognition methods can be used to dramatically improve hazard recognition. This possible improvement is especially important because workers' ability to identify hazards is essential to their ability to protect themselves. Moreover, the workers' ability to correctly identify hazards improves the job hazard analyses process, site audits, and all other safety management initiatives. This research summary describes the background for the research, the three strategies that were tested, the specific field testing protocol, and the results and conclusions of the research effort.

1

Introduction

Construction workers are highly susceptible to occupational injuries. Research indicates that the fatality and disabling injury rates in the construction industry is about three times higher than the all-industry average (Pinto et al. 2011). Such high injury rates are due in part to workers' inability to recognize and respond to potential hazards in the dynamic environments typical of construction (Carter and Smith 2006).

Figure 1 represents a simple conceptual model of a safety management approach that is centered on hazard recognition skills. In this model, an injury occurs when a hazard is present, and an individual is actually exposed to it in the absence of adequate controls. As shown in the framework, hazards that are not proactively recognized are not included in the risk evaluation process. This often results in a sub-optimal safety management program.

Typically, when reviewing construction documentation and conducting field observations, management can rely on experience to identify hazards associated with work tasks. A fundamental but often incorrect assumption underlying such an approach is that workers are as capable as management at predicting work sequences and associated hazards. Unfortunately, new workers may be unfamiliar with construction processes and incapable of recognizing their hazards. In order to enhance hazard recognition skills, employers often put workers through formal hazard recognition training programs. Such current training methods are based on conventional classroom instructional techniques, which often fail to adequately engage workers. Especially challenging is engaging the attention of younger (Generation Y) workers.

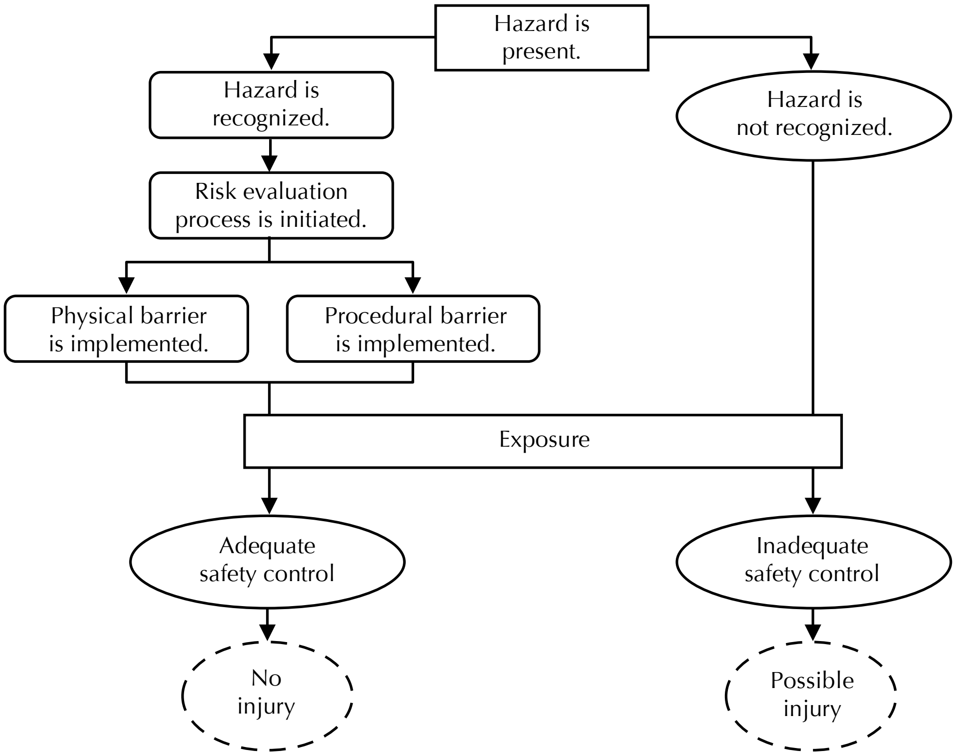

Figure 1. Conceptual Safety Management Protocol

In response to this imminent need, RT 293 explored new hazard recognition improvement strategies in a multi-phase study. The research team developed and refined three transformative hazard recognition strategies that incorporate essential theories from the field of psychology and other behavioral sciences. To ensure that these strategies do indeed increase hazard recognition skills, the team performed experimental field trials using the multiple-baseline testing (MBT) approach. The remainder of this research summary describes the state of hazard recognition programs in the industry, new methods identified through literature review and group brainstorming, the RT 293 approach to selecting the three strategies with the greatest potential for step-change improvement, the team's methods of experimental field testing and validation, the salient results, and the implications of these results.

2

Hazard Recognition Background

Several formal and systematic approaches have been developed to improve hazard recognition in construction. These methods can be broadly classified as either predictive or reactive in nature. Predictive hazard recognition methods such as the Job Hazard Analysis (JHA) require workers to mentally visualize activities that they will undertake to complete specific work tasks. Based on the activities, workers attempt to identify all relevant and potential hazards. Other programs, such as task analysis and regular safety task-planning sessions, follow very similar approaches. Such methods, although they have contributed significantly to safety improvement, have some inherent limitations. First, hazard recognition methods that focus on isolated job-tasks or procedures fail to recognize additional hazards that may arise due to adjacent work and/or any changes in scope, work methods, and/or conditions (Rozenfeld et al. 2010). Second, the approach assumes that workers can correctly predict how tasks will be performed and can identify the hazards associated with these predictions. Finally, these strategies operate under the assumption that workers are able to recognize all hazards associated with the daily tasks that are to be performed (Fleming 2009).

Reactive and retrospective methods of hazard recognition usually rely on past experience or injuries to determine potential hazards for a given work-setting. Often, employers compile lessons learned from past projects and then disseminate the material through training that involves conventional instruction. Like the predictive hazard recognition methods, the retrospective methods have various weaknesses. First, past incidents and near misses are often not reported, and reports are often not thorough enough for learning and future improvement (Dong et al. 2011). Second, injury records reflect only a small subset of potential scenarios that resulted in injuries (Rozenfeld et al. 2010). Third, in environments as dynamic as the construction industry, generalizing accidents across different settings is often invalid. Finally, transferring such an enormous amount of information to workers by means of inefficient instructional methods is unrealistic (Fleming 2009).

To ensure effective learning, hazard recognition training programs must be tailored to the learning styles of the workers. Traditional lecture-based training programs in which the trainee plays a dependent or passive role are often ineffective for training adult learners. Adult workers learn better when programs are based on the principles of andragogy (adult learning), which allow the workers to be involved in building context, setting objectives, cooperatively and interactively delivering instructional material, and forming plans (Knowles et al. 2012). Methods that encourage active participation and visual learning are particularly effective. Given these requirements for effective adult education, RT 293 based the three interactive strategies it tested—SMQM, SAVES, and the HIT Board—on an easily internalized mnemonic for the different energy sources that underlie hazards; the team hypothesized that such a combination of techniques would efficiently engage workers during the hazard recognition training process and improve their cognitive retrieval of hazards types when tested.

3

Research Methods

The objective of this study was to develop and test new, potentially transformative hazard recognition strategies for step-wise improvement in safety performance. The research team aimed to develop techniques that incorporated industry best practices and relevant theories from psychology and other behavioral sciences. The team conducted research in three segregated but interrelated phases that each addressed current weaknesses in safety training, planning, and execution. In the first phase, the team drew up a comprehensive list of hazard recognition strategies, and then used the nominal group technique to select three for further development and testing. The chosen techniques were SMQM, SAVES, and the HIT Board. In the second phase, because these three safety strategies were new to the industry, the team developed and refined them for use on the construction jobsite. In the third and final phase, the team field tested the three strategies to determine their impacts on hazard recognition skills. The overall aim of this research was to experimentally test the hypothesis that an appropriately designed strategy causes a measurable increase in the proportion of hazards identified and communicated before work begins.

Phase I: Selection of Transformative Hazard Recognition Program Elements

The objective of the first phase, as shown in Figure 2, was to select hazard recognition program elements that could significantly improve hazard recognition levels on construction worksites. The research team gathered this information from an extensive review of safety literature across multiple industries, including construction, mining, manufacturing, chemical, and the military. The team also gathered data from benchmarking reviews of hazard recognition elements used by CII member organizations, and from brainstorming sessions on elements that are theoretically implementable but not generally utilized. From this extensive review, the team identified more than 100 program elements.

