The Effect of Hazard Clustering and Risk Perception on Hazard Recognition

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Abstract. Active mining operations are complex, dynamic environments that can present workers with an array of potential safety and health challenges. From missing fire extinguishers to large equipment and falling rocks, hazards exist that mineworkers must be cognizant of to keep themselves and their coworkers safe. While hazard identification is a key skill that mineworkers must possess to ensure workplace safety, the location and perceived risk of the hazards may alter this ability. To further explore these effects, NIOSH researchers conducted a study to characterize how mineworkers search for and identify hazards. Researchers asked participants to search 32 static panoramic scenes depicting typical locations at a surface stone mine—pit, plant, roadway, and shop—with each containing zero to seven hazards. Mineworkers tended to miss hazards when they were in clusters—i.e., where two or more hazards appeared within the worker's central field of view. This paper examines the relationship of clustered hazards, perceived risk and identification accuracy and how location and experience affect it. Based on the results, strategies will be suggested that mineworkers can use to help identify hazards in their workplace.

Keywords: Visual search · Simulator · Mineworker safety

1 Introduction

The mine environment poses significant challenges for operators to provide a safe and healthy workplace, as evidenced by the sharp increase in the number of fatalities in metal/nonmetal (M/NM) mines between 2013 and early 2015 [1]. In response, the Mine Safety and Health Administration (MSHA) provided a renewed focus on workplace exams. In 2017, MSHA amended the workplace exam rule with the intent to improve identification of dangerous conditions and promote corrective action before accidents occur [2]. The final rule requires examinations to occur in a timelier manner and increases accountability by requiring the reporting of hazards that are not immediately corrected in exam reports. The final rule also requires a "competent person" to conduct workplace exams, but there is no guidance as to the qualifications of this person. The Code of Federal Regulations (30 CFR 56.2) merely states that such a person must possess abilities and experience that fully qualify them for such assigned duties [3].

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At the most basic level, to complete a workplace exam successfully, a competent person must be able to recognize and mitigate hazards in the environment. Hazard recognition generally involves the identification and assessment of hazards; this relies heavily on the visual perception and decision-making abilities of the mineworker preforming the exam. Unidentified mine site hazards pose a risk to workers at the site. Therefore, understanding the factors that affect visual search and decision-making performance is crucial.

Visual search errors are generally thought of as perception issues that can be caused by a lack of skill, knowledge, or attention in relation to what or how to search. Specifically, scanning and recognition visual search errors occur when an individual either never fixates on an object or fails to recognize an object as an important feature that requires further examination. Decision-making errors are related to recognition errors in that they are based on knowledge and skill, but are top-down errors associated with cognitive processing [4]. Both visual search and decision-making errors have been studied in many fields and include several overarching factors: scene complexity, attention, salience, expectations, and experience.

Overall, scene complexity reduces search and decision-making performance. By increasing the number of salient objects in a scene, clutter reduces the prominence and accessibility of search targets [5]. Furthermore, the mere presence of any foveal stimulus has been shown to reduce the useful field of view (UFOV)—the area of vision that can acquire information during a fixation [6]. Visual clutter enhances the reduction of UFOV and is particularly prominent when background object and target similarity is high [7–9]. Consequently, visual clutter is believed to increase search times as a result of the increased number of fixations required to locate a hazard among distractors [8, 10]. It has also been shown that background information influences search time more than image area and density, suggesting that overall scene complexity may be more detrimental to search performance than local clusters [11]. Practically, all of these effects have been demonstrated in hazard recognition while driving, where hazard recognition performance is worse on busy urban roads than rural roads [12].

Visual clutter also requires more attention to process, but attention is a limited resource. It would be impossible for a mineworker to fully scan every inch of a mine site. Therefore, hazard salience plays a critical role. In radiology, among other fields, research has shown that less salient targets are more likely to be missed [13]. For hazard recognition, more risky hazards may be more salient. Salience can also be related to expectations. Studies on inattentional blindness have shown that viewers frequently fail to recognize unexpected changes to aspects of a video scene if they are given a cognitive task related to another aspect of the display [14]. Researchers also demonstrated that even with prior knowledge of an unexpected event, viewers were no less likely to notice any other unexpected event [14].

