Applied Ergonomics 43 (2012) 1058–1065

Contents lists available at SciVerse ScienceDirect

Applied Ergonomics

journal homepage: www.elsevier.com/locate/apergo

A visual warning system to reduce struck-by or pinning accidents involving mobile mining equipment

J. Sammarco*, S. Gallagher, A. Mayton, J. Srednicki

National Institute for Occupational Safety and Health, 626 Cochrans Mill Road, PO Box 18070, Pittsburgh, PA 15236, USA

ARTICLE INFO

Article history:
Received 8 July 2011
Accepted 19 March 2012

Keywords:
Mining
Visual warning
Visual reaction time

ABSTRACT

This paper describes an experiment to examine whether a visual warning system can improve detection of moving machine hazards that could result in struck-by or pinning accidents. Thirty-six participants, twelve each in one of three age groups, participated in the study. A visual warning system capable of providing four different modes of warning was installed on a continuous mining machine that is used to mine coal. The speed of detecting various machine movements was recorded with and without the visual warning system. The average speed of detection for forward and reverse machine movements was reduced by 75% when using the flashing mode of the visual warning system. This translated to 0.485 m of machine travel for the fast speed condition of 19.8 m/min, which is significant in the context of the confined spaces of a mine. There were no statistically significant differences among age groups in the ability to detect machine movements for the visual warning modes in this study. The visual warning system shows promise as a safety intervention for reducing struck-by or pinning accidents involving continuous mining machines. The methods and results of this study could be applied to other moving machinery used in mining or other industries where moving machinery poses struck-by or pinning hazards.

Published by Elsevier Ltd.

1. Introduction

Approximately 619,000 people were employed, directly and indirectly, in the U.S. mining industry during 2008 (BLS, 2009). Mining operations are located underground and on the surface; the various commodities mined are categorized as metal, nonmetal, and coal. Coal mining is particularly noteworthy given that coal-fired electrical generation plants provide about half of the electricity in the United States. Mining operations, regardless of the location and commodity, use large, mobile equipment to mine and transport the commodities. Mobile machinery poses a significant safety risk to workers who can be struck-by or pinned, resulting in worker injury or death.

The National Institute for Occupational Safety and Health (NIOSH) is conducting research to reduce struck-by or pinning accidents in mining. These machine-related accidents are at the forefront of NIOSH stakeholder concerns. Stakeholders including mining companies, equipment manufacturers, and academia were directly contacted to identify critical research needs to improve miner safety with respect to machine safety. Reducing struck-by or pinning accidents was tied with improving mine lighting as the top critical research area for machine safety research. The stakeholder concerns are well founded given mine accident data collected by the Mine Safety and Health Administration (MSHA). Our analysis of MSHA accident data (MSHA, 2000–2009) from 2000 to 2009 indicated that 49 fatalities and 4914 nonfatal days lost (NFDL) occurred in the underground coal mining industry that were described as struck-against or struck-by and caught or pinned in-under-between. Of these, 12 fatalities and 226 NFDL were associated with the Continuous Mining Machine (CMM), tunnel borer, or similar machinery. An MSHA report (Dransite and Huntley, 2011) indicated that 33 fatalities involving a CMM occurred from 1984 to March of 2011. The operator controlling the CMM had the highest accident frequency, and the most dangerous activity was moving the CMM to a new location. Performing maintenance was the second most dangerous activity. Most fatalities occurred at the right rear of the CMM. In all accidents, poor work practices were contributing factors given that the miners were positioned within the turning radius of an active, electrically-powered CMM.

The CMM is a tracked machine that cuts coal by using a cylindrical cutting head. The CMM gathers the coal with mechanized arms and transports coal using a conveyor system that runs the length of the machine. The CMM movements are controlled by an operator who typically stands at the rear of the CMM (Fig. 1). The

* Corresponding author. Tel.: +1 412 386 4507; fax: +1 412 386 6710.
E-mail address: jsammarco@cdc.gov (J. Sammarco).

0003-6870/$ – see front matter Published by Elsevier Ltd.
doi:10.1016/j.apergo.2012.03.006

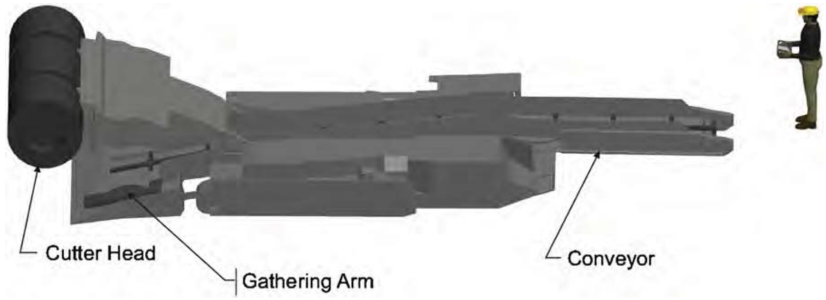

Fig. 1. Depiction of the CMM and operator relationship – the miner operator stands at the rear and operates the CMM by remote control. The cutter head cuts the coal which is then "swept" onto a conveyor by gathering arms. Coal exits the rear of the conveyor onto a shuttle car (not shown) that transports the coal. The conveyor boom can swing left or right as needed.

operator uses a remote-control pendent that wirelessly interfaces to the CMM. The machine movements controlled by the operator include: machine pivot left or right, machine forward or reverse (fast or slow speeds), and conveyor swing left or right.