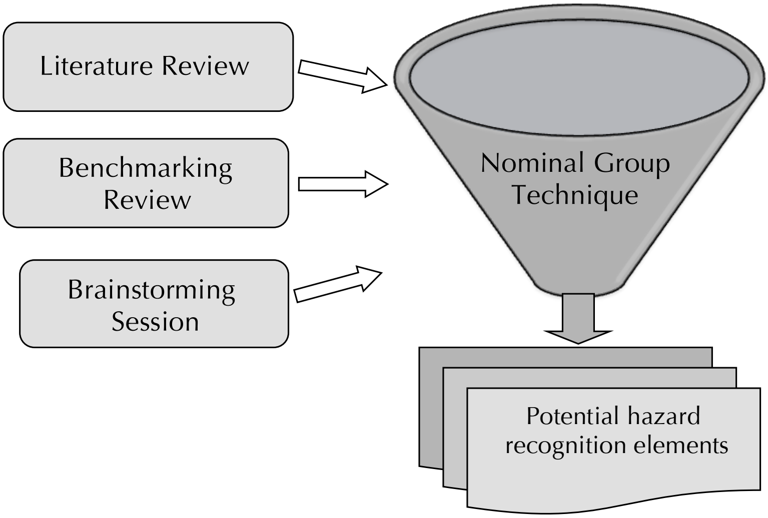

Figure 2. Selection of Hazard Recognition Elements

The next step was to short-list the most promising elements for further refinement and testing. Strategies that were inappropriate for dynamic environments such as construction, or that could not be reasonably developed or adjusted for construction were eliminated. Next, the research team served as an expert panel to rate the strategies, using a 1–5 Likert scale, with a 1 rating meaning "strongly disagree" and a 5 rating meaning "strongly agree." (For details on the rating criteria, see Appendix A.) The team members rated the strategies using the nominal group technique (NGT), which required them to rank the strategies, discuss the results, and re-rank the strategies several times until group consensus was achieved. This process was facilitated by a group decision support software application called Grouputer. It allowed team members to use their personal computers simultaneously and anonymously to rate each strategy. This form of parallel rating effectively reduced any bias that might be due to dominance or the "bandwagon effect" (Kennedy and Clinton, 2009). (For more detail on the NGT process used for this study, please see Research Report 293-11.)

The 14 research team experts who rated the strategies each had more than 10 years of safety management experience. In total, the team members had accumulated more than 352 years of construction safety management experience during their careers. In addition to their professional experience, seven members were Certified Safety Professionals (CSP), and five were Certified Hazardous Materials Managers (CHMM). The team also included one or more members who had obtained the following licenses: Professional Engineer (PE); Occupational Health and Safety Technologist (OHST); Compliance Safety and Health Officer (CSHO); and Certified Industrial Hygienist (CIH). A broad range of industry sectors were represented on the team, and several members were active in various health and safety committees, e.g., the American Society of Safety Engineers, the National Safety Council, the Accident Prevention Association, and local safety councils. The team also had five members with master's degrees, and six with bachelor's degrees in safety-related fields of study.

The NGT process yielded 1,400 ratings. To effectively compare ratings among experts, mean ranks were computed for each criterion. When mean ranks are used, the strategy that is rated highest for a criterion by most of the experts is assigned the highest rank for that criterion. The average of the ranks is then accumulated across all the criteria to determine the relative effectiveness score for each strategy. Table 1 shows the results of these calculations. As shown, the pre-job safety meeting quality measurement tool emerged as the strategy with the highest potential, followed by the augmented virtual reality training environment.

Table 1. Relative Effectiveness Score for
Top 10 Hazard Recognition Program Elements

Hazard recognition strategy elements	Relative effectiveness score
1. Pre-job safety meeting quality measurement tool	74.71
2. Augmented and interactive reality training environment	58.29
3. Senior leadership engagement in JSA process	55.89*
4. Physical area hazard simulation	55.49**
5. Safety situational-awareness training	55.25***
6. Hazard identification board	54.92
7. Foreman one on one with employee	52.76
8. Precursory visual cues	49.48
9. JSA post-kick-off audit	48.81
10. Video/photo monitoring and feedback	44.40

* Combined with 1
** Not testable with available resources
*** Combined with 2

Phase II: Development of Transformative Hazard Recognition Strategies

The objective of the second phase was to build and refine the top three hazard recognition strategies identified in the previous phase. (See Table 1.) After discussing the results of the NGP process, the research team decided to combine several complementary strategies. The first such combination was the pairing of the pre-job safety meeting quality measurement tool with senior leadership engagement in the jobsite safety audit (JSA) process. From this combination, the team developed the Pre-job Safety Meeting Quality Measurement (SMQM) maturity model. To create the second strategy, the team combined the hazard identification board with precursory visual cues to form the visual-cue-based Hazard Identification and Transmission (HIT) Board. The team then combined the augmented and interactive virtual reality training environment with safety situational-awareness training to develop the System for Augmented Virtuality Safety (SAVES) tool. Finally, it should be noted that the team eliminated the physical area hazard simulation element due to budget constraints and because of its highly disruptive and, thus, un-testable nature.

The team recognized that, to facilitate retention of new information, motivate workers to actively participate in the hazard recognition process, and improve worker hazard recognition skills, the research had to incorporate theories from psychology and other behavioral sciences. Table 2 presents the various techniques incorporated during tool development.

The team based all three hazard recognition strategies on the overarching principle of energy-based retrieval mnemonics. Retrieval mnemonics is a technique through which information is organized in a specific manner to help the human brain retain and retrieve it as desired (Scruggs et al. 2010). This approach involves an encoding process whereby the brain converts the information into mental cues and stores it in a retrievable form.

Several forms of retrieval mnemonics are commonly used to facilitate both retention and retrieval. One example is acronymic mnemonics, which involve the formation of acronyms from the first letters of several items that are to be remembered. Another example is story mnemonics, which involve constructing narrative stories around information that is to be remembered. RT 293 integrated the categorical organization mnemonics method, which, research indicates, are particularly effective with adult learners. The categories of mnemonics used in this study are the hazardous energy sources suggested by Fleming (2008). According to this method, all safety hazards are linked to the potential release of specific energy types (e.g., gravity, temperature, or pressure). To facilitate the instruction and categorization of these mnemonics, the energy disc shown in Figure 3 was developed. (Definitions for each of the energy sources shown on the disc are provided in Appendix B.)

Table 2. Techniques Incorporated into the RT 293 Strategies

Theories	Brief description
Retrieval mnemonics	A technique through which information is organized specifically to help the human brain retain and retrieve it when desired (Scruggs et al. 2010).
Goal-setting	A psychological approach to motivate individuals into direct action towards goal attainment (Locke et al. 1981).
Feedback	A moderating method to increase the likelihood that an individual or a group of individuals will set goals to improve performance (Renn and Fedor 2001).
Self-regulation	A self-observational method that helps individuals compare their behavior with set goals, to reinforce continual goal commitment (Latham 2007).
Game theory	An educational training method that uses a gaming environment to impart knowledge, while also making learning fun (Zyda 2005).
Situational awareness	An approach to enhancing an individual's capacity to perceive, comprehend, and respond to hazardous stimuli (Endsley et al. 2011).
Visual cue	A form of sensory cue that provides individuals with signals or gives them prompts to respond to signals (Hsiao and Simeonov 2001).
Real-time signal detection	A method that facilitates individuals' responses to specific stimuli when detected, thus reducing the need to forecast or predict future conditions.

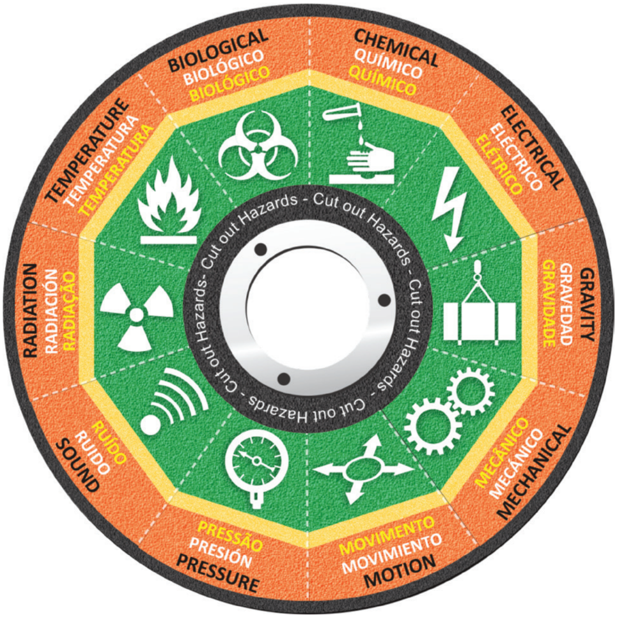

Figure 3. Energy-based Retrieval Mnemonics

Strategy 1 – Pre-job Safety Meeting Quality Measurement (SMQM) Maturity Model

The SMQM maturity model provides a method for measuring the quality of the pre-job safety meeting. This tool includes nine evaluation criteria: 1) identify the job; 2) identify basic steps; 3) hazard identification and mitigation; 4) location of discussion; 5) supervisor leadership; 6) crew participation; 7) documentation; 8) job changes; and 9) evaluation. Each of these criteria has three levels of achievement: mature, less mature, least mature. The model provides clear operational definitions for each level of each criterion. Once assessment is complete, management can identify opportunities for improvement by reviewing the descriptions of the higher levels of achievement for their areas of weakness, and instituting action to raise performance to those levels.