Expectations have also been shown to reduce hazard identification performance through decision-making errors like satisfaction of search (SOS) errors. SOS errors are defined as a reduction in detection once one hazard has been identified. Because searchers believe that there are limited hazards, once one is found, searchers do not expect there to be any more and stop searching, leading to missed hazards. Just like visual clutter, SOS effects have been demonstrated over various domains including radiology, cognitive psychology, and security screening [13]. Additionally, it has been shown that when target salience is variable, SOS errors lead to the more salient targets being identified either in a cluster or in isolation from distractors [15].

In combination with complexity, attention, salience, and expectations, experience has been shown to have an interacting effect on hazard recognition ability. Experts benefit from unique perception skills related to visual search and decision-making that enable them to recognize what is typical in a situation, perceive subtle discriminations, and quickly perceive, understand, and project future events [16]. Recognizing typicality allows experts to sort through cluttered scenes and only focus on relevant information. Discrimination allows experts to focus directed attention to differentiate details that less experienced people may not recognize. Mental modeling and situational awareness allows experts to better understand and recognize hazards as well as assess risk associated with potential outcomes.

The perception skills of experts have been demonstrated across many domains. Primarily based on visual search, numerous automotive studies have demonstrated the experience effect, finding that inexperienced drivers tended be more inflexible with their visual search patterns and were unable to adapt their attention as scene layout and complexity changed, resulting in poorer hazard recognition possibly due to reduced awareness and attention [18–21]. However, studies have also demonstrated the importance of targeted experience. Perlman et al. found that experienced safety professionals in construction outperformed both the less and similarly experienced workers on hazard recognition, indicating that experience needs to be task-specific for the worker to reap the benefits [17]. Eiter et al. also found a similar result with safety professionals and mineworkers performing workplace exams [22].

In order to systematically characterize image context, risk perception, experience, and their effects on hazard recognition accuracy, the National Institute for Occupational Safety and Health (NIOSH) conducted a research study in a simulated environment. The goal of this study was to simulate performing workplace exams within a controlled laboratory setting using an immersive virtual reality (VR) simulator. Mineworkers of varying experience levels were asked to search a series of panoramic images depicting typical work environments at a surface limestone operation. For this study, realism was prioritized over homogeneous hazard distribution. Representative locations (i.e., pit, plant, roadway, and shop) were also chosen to account for natural context variability. However, some locations at mine sites are inherently more visually cluttered than others (i.e., shop and plant). As a result, hazards were clustered in many images, where one or more hazard was within the participant's near-peripheral field of view. The clustering of hazards exemplifies a special case of visual clutter. Therefore, this naturalistic setup provided the opportunity to further explore hazard recognition performance by investigating the relationship of hazard clusters with perceived risk, experience, and accuracy.

The first hypothesis is that mineworkers are less likely to identify hazards in visually cluttered environments, including both local clustering as well as an overall cluttered environment. The second hypothesis is that mineworkers are more likely to identify hazards that they perceive to be higher risk based on accident severity, accident probability, and overall risk. The third hypothesis is that mineworkers with more safety experience are more likely to identify hazards. By better understanding these factors, NIOSH can begin to tailor safety interventions to make mine examinations more effective, and thus reduce the likelihood of future workplace injuries.

2 Methods

2.1 Participants

A total of 49 individuals completed the study after providing informed consent to participate in the institutional review board approved protocol. Participants were screened for visual acuity of 20/40 or better, vision disorders, and color blindness. All participants were also screened for full peripheral vision of −45 to +85° in both eyes. Study participants were volunteers with varying levels of experience working in surface mining operations. The participants were categorized by expected experience level ranging from student (n = 14), inexperienced miners (n = 12), experienced miners (n = 11), and safety professionals (n = 12), where safety professionals had at least 2 years of experience in an environmental, health, or safety position for a mine operator or government agency, experienced miners had more than 2 years of experience as a mineworker or supervisor, inexperienced miners had some but less than 2 years of experience as a mineworker or supervisor, and students were defined as a person enrolled in a mining-related program that is not otherwise classified. For more detailed demographics, see Eiter et al. [22].