One mitigation strategy to address struck-by or pinning accidents is to provide guidance to help CMM operators to understand and avoid potentially dangerous areas. During 2004, a "red zone" pictorial was developed from practical experience by MSHA and the Virginia Department of Mines, Minerals and Energy (MSHA, 2004). This pictorial depicts various hazardous zones to avoid during various CMM operations. Another mitigation strategy in mining is to use a proximity detection system that would alert miners if they are close to the CMM, or potentially shut down the machine if they are within an unacceptable distance from the machine.

A tag-based electromagnetic proximity detection technology was developed at NIOSH (Schiffbauer, 2002) and was ultimately licensed as a commercial product approved by MSHA. A more advanced NIOSH-developed prototype electromagnetic proximity detection system is being developed for a CMM at the NIOSH research facility in Pittsburgh, PA (Carr et al., 2010). This technology comprises a number of electromagnetic field generators mounted on a CMM and magnetic flux density sensors built into a Personal Alarm Device worn by the CMM operator. This new system can determine the two or three-dimensional position of the CMM operator relative to the machine and selectively disable only specific machine functions that pose an unacceptable risk.

While proximity warning systems hold much promise, there are shortcomings that include complex system installation issues, unintended machine shutdowns, and significant cost. Hence a simpler alternative was developed called the visual warning system (VWS), which visually alerts miners of impending machine motion and conveys the direction of machine motion. The main objective of the NIOSH research presented in this paper was to empirically determine if the VWS improved visual performance to detect CMM movements so that miners could avoid struck-by or pinning hazards. A second objective was to determine if age is a factor. This is important to consider because of the aging U.S. mine workforce, which has an average age of approximately 42 years for all of mining and about 45 years for coal mining (BLS, 2009).

2. Methods

2.1. Participants

NIOSH personnel at the Pittsburgh, PA, location were recruited for the tests. Participation was voluntary, and no NIOSH personnel involved in the research were used. Twenty-seven males and nine females took part in the testing. There were twelve participants each in the age groups of younger (18–25 years), middle (40–50 years), and older (51+ years). The mean ages were 21.6 years, 47.3 years, and 56.5 years, respectively. The oldest subject was 61 years old. The age group from 26 to 39 years was not used because there are generally minimal changes in vision for those ages (Blanco et al., 2005). Volunteers that had radial keratotomy, monocular vision, glaucoma, or macular degeneration were excluded. Only the volunteers that passed vision tests for distance visual acuity of 20/40 or better, contrast sensitivity of 1.72–1.92 values of log contrast sensitivity, the absence of color vision deficiency, and peripheral vision of at least 80° for each eye were accepted for the study. Participants signed an informed consent form and were instructed about their right to withdraw freely from the research at any time without penalty. The protocol for this study was approved by the NIOSH Human Subjects Review Board.

2.2. Visual warning system (VWS)

The VWS was conceived as a safety intervention to reduce struck-by or pinning accidents involving moving machinery. The VWS was intended to improve the visibility of a mining machine and to provide visual stimuli to alert miners of impending and active movements, as well as conveying the type of movement. In general, simple visual reaction times are longer than simple auditory reaction times; however, audible stimuli were not used given the highly mechanized environment of underground mining

Fig. 2. The visual warning system installed on a continuous mining machine. The red warning light indicates that the conveyor is going to swing to the right. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

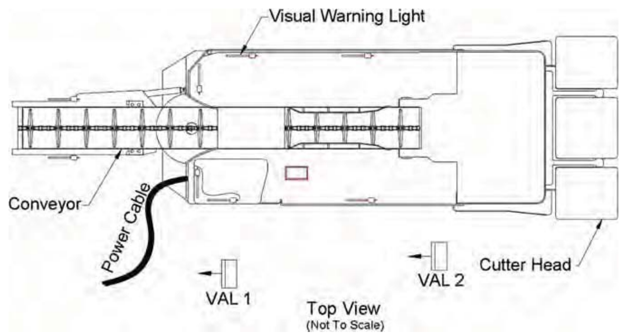

Fig. 3. A top view of the CMM. Two video monitors were placed at the visual attention locations (VALs). These were used to create a visual task for the subject.

operations, which routinely exposes miners to noise that can mask audible alarms. Secondly, it was highly desirable to associate the warning with a specific location in space; thus a visual stimuli would be advantageous as compared to an audible one (Sanders and McCormick, 1993). When considering auditory and visual spatial stimulus response situations where the response is directly related to the stimulus location, some research results have indicated that reactions to visual signals are generally faster than those for auditory signals (Lee and Chan, 2007). Considering these results, it would be advantageous to underground miners to use, wherever possible, visual signals rather than auditory signals to improve hazard detection and thereby minimize health and safety risks.