After creating this basic outline of the model, the research team surveyed its members to gather information to populate the model. For each section, the team as expert panel provided qualifying criteria for a mature crew (i.e., best practices), a less mature crew (i.e., practices of a better-than-average crew), and a least mature crew (i.e., practices of a worse-than-average crew). In total, after considering the three sections and the three maturity levels, the expert panel provided information for 27 fields. The team further refined the SMQM model during two teleconferences. (To see the model in its entirety, refer to Appendix C.)

RT 293 built the SMQM maturity model on the principal assumption that, with use, the proportion of hazards recognized and communicated would increase because the strategy facilitates the following four techniques: 1) use of energy-based retrieval mnemonics to recognize hazards associated with construction processes; 2) goal setting based on the assessment of the quality of pre-job safety meetings; 3) feedback to the supervisor on areas that need additional improvement; and 4) comparison of current performance with mature work groups that provides an opportunity for self-regulated improvement.

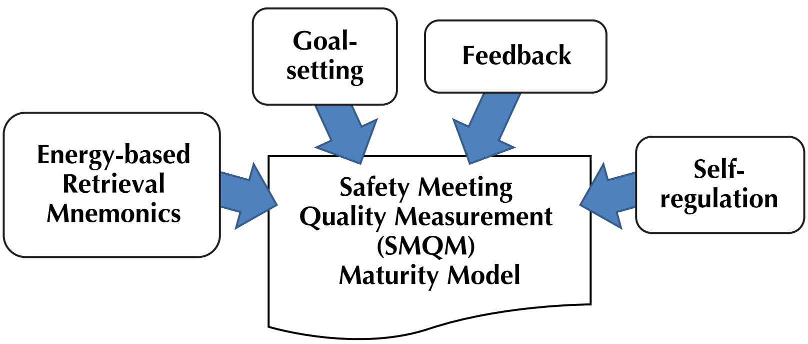

Figure 4. Components of SMQM Model

The reader should note that, while Appendix C presents the SMQM tool in its entirety, the research team expects users to adapt it for use on their jobsites and within their project culture. Once the SMQM practices have been operationalized, users may also create a simplified version of the tool to meets their specific needs. The team does not recommend converting the tool into a checklist, since the RT 293 testing experience showed that the rich content and the process of measuring the quality of a safety meeting *in the field* were primary benefits of the strategy.

Strategy 2 – Hazard Identification and Transmission Board (HIT Board)

The HIT Board, shown in miniature in Figure 5, is another effective tool for helping workers recognize and communicate hazards. The strategy involves the use of a specially designed 36-inch × 36-inch board with magnetic visual-cue display components representing each of the energy sources shown in Figure 3. The board facilitates the pre-task safety planning process, during which workers should review the energy sources to identify hazards that they may encounter while performing work tasks. Unlike other strategies, the HIT Board also permits workers to identify and communicate additional hazards, before exposure and in real time, as the work progress. Hazards are considered identified as long as they are recognized prior to exposure. Thus, the method facilitates proactive hazard recognition and communication, which, in turn, drastically reduces the challenges associated with precisely predicting work tasks and relevant hazards. The HIT Board also holds transparent plastic folders in which the workers can display permits, JSAs, or any other information that should be readily accessible. All of these features make the board convenient to use and easy to integrate into other work processes.

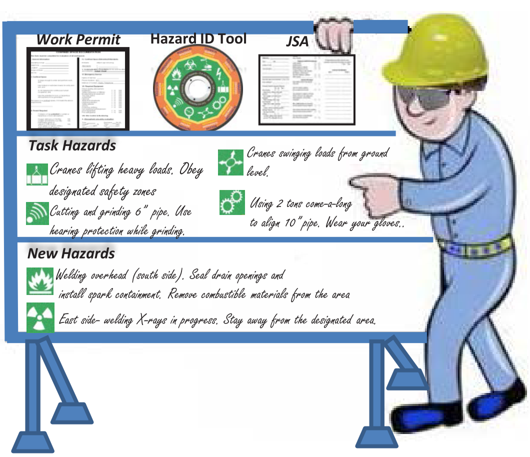

Figure 5. HIT Board Illustration

In order to develop the protocol for field execution of the HIT Board, the research team held a brainstorming session to devise an initial deployment framework. This initial framework consisted of general descriptions of the following elements: 1) identify the job; 2) evaluate tools and environmental conditions; 3) deploy the method for identifying and mitigating hazards; 4) provide details on displaying permits and JSAs; 5) determine HIT Board placement location; and 6) create a list of action items required of the supervisor and crew members. After the team created this basic framework, it distributed questionnaire surveys to the expert panel to gather information for developing the implementation protocol. Once gathered, the information was used to refine the implementation protocol as needed. The research team expected that the HIT Board would significantly increase the proportion of hazards recognized and communicated because it performs the following functions: 1) facilitates use of the energy-based retrieval mnemonics for hazard recognition; 2) provides a categorized visual reminder of possible workplace hazards; 3) allows real-time hazard signal detection and communication, facilitating further hazard identification during execution; and 4) permits comparison of crew performance with the recommended description of implementation protocol. (See Figure 6.)

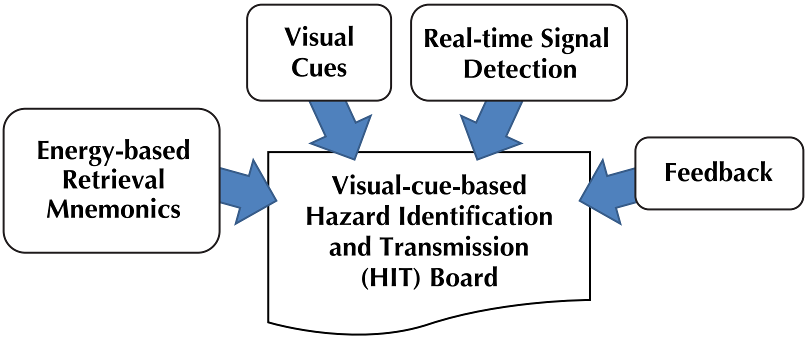

Figure 6. Components of an HIT Board

Strategy 3 – System for Augmented Virtuality Safety (SAVES)

SAVES is an augmented reality training tool that provides participants with a risk-free, high-fidelity virtual environment that replicates actual project conditions. (See Figure 7.) SAVES uses serious gaming to engage workers, allowing them by turn to control an avatar that can explore the game's three-dimensional construction environment. In this augmented environment, the learner-users encounter work scenarios in which they are asked to identify all hazards and indicate their associated energy sources. The system then provides immediate feedback to improve future performance. The goal of the game is to identify all hazards, their associated energy sources, and the appropriate severity level of risk that each hazard introduces. SAVES provides automatic feedback to the user regarding the hazards that were successfully identified, as well as the ones that were incorrectly identified. Through this process of repeatedly exposing workers to various work scenarios, the SAVES tool improves workers' hazard recognition skills. And, to improve worker engagement and encourage discussions, RT 293 designed SAVES for use by small groups of workers.

Figure 7. SAVES Screen Capture

To develop SAVES, the research team initially compiled a repository of more than 1,000 photographs showing hazards and poor work practices. From this repository, the team selected a sub-sample of images depicting hazards and energy sources to which workers may be exposed. Then, using the Unreal Development Kit (UDK) gaming engine, team members incorporated the selected photographs into a building information model (BIM) model of an industrial plant that a CII member organization provided for the team's use.

During the tool's development, RT 293 hypothesized that the proportion of hazards that workers recognized and communicated would increase when they used the SAVES module. (See Figure 8.) The thinking was that such improvement would be due to the system's deployment of the following learning techniques: 1) hazard recognition through the energy-based retrieval mnemonics; 2) worker engagement through serious gaming; 3) worker exposure to work scenarios in which hazards can be recognized and situational awareness skills can be developed; and 4) immediate feedback on the hazards that were and were not successfully identified.