2.2 Panoramic Images

Thirty-two panoramic photographic images of a surface limestone mining operation were used. The images were categorized by location with eight from each of the pit, plant, roadway, and shop (Fig. 1). The pit and roadway images were generally more open lacking additional salient objects aside from the hazards. The plant and shop locations were characterized by significantly more salient object within the images. The plant images feature large conveyors spanning across the area and the shop images were particularly cluttered with shelves packed with various tools and spare parts. Each image contained zero (control) to seven hazards. The hazards were selected to be a representative range of type and severity of hazard based on MSHA data and subject matter expert (SME) feedback from former MSHA inspectors, mine safety professionals, and other mining experts within NIOSH [22].

Fig. 1. Image examples from the pit, plant, roadway and shop locations (left to right).

2.3 Procedure

Data collection took place in the Pittsburgh Mining Research Division (PMRD) Virtual Immersion and Simulation Laboratory (VISLab). The main VISLab simulator uses a 360° panoramic projection screen that is 10 m in diameter by 3 m tall. Imagery is front-projected onto this screen from six high-definition projectors (Titan 1080p 3D, Digital Projection, Kennesaw, GA) to create a seamless image. The screen provides a visual field that is about 35° vertically from the center of the area.

Ten motion-tracking cameras (T20, Vicon, Oxford, UK) were used in concert with eye-tracking glasses (ETG 2.0, SensoMotoric Instruments, Teltow, Germany) to track participant movement and resolve their point of regard within the display space. The study image sequencing was controlled by an in-house Unity application (Unity Technologies, San Francisco, CA). See Bellanca et al. for a more detailed discussion of the development of the images, laboratory setup, and data collection methods [23].

Participants were fitted with eye-tracking glasses connected to a small laptop placed in a backpack worn by the participant. Participants were also given a hand grip button in their dominant hand that was connected to wireless data streaming hardware that was also placed in the backpack. The eye-tracking glasses have passive motion-tracking markers to track the participant's head position, and several additional markers were placed on the participant's torso to resolve head motion relative to the body frame. A series of calibration tests for the motion-tracking system and eye-tracking glasses were then conducted in the 360-degree simulator to ensure the data collection software was accurately capturing the participant's gaze within the screen space. Once the data collection instruments were calibrated, researchers presented two panoramic images to the participants to allow them to familiarize themselves with the 360-degree simulator and button press control.

Once acclimated, participants were presented with the 32 images in four sets of eight grouped by location category (pit, plant, roadway, and shop). Blocks were randomized across participant category, and images were randomized within location category. Participants were allowed two minutes to view each image and were instructed to press the hand grip button as quickly as possible when they identified a hazard. If they decided they had identified all the hazards in an image, participants could press a second button on the hand grip to end that trial early. Once all images were complete, the glasses, markers, and backpack were removed.

Following the hazard identification, participants were debriefed about all the images and the hazards. Regardless of identification, participants were asked to complete a risk assessment for each of the hazards. The risk assessment measure used for the study was adapted from Perlman et al. [17], where participants were asked to use a 5-point Likert scale to rate accident severity, accident probability, and overall risk as described in Table 1.

2.4 Eye-Movement Data Processing

The eye-tracking data was transformed into image space via motion-tracking data such that hit/miss accuracy could be calculated using a region of interest (ROI) and the button press timing. ROIs of hazards were pre-defined based on input from SMEs.

Table 1. Risk assessment instrument.

	Assessed risk value				
	1	2	3	4	5
Accident severity	No injury	Minor injury no leave	Injury $\geq$ 3 days leave	Non-fatal major injury	Fatal
Accident probability	Very unlikely	Fairly unlikely	Average likelihood	Fairly likely	Very likely
Risk level	Very low	Low	Medium	High	Very high

Fixations were calculated using a dispersion algorithm (minimum duration of 75 ms, maximum dispersion of 50 pixels) on the scan path data. Hits or misses on the button presses were based on the central gaze position of the fixation prior to the button press. Criteria for hit classification were developed to account for intention (requiring a prior fixation near the target), decision-making, and motor delay (for late hits) [24] as described previously by Eiter et al. [22]. All button press data was visually verified by a member of the research team and reviewed by a second team member if necessary.