The test machine was a CMM. The VWS mounts to the CMM and electrically interfaces to the CMM's control subsystem. The VWS has its own control subsystem and eight luminaires that each uses a red, 1-W light-emitting diode (LED) to illuminate a 0.6-m-long, 14-mm-diameter side-emitting optical fiber (Fig. 2). Red was selected because it is associated with warning or danger in mining. For instance, emergency stop switches on mining machinery are colored red and the "red zone" pictorial was developed that depicts various red-colored hazardous zones to avoid during various CMM operations (MSHA, 2004). However, other colors, such as yellow and blue, are used for flashing lights that are associated with warning or caution in other industrial contexts. A study of perceived hazards indicated that red, as compared to yellow and blue, was perceived to indicate the highest hazard severity (Chan and Annie, 2009). This same study indicated that a flash rate of 4 flashes per second, or 4 Hz (Hz), was perceived to indicate the highest hazard severity compared to flash rates of 1, 2, and 3 Hz. A study of automotive rear warning lights indicated that a light flashing rate of 4 Hz was optimal (Wierwille et al., 2006). Thus, a 4 Hz flashing rate was selected for the VWS. The VWS luminaires were strategically placed about the machine's perimeter (Fig. 3).

Table 1
The thirty combinations of machine movement and visual warning system modes.

CMM		VWS mode				
Viewpoint	Movement	None	Static	Flash	Directional	Progressive
Rear	Reverse fast	X	X	X	X	X
Rear	Reverse slow	X	X	X	X	X
Rear	Pivot left	X	X	X	X	
Rear	Conveyor right	X	X	X		
Front	Forward fast	X	X	X	X	X
Front	Forward slow	X	X	X	X	X
Front	Pivot right		X	X	X	

The VWS identifies the impending machine movement based on the machine control inputs and selects the appropriate luminaires for the machine areas that could pose a struck-by or pinning hazard. Next, it activates the red warning lights in those hazardous machine areas to improve machine visibility and indicate the type of machine movement.

2.3. Test apparatus

Testing was conducted at the Mine Illumination Laboratory (MIL) at the Pittsburgh, PA, location of NIOSH. The MIL is a simulated underground coal mine environment that has various test equipment, data acquisition and control systems, and networked computers. Due to safety concerns, the experiment was conducted in a simulated environment that used a high-definition video-based CMM simulator developed by NIOSH rather than in a real coal mine using an actual CMM. Video scenes were recorded of a CMM with a VWS installed. A special dual-tone, multi-frequency (DTMF) audio track supplemented the high-definition video and was not audible to the participants. The DTMF audio track served as a marker to designate when the CMM received an electrical actuation signal for machine movement and triggered the data acquisition and control system to begin recording data. The 3.3-m-wide by 10.9-m-long CMM was operated within the MIL for the following movements: forward fast and slow, reverse fast and slow, pivot left and right, and conveyor swing left and right. The fast speed was 19.8 m/min and slow was 4.6 m/min, the pivot left or right rate was 3.2°/s, and the conveyor swing rate was 12.1°/s. When miners operate a CMM, they are cognizant of two critical visual attention locations (VALs) at the right-side front and rear of the CMM (Fig. 3). The front VAL is important for positioning the CMM's cutting head within the coal seam. The rear VAL is important because the electric power cable is in that area, and the CMM operator must exercise caution to prevent cable damage. Therefore, visual tasks were created for the participants that would approximate the visual tasks of a miner operating the CMM to cut coal. This was done by using two 48.26-cm computer monitors, each placed at a VAL,

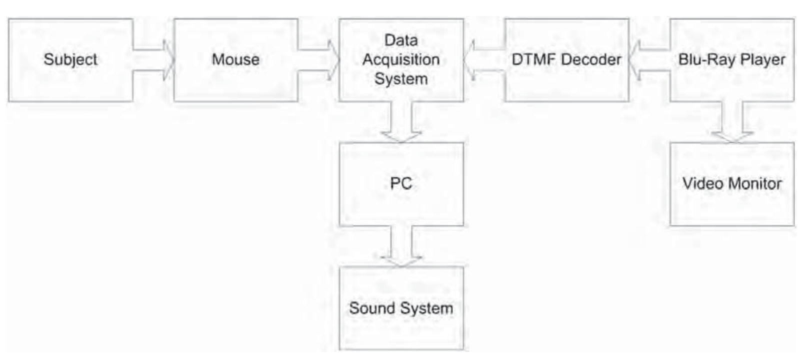

Fig. 4. A block diagram of the CMM simulator.