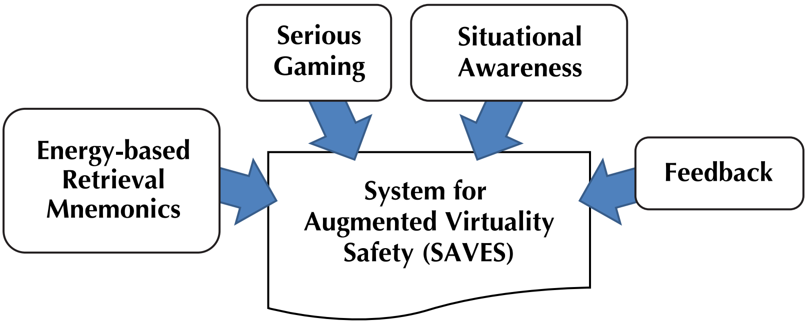

Figure 8. Components of the SAVES Model

Phase III: Empirical Field Testing Using Multiple Baseline Design

After developing three strategies, the research team aimed to empirically test the impacts of each strategy on hazard recognition and communication skills. The goal of this phase was to test the null hypothesis that *the use of the individual strategies (reinforced with theories from psychology and the other behavioral sciences) does not measurably increase the proportion of hazards identified and communicated*. Several research design methodologies have been suggested in the literature to test the effects of similar interventions. For example, several studies use before-and-after (AB) testing or withdrawal designs to make causal inferences. For the purposes of this study, the team dismissed these forms of research design, due to the limited internal validity provided by the AB methodology and the unethical nature of withdrawing a positive safety strategy that enhances human health and well-being. After careful consideration, the team decided to use the multiple-baseline testing (MBT) approach, a quasi-experimental method.

Because the MBT design consists of a multiple number of concurrent AB designs, it notably prevents external factors from distorting results and improves the generalizability of findings. In this approach, the interventions are administered to the individual groups on a staggered basis. That is, after gathering adequate baseline measurements (prior to the intervention), the intervention is introduced to one crew, while the others continue in the baseline mode. Eventually, every group receives the intervention on a time-lagged basis. The strength of the MBT design lies in the fact that outcomes can be compared within each group prior to and after the introduction of the intervention, and across the groups. If a significant change in performance is noticeable across groups just when the intervention is introduced, then that change can be attributed to the intervention. (Figure 9 illustrates this experimental protocol with hypothetical data.) RT 293 team members identified several large and stable projects for field testing in various locations in the U.S. The team decided to test **<u>each</u>** strategy with six crews from two independent projects.

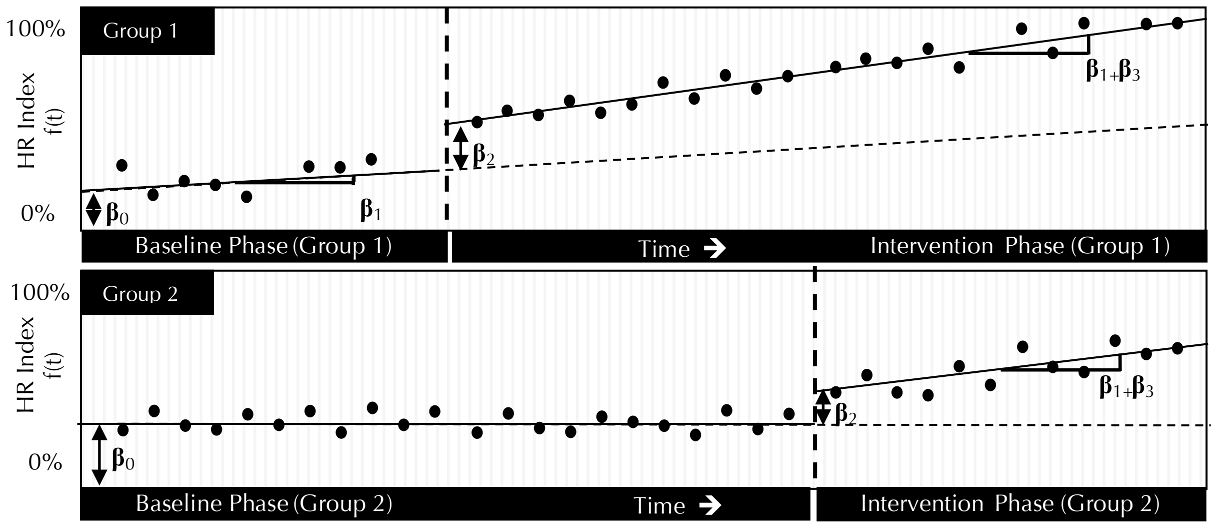

Figure 9. Multiple Base-line Testing Method with Hypothetical Data

Measuring hazard recognition – The team devised a metric called the hazard recognition (HR) index to calculate the proportion of hazards recognized. As shown in Equation 1, the HR index is the ratio between the total number of hazards identified by the crew and the total number of hazards that the crew actually encounters. H_{crew} was computed from observations of the pre-task meeting and the categorization of hazards that the crews identified and communicated. To measure H_{total}, site-based panels (each composed of two safety managers and a member of the research team) conducted observations of the work throughout the work period, to record hazards that the workers encountered. Each work period was four hours in duration.

$$HR = \frac{H_{crew}}{H_{total}} \qquad \text{(Equation 1)}$$

Where H_{crew} is the total number of hazards identified in a given period by the crew, and H_{total} represents the total number of relevant hazards present during the testing period.

The HR index for each project site was gathered longitudinally over a two-week period, as per the multiple baselines testing (MBT) protocol. The protocol involved selecting three crews specializing in different trades and gathering baseline measurements of the HR index concurrently over time. After gathering data for six consecutive work periods for each crew, the RT 293 onsite representative introduced the developed intervention to the first crew (Crew 1), while maintaining baseline conditions for the other two crews (Crews 2 and 3). If the intervention induced change, then it was expected that the measured HR index for Crew 1 would significantly improve (or worsen), while the performance of the other two crews remained relatively stable. After two more work periods, the second crew (Crew 2) was provided with the intervention, while the third crew (Crew 3) continued in the baseline for the subsequent two work periods. Finally, Crew 3 also received the intervention, and the HR index for all three crews was continually measured for a total of 16 work periods.

For each crew, the HR index in the pre-intervention phase provided the research team with enough information to forecast performance by means of time-series regression analyses for situations in which the intervention had not been introduced. The projected value could then be compared with the actual hazard recognition level that the crew had achieved in the post-implementation phase (i.e., after the intervention had been introduced). The effect change was the difference in performance between the hazard recognition value projected for the baseline phase and the hazard recognition value expected at the time the intervention was introduced.

Independent validation using high-definition photographs

To validate the results obtained from the multiple baseline study, the research team also conducted pre-tests and post-tests using random sets of representative photographs prior to and after the interventions were integrated into the work process. A random sample of 16 photographs representing diverse construction scenarios were selected from a pool of more than 1,000 photographs for this purpose. For each photograph, RT 293 team members catalogued a comprehensive list of observable hazards. Then, for each crew, the photographs were randomly sorted into two groups: one for the pre-test and the other for the post-test. The proportion of hazards recognized was then calculated using equation 2, and two sample tests were used to compare before and after performance.

$$HR = \frac{H_{crew}}{H_{crew} + H_{panel}} \qquad \text{(Equation 2)}$$

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

4

Experimental Field Testing Results

Case 1: Testing SMQM on a modular construction project

The research team conducted its first field test on an in-house modular construction project in the southeastern United States. Each year, more than 82,000 work hours are accumulated at this facility. Three crews specializing in different trades (i.e., structural, electrical, and piping) participated in the study. Figure 10 shows the hazard recognition index recorded over time. (See Appendix D for the results of the data analysis.)

The results indicate that Crew 1 recognized 40 percent of hazards prior to receiving the SMQM intervention. After receiving the SMQM intervention, an immediate 26-percent increase in hazard recognition was observed. Similarly, Crews 2 and 3 experienced improvements of 31 percent and 38 percent, respectively. The corroborative test using high-definition photographs representing construction scenarios strongly suggested statistically significant improvements ($p < 0.05$) in hazard recognition for Crews 1, 2, and 3 of 43 percent, 52 percent, and 41 percent, respectively.