Hazards were grouped in clusters if two or more hazards were present in an observer's typical UFOV based on the distance between the closest edges of ROI boundaries. Specifically, the polygonal ROI boundaries were simplified to rectangular bounding boxes by using minimum and maximum values in x and y pixel space (Fig. 2). Minimum horizontal angles between each ROI pair were calculated. Pairs of hazard targets were considered to belong to a cluster if the minimum angle was less than or equal to 30°, as is common in standard vision periphery screening tests and considered the typical UFOV [25]. Using this definition, there were 27 clusters in the 32 pictures. The number of clusters per image ranged from zero to three, and the number of hazards per cluster ranged from two to four, with an average of 2.3 hazards per cluster.

2.5 Statistical Analysis

The effect of clusters and risk were analyzed in two different ways. First, to capture the effects of the predictors on identification of individual hazards, hit/miss accuracy was modeled using generalized estimating equations (GEEs) with a binomial error distribution and a logit link function. GEE was chosen to account for the possible correlation of hazard identification by subject. A full factorial model was tested including cluster, risk, location, and group. Pairwise comparisons were completed for any significant effect using estimated marginal means. Second, severity, probability, and risk were explored as dependent variables to examine perception trends, especially since the risk assessments were performed on all hazards following identification, and the possibility that awareness of identification influenced perception could not be ruled out. Because hazard realism was given precedence over experimental control, it was not possible to achieve equal distributions of the risk of hazards across the locations. Therefore, location is not considered as a predictor of severity, probability, or risk. For analysis,

Fig. 2. Close-up view of a panoramic image from the mine plant showing an area with clustered hazards where only the highest-rated hazard was identified. Green ROIs indicate a hit; red ROIs indicate a miss. Each ROI is also identified with a unique ID number. The scan path line is color-coded from cool to warm colors before and after the button press. The click icons indicate fixations and the yellow dot represents the fixation location associated with the button press.

these variables were averaged over hit/miss and cluster assignment for each participant. Using the aggregated data, a maximum likelihood linear mixed model analysis was performed. Pairwise comparisons were also completed for any significant effect using estimated marginal means (SAS, Cary, NC). The alpha was set to 0.05 for all multivariate models and post-hoc comparisons.

3 Results

3.1 Accuracy

According to the first hypothesis, overall, hazards in clusters were less likely to be found ($p < 0.001$), where 56% of non-cluster hazards were correct and 48% of cluster hazards were correct. In fact, 14 of the top 20 missed hazards overall were in a cluster.

The GEE also resulted in differences in accuracy by risk ($p < 0.001$), group ($p = 0.001$), location ($p = 0.001$), and the interactions of cluster x location ($p < 0.001$) and risk x group ($p = 0.017$) effect. Risk as a predictor of accuracy supported the second hypothesis, all the levels were significantly different except 1 and 2 ($p < 0.01$, $p = 0.101$), with riskier ratings (5) having a higher likelihood of a hit. The estimated means from 5 to 1 were 67%, 60%, 51%, 43%, and 37%, respectively. The group effect supported the third hypothesis, where the results revealed that the safety professionals performed better than the students and inexperienced mineworkers ($p < 0.01$). The estimated means were 48% for the students, 48% for the inexperienced, 53% for the experienced, and 58% for the safety professionals. The post-hoc analysis of the location effect revealed that accuracy in the shop was significantly better that all other locations ($p < 0.01$), with means of 59%, 48%, 50%, and 49%, running counter to the visual clutter hypothesis. Looking closer at the location-cluster interaction effect revealed that accuracy was significantly better for non-clustered hazards in the more cluttered plant and shop locations ($p < 0.001$) and not significantly different for the pit ($p = 0.840$) and roadway ($p = 0.419$) as depicted in Fig. 3.