Table 2
Results of contrasts examining influence of lighting and operator positions on time to detect for forward or backward machine motions (Note: contrasts were tested using the natural log of detection time).

Contrasts	Results of contrast	*T*-statistic	*P* (*T*-statistic)	SE (Contrast)	Interpretation
Operator front v. rear	−1.446	−0.45	0.652	3.20	No difference in movement detection viewing front versus rear of machine
No lighting v. any lighting	19.325	55.24	<0.0001	0.350	Forward or backward machine movement detected more quickly in lighted conditions compared to non-lighted conditions
Static lighting v. dynamic lighting	1.815	6.66	<0.0001	0.273	Forward or backward machine movement detected more quickly in dynamic lighting conditions compared to static lighting
Progressive v. directional/flash	0.977	5.08	<0.0001	0.192	Forward or backward machine movement detected more quickly with directional and flashing lighting compared to progressive lighting
Directional v. Flash	0.639	5.75	<0.0001	0.111	Forward or backward machine movement detected more quickly with flashing lighting compared to directional lighting

which randomly displayed a full-screen sized white letter on a black background. The participants would then need to scan these two VALs and read aloud the letters when they would randomly appear on the screen at one of the VALs.

The main components of the CMM simulator (Fig. 4) consisted of a 1.06-m video monitor, an audio system, high-definition video recordings of CMM movements and VWS warning modes, a laptop computer, a PC-based data acquisition system, and a PC mouse used as the participant's input device. Participants, positioned approximately 2.74 m from the video display screen, would depress the mouse button to begin the video scene and keep it depressed until they detected a machine movement. The average luminance (light the eye sees) of the video display screen was 15.3 cd/m^2 (nits); whereas the average illuminance (light striking a surface) was 1.3 lux at the subject's eyes. A separate audio track pre-recorded at a coal mine was played to simulate the mining environment; however, this audio track did not provide audible cues of machine movement. The average sound level from the audio track was 74.9 dB. At the time machine movement was initiated, the pre-recorded DTMF audio track triggered the data acquisition and control to begin recording data. The DTMF signal is comprised of two pure sine wave tones at varying frequencies. While it is commonly used in touch-tone phones, it can also be used as a communication link between two electronic systems. The DTMF signal is desirable because it can prevent any harmonics from being misinterpreted as part of the signal. Participants lifted their finger off the PC mouse button when they detected movement from the machine. This triggered the data acquisition and control to stop recording data and save the data to the laptop. The collected data consisted of the participant's reaction time (RT) defined as the time from the machine actuation to the release of the PC mouse, the warning light mode, the nature of the CMM movement, the date, and time of day. For simple tasks such as lifting a finger off a key in response to a light, the shortest possible RT is 0.15 s and the typical RT values are 0.20 or 0.25 s (Dorwatzky, 1981). This information was directly applicable to this study given that the participants lifted their finger off the PC mouse button; therefore, it was used to identify data outliers potentially manifested by participants anticipating the visual stimulus. Any RT datum less than 0.15 s was identified as an outlier and was not included in data analysis.

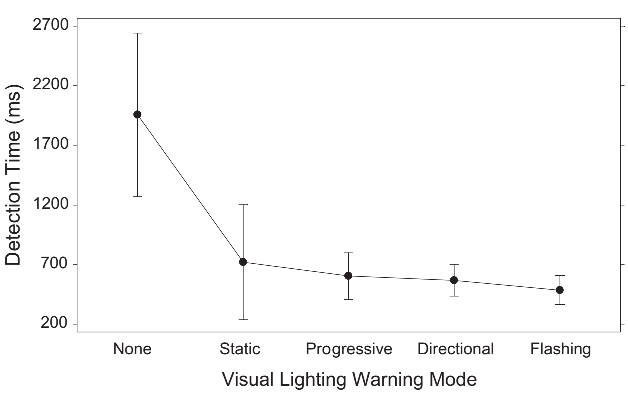

Fig. 5. Detection time as a function of visual warning lighting modes for an average of forward and reverse machine motions. Error bars represent the standard deviation.

2.4. Experimental design

Participants were asked to identify when they detected a visual warning light or when they detected the start of CMM movement. Each subject was presented with 30 unique video scenes containing visual warning modes and CMM movement combinations. Each video scene contained a single visual warning mode and CMM movement. Five visual warning modes were studied: 1) None: no visual warning is given at any time; 2) Static: the luminaires for a given machine movement will turn on and stay on as long as the machine function is actuated; 3) Flash: the luminaires for a given machine movement will flash at 4 Hz as long as the machine function for movement is actuated; 4) Directional: the luminaires for a given machine function will provide a directional warning (4-Hz direction sequence), as long as the machine function is actuated; 5) Progressive: each luminaire turns on sequentially and stays on until the last luminaire in the sequence is on. The directional and progressive warning modes conveyed the direction of machine movement. The ability to detect motion of the machine was tested using various visual warning modes for these machine movements: 1) reverse fast, 2) reverse slow, 3) pivot left, and 4) conveyor swing right.[1] A second viewpoint was established when the CMM operator was positioned at the front of the machine for these machine movements: 5) forward fast, 6) forward slow, and 7) pivot right. The presentation order of the video scenes listed in Table 1 was counterbalanced with the presentation order reversed for half of the participants.