Case 2: Testing SMQM on a power plant project

Case 2 was conducted on a natural-gas-based power generating plant located in the southern United States. The total contract price of the project was $550 million, and over 300,000 worker hours were accumulated each year at this facility. As in case 1, three crews specializing in different trades (i.e., civil, piping, and equipment operation) participated in the study.

Figure 11 present the results of the study, which indicate that Crew 1 recognized 40 percent of the hazards prior to receiving the intervention, and 55 percent after receiving the intervention. Thus, Crew 1 realized a 15-percent increase in the proportion of hazards recognized after the intervention. Similarly, Crews 2 and 3 realized 23 percent and 18 percent increases in the proportion of hazards recognized, respectively.

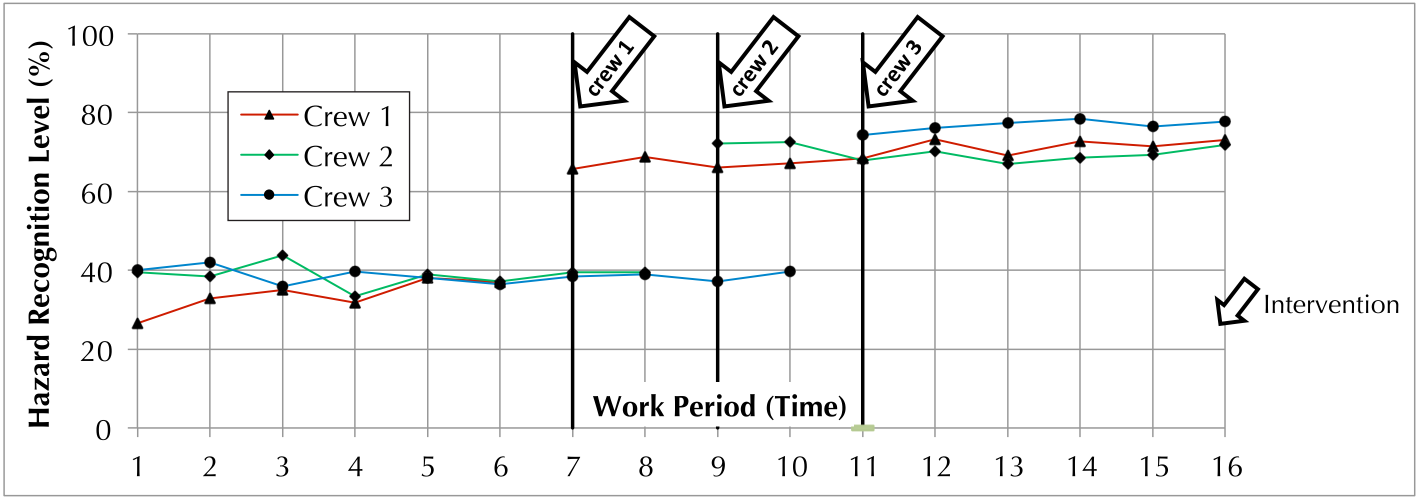

Figure 10. Case 1: SMQM Model Intervention Results

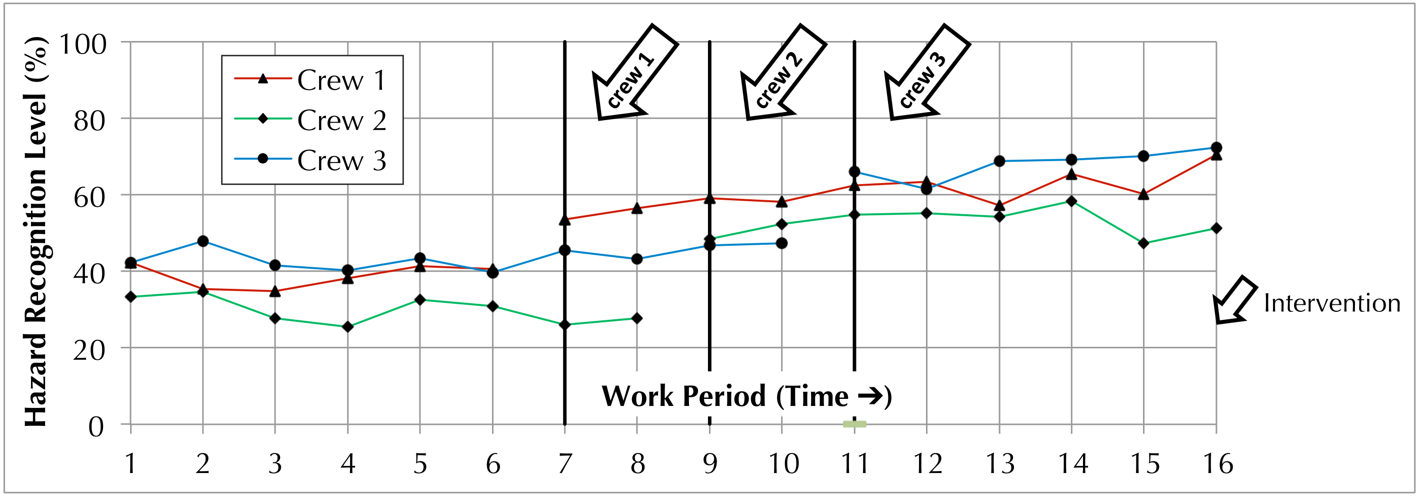

Figure 11. Case 2: SMQM Model Intervention Results

The corroborative tests using the high-definition photographs revealed statistically significant ($p < 0.05$) improvements for all crews. In this test, Crew 1 realized a significant improvement of 29 percent, while Crews 2 and 3 improved 35 percent and 25 percent, respectively. (See Appendix D for a detailed presentation of these results.)

Case 3: Testing SAVES on an oil and gas facility

This study was conducted at an oil and gas facility involved in the manufacturing of oil additives in the southern United States. The company opted not to reveal the annual revenue of the facility, citing confidentiality concerns. The facility employs more than 650 workers and accumulates an average of 277,400 work hours every year. Three crews from different trades (i.e., civil, maintenance, and mechanical) were identified to participate in the research study.

Figure 12 shows the hazard recognition performance of the crews at this facility. (See Appendix D for a detailed presentation of these results.) As can be seen, the proportion of hazards identified by Crew 1 increased from 43 percent to 72 percent. This means that, upon receiving the SAVES intervention, Crew 1 realized a 29-percent improvement. Crews 2 and 3 also improved significantly, with respective gains of 20 percent and 44 percent.

The corroborative test involving the pre-test, and a post-test, also revealed a significant increase ($p < 0.05$) in the proportion of hazards recognized. In this test, Crews 1, 2, and 3 exhibited increases in hazard recognition of 32 percent, 31 percent, and 36 percent, respectively.

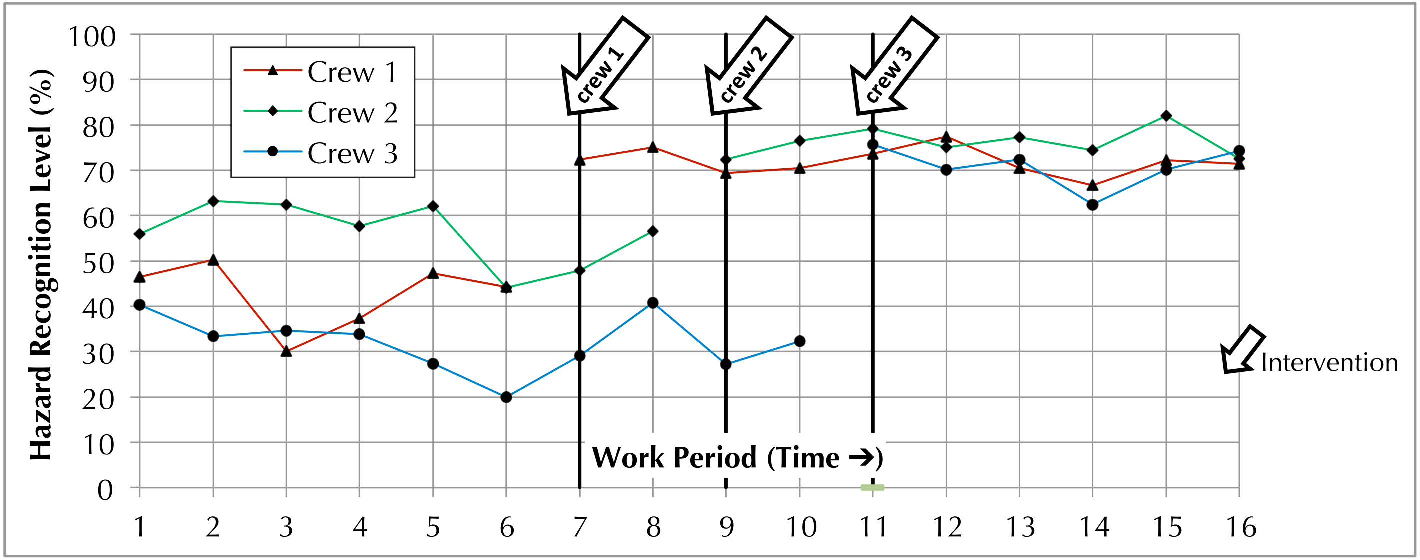

Figure 12. Case 3: SAVES Module Intervention Results

Case 4: Testing SAVES on a fluff pulp processing facility

The Case 4 project involved major maintenance and construction in an industrial setting in the southeastern United States. The facility manufactured fluff pulp for various applications, and accounted for approximately 20,000 work hours every year. As in the other projects studied, three crews from different trades (i.e., electrical, iron workers, and insulators) participated in the study.