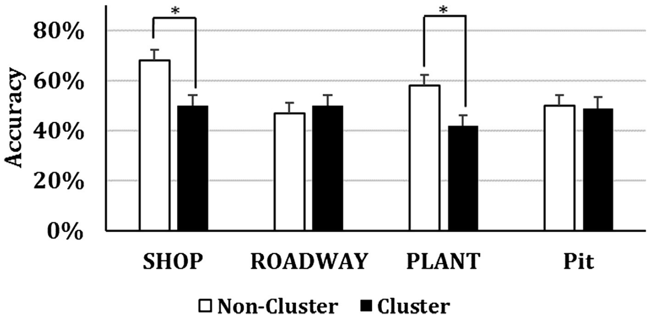

Fig. 3. Graph depicting the estimated marginal means of accuracy derived from the GEE model for clustered (black) and non-clustered (white) hazards by location. Bars connected with an (*) indicate significant differences at $p < 0.01$.

3.2 Perceived Risk

According to the second hypothesis, identified hazards on average were perceived as more severe, more probable, and overall riskier as displayed in Table 2. This is congruent with the significant correlation of risk and accuracy found in the GEE model.

Table 2. Estimated marginal means of average risk assessment ratings.

	Hazard Identification		
	Hit	Miss	Significance
Severity	3.542	3.313	<0.0001
Probability	3.248	2.899	<0.0001
Overall risk	3.482	3.142	<0.0001

Across the three risk variables, clusters were only found to be significant in the severity rating, where both the main cluster effect and cluster-accuracy interaction effect were found to be significant. Specifically, the results indicate that hazards in a cluster tended to be perceived as less severe ($p = 0.015$), with an average rating of 3.386 for clustered hazards and 3.469 for non-clustered hazards. Similarly, the cluster-accuracy interaction effect revealed that missed non-clustered hazards (3.238) tended to be perceived as less severe than missed clustered hazards (3.387) (p = 0.002), while identified hazards were not significantly different (p = 0.748).

Congruent with the GEE, there was a significant group-accuracy interaction for overall risk (p = 0.049). Analysis of the group-accuracy interaction effect for overall risk showed that group was significant for missed hazards (p = 0.030), but not for hit hazards (p = 0.280). Furthermore, for missed hazards, risk ratings of experts were significantly higher than ratings of safety professionals (p = 0.009) and ratings of students (p = 0.009), as depicted in Fig. 4.

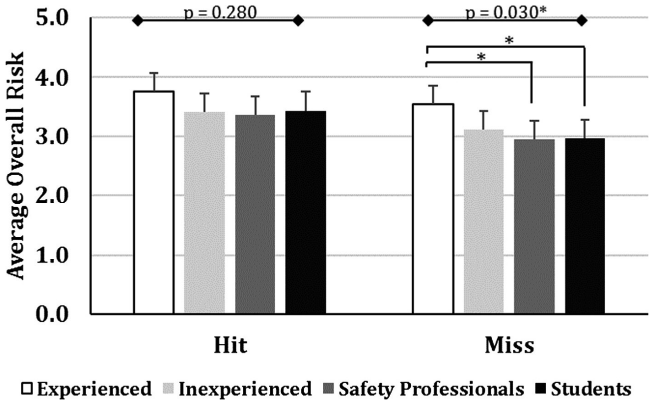

Fig. 4. Graph depicting the estimated marginal means derived from the mixed model of averaged overall risk ratings for hit and missed hazards across group.

4 Discussion and Conclusion

As hypothesized, hazards in clusters were less likely to be found. However, the detrimental effect of visual clutter was not supported in the effect of location. The more subjectively cluttered shop actually had the highest level of accuracy. Further investigation of the cluster-location interaction effect revealed that the two most cluttered environments (i.e. shop and plant) had higher accuracy rates for non-clustered hazards. Though this is counter to the visual search literature, this effect and overall cluster effect may be explained by SOS errors. The more sparse areas could have lead mineworkers to expect fewer hazards; this would lead to early termination in the pit and roadway locations. Similarly, given the overall cluttered nature of the shop once a hazard was found, the mineworker may have moved on to another area of the scene resulting in a low accuracy for cluster hazards as the secondary hazards were less likely to be found. Interestingly, the main effect of location from the GEE was slightly different from that previously estimated without clusters and risk in the model. The previous analysis found that roadway accuracy was significantly worse than the other locations [22]. While the estimated marginal means from the GEE still found the roadway accuracy to be lowest, though it was not significantly so. These differences underscore the importance of visual clutter and risk on accuracy.