[1] Note that forward fast, forward slow, and pivot right CMM movements were not included because the CMM is moving away from the CMM operator and a hazard is not created when the operator is standing at the rear of the machine. Eliminating these movements also reduced testing duration times that, if excessive, could introduce subject fatigue.

Table 3
Results of contrasts examining influence of lighting on time to detect for machine pivot motions (Note: contrasts were tested using the natural log of detection time.).

Contrasts	Results of contrast	*T*-statistic	*P* (*T*-statistic)	SE (Contrast)	Interpretation
Pivot left (rear): No lighting v. any lighting	4.54	33.54	<0.0001	0.136	Pivoting machine movement detected more quickly in lighted conditions compared to non-lighted conditions
Pivot left (rear): static v. dynamic	0.255	2.66	<0.01	0.096	Pivoting machine movement detected more quickly in dynamic lighting conditions compared to static lighting
Pivot left (rear): flash v. directional	−0.017	−0.31	0.76	0.056	No difference in machine movement detection with flashing versus directional lighting
Pivot right (front): static v. dynamic	−0.268	−2.74	<0.01	0.098	Pivoting machine movement detected more quickly in dynamic lighting conditions compared to static lighting
Pivot right (front): Flash v. Directional	−0.190	−3.40	<0.001	0.056	Pivoting machine movement detected more quickly with flashing lighting compared to directional lighting

Note that all warning light modes were not used for all movements. For instance, the conveyor swing movement was left or right so visual warning modes 3 and 4 were not applicable. Thus, a total of 30 conditions were used. The conditions tested are shown in Table 1. *A priori* orthogonal contrasts (each tested using an alpha level of 0.05) were developed to test for differences in the ability of participants to detect machine movements under the various lighting conditions. A repeated measures ANOVA was used to evaluate the influence of warning lights (or lack thereof) on the dependent variable of detection time. Age was treated as a between-subjects variable, and the within-subjects variable was the machine movement and warning light mode combinations contained in Table 1.

2.5. Procedure

Each participant sat in a darkened environment for about 15 min until their eyes adapted. The subject was briefed on the test procedures and performed a warm-up sequence to familiarize themselves with the test apparatus and procedure. Participants were seated directly in front of a video monitor that played the prerecorded CMM scenes representing the test conditions. A computer mouse was used by the participants during testing and served as the "trigger" for the experiment. Prior to the tests, participants were verbally instructed to only press the mouse button when they were told to start the test and to not release the mouse button until they had detected CMM motion or the activation of the visual warning lights. These instructions were also provided in written form on the video monitor prior to the start of each video scene used for the test. Participants performed a visual task in which they were required to focus on video monitors situated at VAL locations at the front of the CMM and verbally repeat a sequence of letters displayed on these monitors. Participants ceased repeating the letters when CMM motion was detected and the mouse button was released. A soundtrack of typical sounds or machinery "noise" from underground mining operations played throughout the experiment to prevent auditory cues that would alert participants to CMM movement.

The tests included 36 scenes with different combinations of CMM movements and visual warning modes; the first six scenes were administered as the warm-up exercise. The warm-up scenes enabled participants to become familiar with the basic operation of the testing apparatus and to ask the test administrator questions. The warm-up scenes included each of the VWS warning modes. Each test scene was approximately 10–15 s long. These scenes were edited such that the CMM movement started at random times so that participants were not able to anticipate when the CMM would move. If participants failed to detect the CMM motion in the allotted time, a time of 10 s was automatically recorded as the detection time and the video cycled to the next 10- to 15-s test scene. Finally, participants were instructed that they could end the test at any point, without penalty, should they feel discomfort or fatigue.

3. Results

Analysis of the residuals versus fitted values for reaction time indicated a fan-shaped pattern to the residuals. Thus, the data were transformed by taking the natural log of the reaction time, which resulted in a normally distributed pattern of residuals. All statistical analyses were performed on the log-transformed data.