Figure 13 tracks the HR index over time. The results indicate that Crew 1 improved its hazard recognition capability by 27 percent immediately after the intervention was introduced. Similarly, Crews 2 and 3 realized an immediate improvement of 31 percent and 27 percent, respectively. (See Appendix D for the complete analysis of these results.) Similarly, the pre-test and post-test revealed significant improvements ($p < 0.05$) in the proportion of hazards recognized. Crews 1, 2, and 3 exhibited increases in hazard recognition of 41 percent, 34 percent, and 44 percent, respectively.

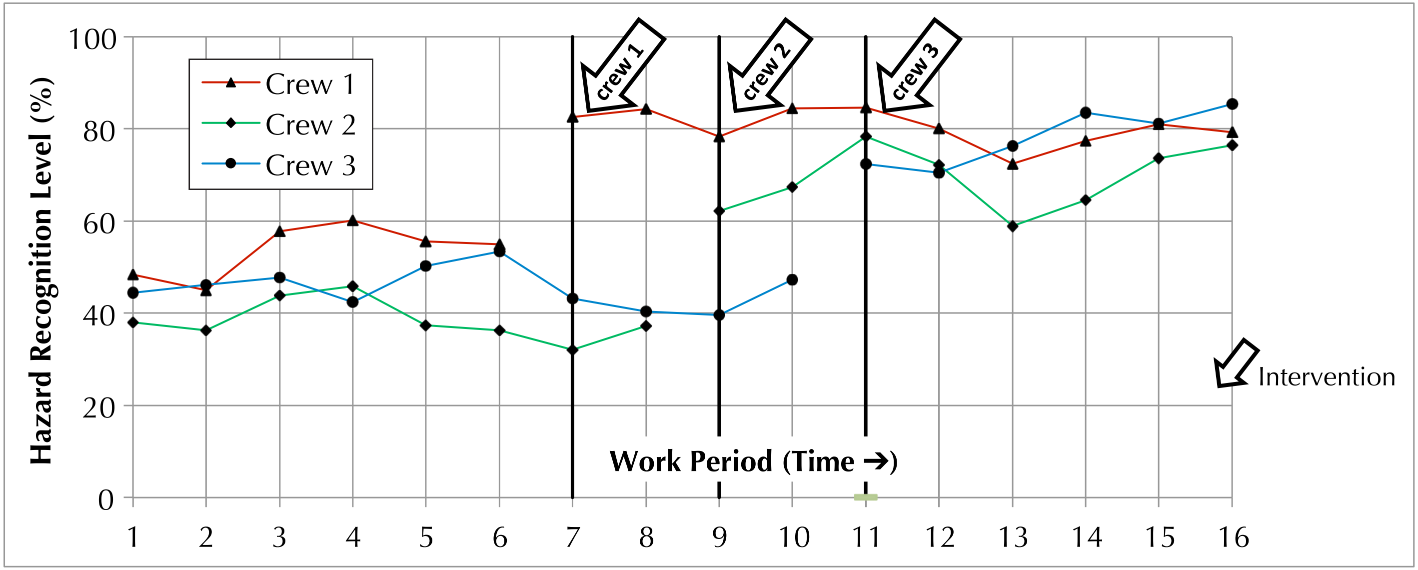

Figure 13. Case 4: SAVES Module Intervention Results

Case 5: Testing the HIT Board on the construction in a food manufacturing facility

The Case 5 project involved general maintenance and construction in a food manufacturing facility. The project accumulated 278,369 work hours every year. Three crews from different trades (i.e., mechanical, electrical, and civil) participated in the study.

The team followed the multiple baseline testing protocol for this case, but, gathered two sets of data for each crew after the introduction of the intervention. The first dataset was the ratio of the hazards that crews could correctly identify using the HIT Board prior to work and during the planning stage. The second set was the ratio of hazards that were identified throughout the day during the execution phase, but before exposure.

Figure 14 presents the data analysis results, which indicate that Crew 1 realized an improvement of 25 percent (from 48 percent to 73 percent) during the planning phase, and an additional nine-percent improvement (from 25 percent to 34 percent) was observed during the execution phase. Similarly, Crews 2 and 3 realized respective improvements of 26 percent and 21 percent during the planning phase. An additional improvement of four percent was observed for both Crews 2 and 3 during execution. (See Appendix D for the complete analysis of these results.) A statistically significant improvement ($p < 0.05$) was observed in the test using photographs for each crew. Crews 1, 2, and 3 exhibited improvements of 39 percent, 32 percent, and 24 percent, respectively.

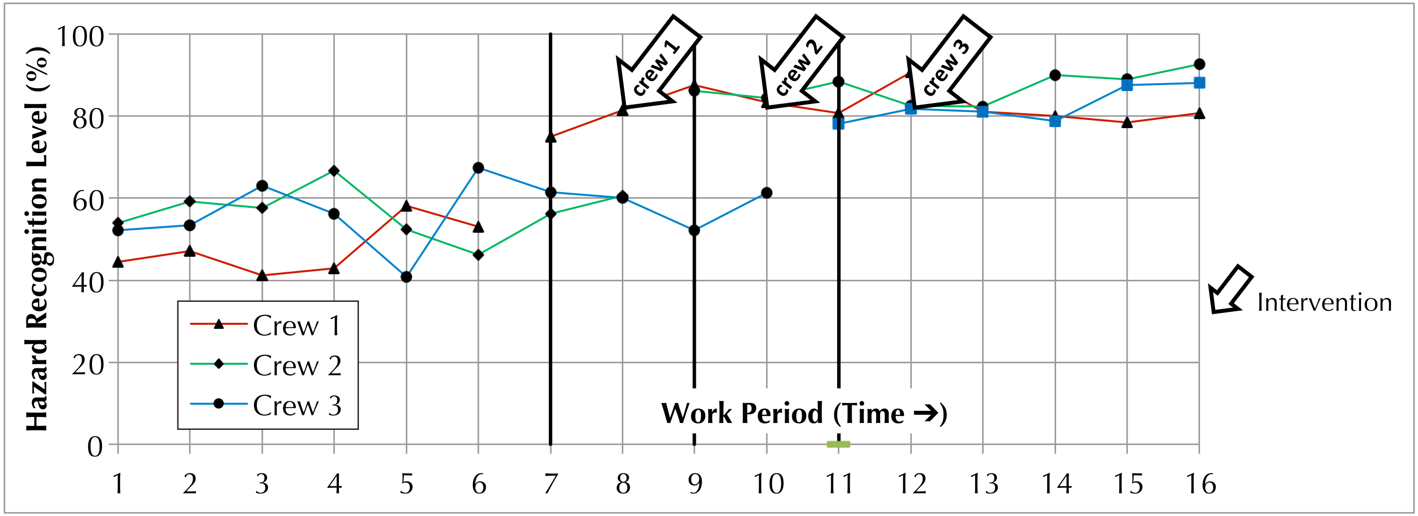

Figure 14. Case 5: HIT Strategy Intervention Results

Case 6: Testing the HIT Board on a detergent manufacturing facility

The Case 6 project was a detergent manufacturing facility, the contractor of which was hired for general maintenance and renovation. The project accumulated an average of 342,250 work hours every year. Two millwright crews and one piping crew were selected to participate in the study.

Figure 15 presents the data analysis results, which indicate that Crew 1 realized an improvement of 29 percent (from 45 percent to 74 percent) during the planning phase, and an additional six-percent improvement (from 29 percent to 35 percent) was observed during execution. Similarly, Crews 2 and 3 realized respective improvements of 19 percent and 24 percent during the planning phase.