Another explanation to the counter location effect could be the size and clarity of the hazards. Due to the naturalistic layout of the images, size and prominence were not evenly distributed. Furthermore, the contextual nature of the hazards makes the definition of size difficult and highly subjective. A more controlled stimulus may be better able to tease these effects apart, as these factors may be obscuring the expected effect.

The analysis supported the second hypothesis that identified hazards are perceived to be riskier. In the context of hazard recognition, risk can serve as a proxy for salience as it relates directly to the task objective of keeping mineworkers safe. In this study, risk was significantly related to accuracy on the level of individual hazards (GEE) as well as in aggregate across conditions (mixed model). However, it is important to note that the risk ratings may be biased because the participants provided these ratings as they reviewed their hazard recognition accuracy. The participants could simply have been justifying their selections by giving them a higher rating. Additional work should be done to systematically explore this relationship.

As alluded to above, a unifying explanation for the visual clutter and risk hypotheses could be SOS errors due to a number of factors (salience, time pressures, or preconceptions about the number of hazards present) [13]. In this case, the assessed severity, probability, and overall risk may be more salient to participants, leading to higher identification rates. Time may have also been a factor because many of the participants were forced to stop searching across the scenes when the two-minute time expired. Because the time-out occurrences were not sufficiently saturated across the groups and locations, this was not explicitly analyzed. A more directed study could confirm this hypothesis. Similarly, the inclusion of control images with no hazards may have also contributed to SOS errors. Although the number of hazards was unknown to the participants during data collection, they were informed that some scenes contained no hazards.

The effect of experience matches with previous work in that targeted experience leads to improved accuracy [16, 22]. The group effect may also speak to potential differences in attentional demands. As exemplified in driving studies, novices underperform experts partially because they have not internalized the search activities, thus requiring more attention and greater potential for errors [26, 27]. Similarly, the experience effect of risk suggests that experienced mineworkers may have more practice at performing risk assessments as they may be more likely to perform workplace exams on a daily basis as a part of their jobs. Experienced workers also have greater exposure to the hazards, and therefore may have a better understanding of the results and likelihood. Given these experience differences, more focus may need to be given to standardizing risk assessments to ensure that proper mitigation efforts are taken.

Mineworkers face a challenging and dynamic work environment that requires diligent attention to occupational risks so that they go home safely at the end of each shift. Improving the knowledge, skills, and abilities with which mineworkers scan their work environments for potential health and safety threats is key to reducing workplace illness and accidents. The important message from this research is that mineworkers, safety professionals, and trainers should be aware of the common shortcomings of human perception and decision-making. By understanding that many individuals will often miss key visual cues in their environment or lack knowledge about certain hazards, we can develop strategies to improve hazard identification performance.

Salience, attention, and experience should be considered in order to actually improve hazard recognition strategies to overcome detriments caused by visual clutter. Specifically, Ball et al. [7] demonstrated that with practice, error rates for identifying off-axis targets were reduced and the UFOV could be expanded by 10°. Therefore, practice can be used to combat visual clutter. In an effort to reduce attentional demands, task-specific risk checklists have also been shown to improve hazard detection, particularly in high-clutter environments. Checklists reduce the cognitive workload of a mineworker preforming a workplace exam as this information does not need to be retained in working memory [29]. More generally, object-based priming (previewing images of hazards that are likely to be encountered) has been shown to improve visual search performance, and thus exposure to example hazards through practice or otherwise may help improve knowledge and decision-making in identifying hazards [28].

Beyond these targeted efforts, a more detailed analysis of the scan path data might reveal behaviors used by participants who were more successful at identifying hazards. For example, it was observed anecdotally that in some cases participants were able to correctly identify additional hazards by making a second pass at the part of the scene containing the clustered hazards. While further analysis and research is needed to verify this observation, such strategies could also eventually be incorporated into training interventions.

Disclaimer. The findings and conclusions in this paper are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of company names or products does not constitute endorsement by NIOSH.

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