The between-subjects variable age group was found not to have a significant effect on the reaction time to detect machine motion ($F_{2,33} = 0.48$, $p = 0.62$). The omnibus F test for experimental conditions was significant ($F_{29,946} = 173.37$, $p < 0.001$). Contrasts involving the visual warning lights indicated numerous and substantial influences on reaction times depending on the lighting provided, as detailed in the sections below. There are a very large number of possible contrasts. The contrasts were selected based on this study's focus on the fundamental machine motions encountered during mining operations that would pose a struck-by or

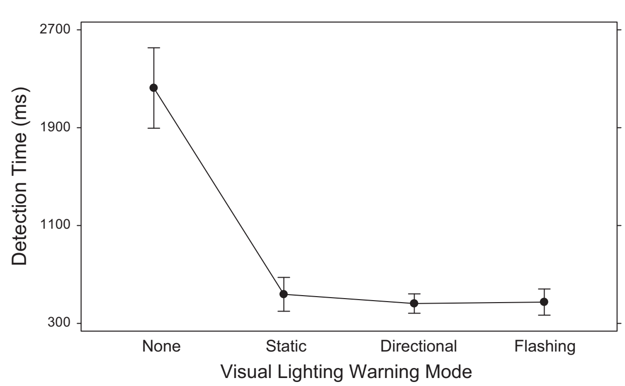

Fig. 6. Detection of machine pivot motions by visual warning lighting mode with operator positioned at the rear of the machine. Error bars represent the standard deviation.

Table 4
Results of contrasts examining influence of lighting time to detect conveyor swing motions (Note: contrasts were tested using the natural log of detection time.).

Contrasts	Results of contrast	*T*-statistic	*P* (*T*-statistic)	SE (Contrast)	Interpretation
Conveyor swing: no lighting v. lighting	0.867	9.03	<0.0001	0.096	Conveyor swing movement detected more quickly in lighted conditions compared to non-lighted conditions
Conveyor swing: static v. flashing	−0.069	−1.25	0.213	0.056	No difference in detection of conveyor swing movement with static versus flashing lighting

pinning hazard to the CMM operator. A lower-bound adjustment calculation indicated that even gross violations of compound symmetry would not affect significance of the results obtained.

3.1. Detecting forward/reverse machine motions

Statistical results for contrasts involving forward and reverse machine motions are provided in Table 2. Fig. 5 provides the detection times as a function of the visual warning modes investigated in this study. In tests involving detection of forward and backward movement, the contrast testing detection time between no lighting versus any lighting was highly significant ($t = 55.24$, $p < 0.0001$). The average detection time for the no lighting condition was 1.96 s while the average for all lighting conditions was 0.59 s. Furthermore, machine movements were detected more quickly in dynamic lighting conditions (the flash, directional, and progressive modes) than with static lighting ($t = 6.66$, $p < 0.0001$), 0.56 s versus 0.71 s, respectively. Within dynamic lighting conditions, differences were also observed. Specifically, the progressive mode was detected after an average of 0.60 s as opposed to an average of 0.53 s for directional and flashing patterns ($t = 5.08$, $p < 0.0001$). Finally, the flashing mode was detected more quickly than the directional mode ($t = 5.75$, $p < 0.0001$), 0.49 versus 0.57 s, respectively.

3.2. Detecting pivoting machine motions

Table 3 provides statistical results of contrasts for pivoting motions of the CMM. Fig. 6 illustrates detection time for pivoting motions with the operator positioned at the rear of the machine. Results were generally similar to those seen with tests involving forward and backward machine motions. Pivoting right (viewed from the rear of the machine) was again detected much more quickly when lights were employed (0.49 s to detect on average) versus no lights (2.23 s on average) ($t = 33.54$, $p < 0.0001$). Dynamic lighting was again detected more quickly than static lighting (0.47 s versus 0.54 s; $t = 2.66$, $p < 0.01$). However, for pivoting motions no difference between flashing and directional patterns was observed (0.48 s versus 0.46 s; $t = -0.31$, $p > 0.05$). Viewing pivoting motions from the front deviated from the patterns above in that static lighting (0.51 s) was detected more quickly than dynamic lighting (0.59 s) ($t = -2.74$, $p < 0.01$). In contrasts of dynamic lighting modes for these tests, directional lighting (0.53 s) was detected more quickly than flashing lighting (0.65 s) ($t = -3.40$, $p < 0.001$).

3.3. Detecting conveyor swing motions

Contrasts for detecting conveyor swing motions are provided in Table 4 and detection times for different visual warning modes are illustrated in Fig. 7. Tests involving detection of conveyor swing motion indicated quicker detection under lighting conditions (0.42 s) than with no lighting (0.65 s) ($t = 9.03$, $p < 0.0001$). However, no differences between flashing (0.41 s) and directional lighting (0.43 s) were observed in detection of conveyor swing motions ($t = -1.25$, $p = 0.21$).

3.4. Detection time by direction and speed

Table 5 provides contrasts examining travel direction and speed of machine movement. As can be seen, contrasts detected an interaction between travel direction and speed, which is depicted in Fig. 8. This interaction indicates that slow movements took longer to detect for reverse movement of the CMM; however, slow movements were actually detected more quickly in forward movement. Fig. 8 also indicates that the variability in detection time was much greater for reverse machine movements compared to forward movements.