An additional improvement of nine percent was observed for Crew 2, and a one-percent boost was observed for Crew 3 during execution. (See Appendix D for the complete analysis of these results.) Similarly, Crews 1, 2, and 3 realized statistically significant improvements ($p < 0.05$) of 35 percent, 23 percent, and 35 percent, respectively, in the corroborative test.

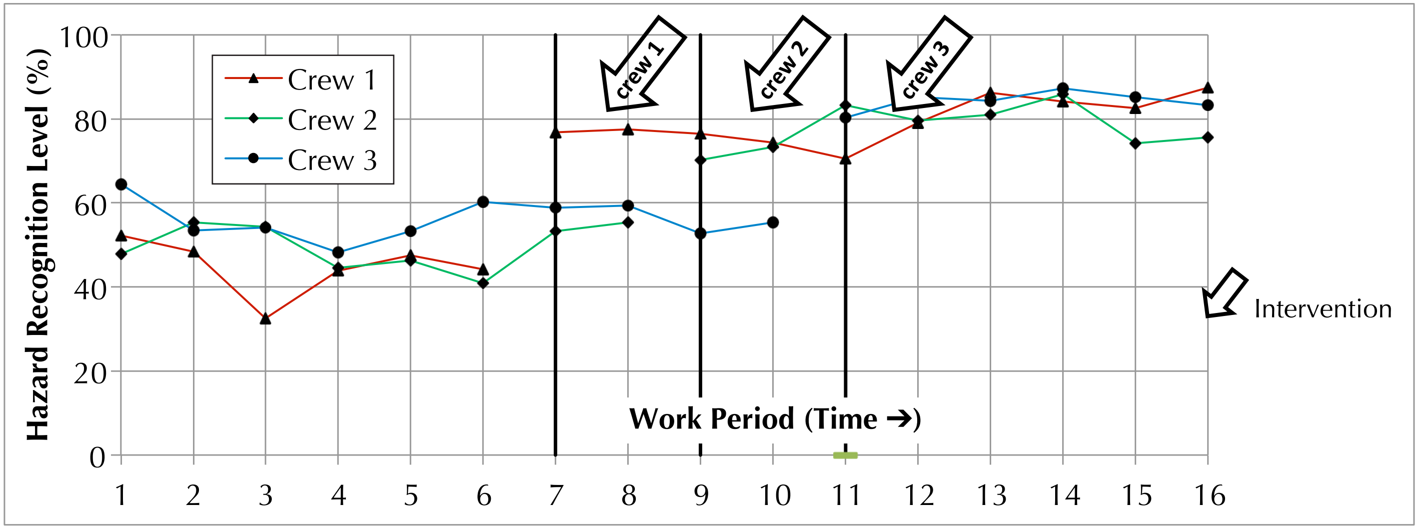

Figure 15. Case 6: HIT Strategy Intervention Results

5

Conclusions

Recognizing hazards is the most essential component of the safety management process. Unrecognized hazards expose workers to unanticipated risk. The results of this study suggest that, on average, construction crews recognize less than 50 percent of the hazards they may be exposed to on the job. To respond to the imminent need for better hazard recognition, RT 293 developed three proactive and transformative hazard recognition strategies: the Safety Meeting Quality Metric (SMQM); the System for Augmented Virtuality Safety (SAVES) tool; and the Hazard Identification and Transmission (HIT) Board. Empirical testing of these strategies on active construction projects revealed statistically significant improvements. Specifically, the SAVES module contributed to a net immediate improvement of 27 percent (with an average improvement of 30 percent). Similarly, the SMQM model contributed to a net weighted overall immediate improvement of 31 percent (with an average improvement of 25 percent). The HIT Board realized a net immediate improvement of 24 percent during the pre-task planning phase (with an average improvement of 24 percent), and 30 percent during the execution phase (with an average improvement of 30 percent). The proportion of hazards recognized can be further increased if management provides feedback to workers after each work period. In addition to these core findings, the team's key take-away from this project include the following:

Key empirical findings

- Work crews on CII companies can miss up to 80 percent of known hazards.
- All three strategies produced dramatic results and improvements.
- All participants' hazard recognition skills are different (with high variability), and all can be improved.
- Hazard identification is at the root of all safety planning efforts.
- Field testing for construction safety is possible.

Key qualitative findings

The strategies developed by RT 293 provide the following benefits:

- All three strategies improve group communications around hazard identification.
- All three strategies increase employee participation and engagement.
- All three strategies enrich safety culture through better hazard recognition.
- All three strategies can be used as a cornerstone of an effective safety program.

This research provides valuable contributions to the construction industry, since hazard recognition is a pre-requisite to making any improvement in safety performance. These proactive hazard recognition methods overcome many of the limitations associated with traditional methods. Future research should focus on industry-specific and worker-centric hazard recognition programs to further improve hazard recognition skills.

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Appendix A

Decision Criteria for Down-selection Process

Strategy No.	Criterion	Description
1	Active	The strategy needs to be participant-centric and encourage the workforce to be involved actively in hazard detection. The strategy must use techniques such as visual or audio cues and focus on getting workers to use their senses.
2	Testable	The strategy needs to be practically testable within both virtual and real environments.
3	Minimally Disruptive	The strategy must be easily integrated with existing work practices, must be user-friendly, and must require only reasonable resources for implementation.
4	Measurable	The degree of implementation or the quality of the system implementation needs to clearly be measurable.
5	Feasible	The strategy that will be implemented will need to be easily implemented with the current level of technology available to the construction industry.
6	Promotes Knowledge Acquisition	The strategy must allow the easy dissemination of knowledge to the workforce and must focus on workers' retention of the knowledge and their long-term improvement.
7	Scalable and Adaptable	The strategy must easily be adaptable to different working conditions, crafts, and locations. The technique must also be easily applied to a large group of workers.
8	Uses Scenario-building	The strategy must have the potential to help workers in scenario-building and must increase the current level of hazard recognition.
9	Promotes Worker Participation	The strategy must be worker-centric and must focus on getting workers actively involved in the aim of improving hazard recognition to improve safety performance.
10	Potentially Valuable	Safety professionals must see promise in the strategy's ability to enhance hazard recognition levels.

Appendix B

Operational Definitions for Energy-based Retrieval Mnemonics

Energy source	Examples
Gravity	Falling objects, collapsing roof, and a body tripping or falling
Motion	Vehicle, vessel, or equipment movement, flowing water, wind, body positioning: lifting, straining, or bending
Mechanical	Rotating equipment, compressed springs, drive belts, conveyors, or motors
Electrical	Power line, transformers, static charge, lightning, energized equipment, wiring, or batteries
Pressure	Pressure piping, compressed gas cylinders, control lines, vessels, tanks, hoses, or pneumatic and hydraulic equipment
Temperature	Open flame and ignition sources, hot or cold surface, liquids or gases, hot work, friction, general environmental conditions, steam, or extreme and changing weather conditions
Chemical	Flammable vapors, reactive hazards, carcinogens or other toxic compounds, corrosives, pyrophorics, combustibles, inert gas, welding fumes, or dusts
Biological	Animals, bacteria, viruses, insects, blood-borne pathogens, improperly handled food, or contaminated water
Radiation	Lighting issues, welding arcs, X-rays, solar rays, microwaves, naturally occurring radioactive material (NORM) scale, or other non-ionizing sources
Sound	Impact noise, vibration, high-pressure relief, equipment noise