4. Discussion

The differences between no visual warning and any type of visual warning were dramatic. For instance, for the forward and reverse CMM movements, the average detection time for the no lighting condition was 1.96 s while the average for the flash mode was 0.49 s. During this 1.47-s difference, or 75% improvement, the CMM would travel 0.485 m given the fast speed of 19.8 m/min. This distance traveled is significant especially when considering the tightly confined spaces of a mine. The most dramatic time difference results were with the machine pivots, where the average detection time for the no lighting condition was 2.23 s, while the average for the dynamic mode was 0.47 s. During this 1.76-s difference, the CMM would pivot 5.63° given the pivot rate of 3.2°/s. Our analysis of the 33 fatalities documented by MSHA (Dransite and Huntley, 2011) indicated that 30 fatalities involved machine forward, reverse, or pivot movements.

Results of this experiment suggest that dynamic lighting patterns enhance motion detection time to a greater extent than a simple static light. Even within the dynamic lighting modes, there were significant improvements in motion detection time with

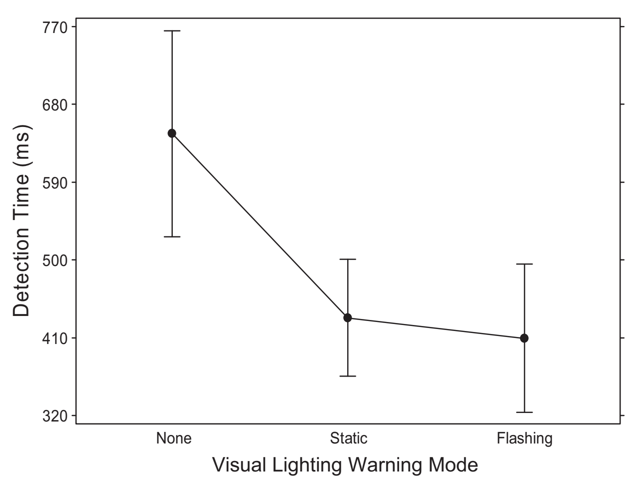

Fig. 7. Detection of conveyor swing motions by visual warning lighting mode. Error bars represent the standard deviation.

Table 5
Results of contrasts examining influence of operator position, machine movement, and machine speed on time to detect motion (Note: contrasts were tested using the natural log of detection time.).

Contrasts	Results of contrast	*T*-statistic	*P* (*T*-statistic)	SE (Contrast)	Interpretation
Front v. rear	−1.446	−0.45	0.652	3.20	No difference in movement detection viewing front versus rear of machine
Forward v. reverse	−0.230	−1.31	0.191	0.176	No difference detecting forward versus reverse machine movements
Fast v. slow	−0.079	−0.45	0.653	0.176	No difference with detection of fast versus slow machine movements
Direction × speed	0.840	4.79	<0.0001	0.176	Forward-fast & reverse-slow detected more slowly than reverse-fast & forward-slow

flashing lights tending to be detected the fastest, followed by directional lighting, and finally the progressive mode. There was one exception to this general rule in that static lighting was detected more quickly than dynamic lighting when viewing pivoting motions from the front of the machine. The reason for this discrepancy is unclear; however, while significant, the detection times in this condition were not substantially large in magnitude for static versus dynamic lighting. Despite this finding, the bulk of the evidence would certainly suggest that lighting over no lighting, dynamic as opposed to static lighting, and flashing lighting as the best of the dynamic lighting alternatives in relation to detection speed.

Age is known to have adverse effects on visual capabilities, including loss of peripheral vision, decreased color vision, and a decreased responsiveness to changes in ambient lighting (Harvard Health Letter, 2006; Boyce, 2003). However, it is interesting to note that there was no statistically significant difference among age groups in the ability to detect machine movements using the visual warning modes in this study. This would indicate that implementing the VWS on underground mining equipment would benefit mine workers of all ages.

Only volunteers that passed vision tests for distance visual acuity, contrast sensitivity, the absence of color vision deficiency, and peripheral vision participated in the study. Therefore, the detection times may not be representative for those people not having normal vision or having a color vision deficiency. The detection times might also differ when the VWS is used on underground mining equipment because the miners are performing numerous mining tasks in a dynamic, harsh environment. This is in contrast to the controlled, benign environment used in the study.