Appendix C

Pre-job Safety Meeting Quality Measurement (SMQM) Maturity Model

Level	Plan		
	Identify the Job	**Basic Steps**	**Hazard Identification & Mitigation**
MATURE (3) To meet the criteria for a score at the Mature (3) level, the score must total 8–9. However, if any component scores at the Least Mature (1), level, reduce the score to the Less Mature (2) level.	The job as discussed is detailed and specific, adequately identifying the work to be performed, the tools that may be used, and the environmental conditions at the jobsite. If multiple jobs are being conducted, separate pre-job meetings are conducted for each job.	The basic steps of the job are discussed and explained in sequential order. The integration of steps is discussed in enough detail to accurately describe the entire process of completing the job. The relationship between the worker, the task, the tools, and the work environment are detailed.	Relevant energy sources and specific hazards are addressed and discussed for the job; subsequent plans to mitigate the hazards are fully addressed (e.g., permits, tools, equipment, training, and/or procedures). Evaluate activities for task demand (task difficulty) and suggest safety measures that may reduce task difficulty. Compare alternative means and methods to accomplish specific tasks with safety as the focus, and implement the best (less hazardous) alternative. In addition, potential hazards in surrounding work areas, or associated with adjacent work, are discussed and properly mitigated. STOP Work Authority is discussed and the specific work area conditions (e.g., wrong tool or equipment, not enough or the wrong people, or lack of clear understanding) and general work area conditions (e.g., weather, adjacent work, emergencies, major weather events, or plant alarms) that will stop work are addressed.
LESS MATURE (2) To meet the criteria for an overall score at the Less Mature (2) level, the score must total 14–22.	The job as discussed is specific (i.e., work tasks are appropriately identified). However, it is not detailed (associated tools and work methods are not thoroughly detailed) and, therefore, does not identify all of the work to be completed. Tools required to complete the job and environmental conditions are ignored.	The basic steps of the job are discussed and explained in sequential order. However, the integration of steps is discussed only in general terms. The relationship between workers tasks and tools is not considered.	Relevant energy sources and specific hazards are addressed and discussed; subsequent plans to mitigate the hazards are addressed (e.g., permits, tools, equipment, training, or procedures). However, potential hazards in surrounding work areas, or associated with adjacent work, are not discussed. Alternative means and methods are not discussed. STOP Work Authority, although recognized as general safety policy, is not particularly addressed.
LEAST MATURE (1) To meet the criteria for an overall score at the Least Mature(1) level, the score must total 59–13.	The job as discussed is not specific; as a result the job activity is inadequately identified.	The basic steps of the job are discussed. However, the steps are not discussed sequentially and do not accurately describe the entire process of completing the job.	Only a few energy sources are addressed, and only basic hazards and controls are discussed (e.g., permits and procedures). STOP Work Authority is not upheld or discussed.

Level	Do			
	Discussion Location	**Supervisor Leadership**	**Crew Participation**	**Documentation**
MATURE (3) To meet the criteria for a score at the Mature (3) level, the score must total 8–9. However, if any component scores at the Least Mature (1), level, reduce the score to the Less Mature (2) level.	The pre-job discussion takes place where the job is to be performed. This discussion includes final supervisor review and verbal approval to proceed with the work. This discussion involves a pre-inspection of the condition of tools, plants, and equipment for the task to be accomplished. A pre-job preliminary discussion may take place away from the worksite (e.g. construction trailer, gang box, or conex, office) but the pre-job discussion is finalized where the job will take place.	Supervisor or crew lead facilitates the pre-job and asks specific questions of multiple workers to obtain their input regarding planning and conducting the work safely. Supervisor solicits active participation of all crew members and encourages members to lead various pre-job discussion components. Supervisor upholds and empowers workers to use STOP Work Authority. Supervisor evaluates awareness and competency of the crew in terms of accomplishing the job.	Each crew member offers input, asks questions, and actively listens during the pre-job discussion. Crew members are given the opportunity to communicate to the supervisor any additional resources (e.g., PPE) they may need to perform the task safely. Crew members may lead various pre-job discussion components.	All components of the pre-job meeting are accurately documented on the appropriate project pre-job form. The pre-job form is reviewed and signed by each crew member, and signature approval is provided by the supervisor or crew lead. Following any STOP Work Authority or changes to the job, the changes are documented on the pre-job form. Changes are noted as an update.
LESS MATURE (2) To meet the criteria for an overall score at the Less Mature (2) level, the score must total 14–22.	Pre-job discussion takes place away from the site of the job (e.g. construction trailer, gang box, or conex, office). Supervisor's final verbal approval to proceed with the work takes place away from the job site. Pre-inspection of tools, equipment and plants is not performed.	Supervisor or crew lead facilitates the pre-job discussion and asks specific questions of multiple workers to obtain their input regarding planning and conducting the work safely. Supervisor does not discuss STOP-Work Authority.	Multiple crew members offer input, ask questions, and actively listen during the pre-job discussion. Crew members do not actively communicate required safety resources to the supervisor	All components of the pre-job meeting are accurately documented on the appropriate project form. The pre-job form is reviewed and signed by each crew member, and is approved by the supervisor or crew lead. Changes to the work are not noted on the pre-job form.
LEAST MATURE (1) To meet the criteria for an overall score at the Least Mature(1) level, the score must total 59–13.	Pre-job discussion takes place away from the site of the job (e.g. construction trailer, gang box, or conex, office). Work commences prior to supervisor's verbal approval, but eventually, the supervisor does approve the pre-job.	Supervisor or crew lead facilitates the pre-job discussion. There are only minimal attempts by the supervisor or crew lead to obtain worker input regarding planning and conducting the work safely.	Only a few members of the crew offer input, ask questions, and actively listen during the pre-job discussion.	Most of the components of the pre-job meeting are documented properly. The pre-job form is reviewed and signed by each crew member, and is approved by the supervisor or crew lead supervisor.

Level	Assess & Adjust		Score
	Job Changes	Evaluate	
MATURE (3) To meet the criteria for a score at the Mature (3) level, the score must total 8–9. However, if any component scores at the Least Mature (1), level, reduce the score to the Less Mature (2) level.	After lunch or breaks, the supervisor revisits the job site(s) and assesses and identifies any changes or potential changes for the job (e.g., work or equipment change, change in crew members, or visitors). The supervisor regroups the crew and discusses the remaining steps for the job and its associated hazards, including additional mitigation measures for any changes or potential changes that may occur. If anything unexpected is encountered, work is stopped. Implications and corresponding changes are discussed and agreed to prior to restarting work.	At the end of the day, areas of concern (e.g., components of the tool not utilized) are pointed out by the supervisor. Feedback and changes to improve performance levels are discussed. Hazards that may have gone unidentified are recognized and recorded as lessons learned.	**27** **26** **25** **24** **23**
LESS MATURE (2) To meet the criteria for an overall score at the Less Mature (2) level, the score must total 14–22.	After lunch or breaks, the supervisor revisits the job site(s) and assesses and identifies any changes or potential changes for the job (e.g. work or equipment change, change in crew members, or visitors). However, the supervisor only regroups the crew if there are any changes to discuss.	Areas of concerns are pointed out by the supervisor, at the end of the day. Unidentified hazards are not recorded and no feedback is elicited.	**22** **21** **20** **19** **18** **17** **16** **15** **14**
LEAST MATURE (1) To meet the criteria for an overall score at the Least Mature(1) level, the score must total 59–13.	The supervisor revisits the job site but only if known changes have taken place (e.g., job shut-downs or facility emergencies). The supervisor may or may not regroup the crew to discuss the changes.	No follow-up of performance is conducted.	**13** **12** **11** **10** **9**

Appendix D

Multiple-baseline Testing Field Test Results

SMQM Results					
		HR_{bL}	HR_{I}	D	p-value
Case 1	Crew 1: Structural	40	66	26	< 0.01
	Crew 2: Electrical	39	70	31	< 0.01
	Crew 3: Hydro-testing	39	77	38	< 0.01
Case 2	Crew 1: Civil	40	55	15	< 0.01
	Crew 2: Plumbing and Piping	30	53	23	< 0.01
	Crew 3: Equipment Operators	46	64	18	< 0.01

HR_{bL} = predicted HR index from baseline phase (before)

HR_{I} = expected HR index from intervention phase (after)

Δ = percent improvement

SAVES Results					
		HR_{bL}	HR_{I}	D	p-value
Case 1	Crew 1: Civil	43	72	29	<0.01
	Crew 2: Maintenance	56	76	20	<0.01
	Crew 3: Mechanical	29	73	44	<0.01
Case 2	Crew 1: Electrical	54	80	27	<0.01
	Crew 2: Iron Workers	38	69	31	<0.01
	Crew 3: Insulators	44	71	27	<0.01

HR_{bL} = predicted HR index from baseline phase (before)

HR_{I} = expected HR index from intervention phase (after)

Δ = percent improvement

HIT Results								
		Planning Phase				**Execution Phase**		
		HR_{bL}	HR_{I}	D	p-value	HR_{I}	D	p-value
Case 5	Crew 1: Mechanical	48	73	25	<0.01	82	34	<0.01
	Crew 2: Electrical	57	83	26	<0.01	87	30	<0.01
	Crew 3: Civil	57	78	21	<0.01	83	26	<0.01
Case 6	Crew 1: Millwright	45	74	29	<0.01	80	35	<0.01
	Crew 2: Plumbing and Piping	50	69	19	<0.01	78	28	<0.01
	Crew 3: Millwright	56	80	24	<0.01	81	25	<0.01

HR_{bL} = predicted HR index from baseline phase (before)

HR_{I} = expected HR index from intervention phase (after)

Δ = percent improvement

Notes

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