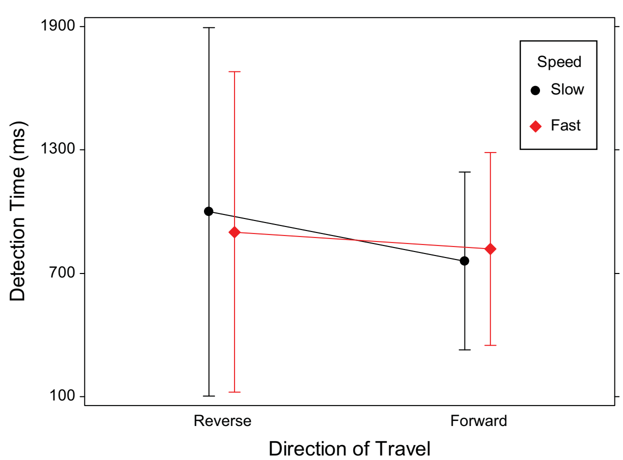

Fig. 8. The interaction of CMM direction of travel and speed on the time to detect machine motion. Error bars represent the standard deviation.

The research scope was limited to issues of visual warning and detecting machine movements. It did not address perception of machine movement that might be a factor contributing to machine accidents involving the machine operator, which comprise the majority of struck-by or pinning accidents. We hypothesize that some operator accidents occurred because perceptions of machine movement were distorted to be slower than actual. Large moving objects appear to move slower in visual environments characterized by low contrast and luminance (Antis, 2003). We also hypothesize that the VWS can improve perceptions of movement in such visual environments. These hypotheses will be addressed in future NIOSH research.

Another limiting factor was recognition of the CMM direction of movement. Although it was not included in the scope of the study, several of the visual warnings provided indications of movement direction. This directional indication may prove helpful for avoiding accidents where mode confusion is a factor. For instance, mode confusion accidents can occur when the operator stands in front of the machine and desires to move the machine in reverse (away from the operator). In this circumstance, the operator potentially could mistakenly push forward the levers controlling machine travel direction since the normal operator position is at the rear of the machine where the forward lever actuation results in the machine moving away rather than toward the operator.

5. Conclusions

Results of this experiment clearly demonstrate the VWS, as installed on a continuous mining machine that typically operates in a mesopic[2] environment, vastly improves an individual's ability to quickly detect machine motions, in many cases by well over 1 s. As such, use of the VWS would appear to be an important tool to alert underground miners to impending or active machine motions and may help prevent the incidence of struck-by or pinning accidents in underground mining. The methods and results of this study may have application to other moving machinery used in mining or other industries where moving machinery poses struck-by or pinning hazards.

Disclaimers

Mention of any company or product does not constitute endorsement by NIOSH. The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

[2] The intermediate range of luminances between photopic (daylight luminance levels) and scotopic (moonlight luminance levels). As defined across the mesopic range, both cone and rod photoreceptors of the retina are working, but the contribution of the cones varies, decreasing as the levels approach the mesopic–scotopic boundary (Keith, 2010). The mesopic-scotopic boundary is 0.001 cd/m^2, and the mesopic–photopic boundary is 0.6 cd/m^2 (Rea et al., 2004).

Acknowledgments

The studies described in this paper were conducted with assistance from NIOSH personnel J. Bartels, M. Reyes, M. Nelson, and A. Cook. Vision testing was conducted by M. A. Rossi, R.N.

References

Antis, S., 2003. Moving objects appear to slow down at low contrasts. Neural Networks 16, 933–938.
Blanco, M., Hankey, J., Dingus, T., 2005. Enhanced Night Visibility Series. In: Phase II-Study 2: Visual Performance during Nighttime Driving in Rain, vol. IV. Department of Transportation, U.S. No. FHWA-HRT-04–135.
Boyce, P., 2003. Human Factors in Lighting, second ed. Taylor & Francis, New York.
Carr, J., Jobes, C., Li, J., 2010. Development of a Method to Determine Operator Location Using Electromagnetic Proximity Detection. International Workshop on Robotic and Sensors Environments (ROSE), Phoenix, AZ.
Chan, A.H.S., Annie, W.Y., 2009. Perceptions of implied hazard for visual and auditory alerting signals. Safety Science 47, 346–352.
Dorwatzky, J.N., 1981. Motor Learning: Principles and Practices, second ed. Burgess Publishing Company, Minneapolis, MN.
Dransite, J., Huntley, C., 2011. Remote Control Fatal Accidents Analysis Report of Victims Physical Location with Respect to the Mining Machine. US Dept. of Labor, MSHA.
Harvard Health Letter, Blinded by the night, 2006, 31 (5).
Keith, D.M., 2010. Mesopic vision and outdoor lighting criteria. http://resodance.com/ali/mes_crit.html (accessed 10.01.11.).
Lee, F.C.H., Chan, A.H.S., 2007. Attending visual and auditory signals: ergonomics recommendation with consideration of signal modality and spatial stimulus–reaction (S–R) compatibility. International Journal of Industrial Ergonomics 37, 197–206.
Mine Safety and Health Administration (MSHA), 2000. Mining Industry Accident, Injury, Employment, and Production Statistics.
Mine Safety and Health Administration (MSHA), 2004. Red Zones are No Zones for Mining with Remote Control Continuous Miners.
Rea, M.S., Bullough, J.D., Freyssinier-Nova, J.P., Bierman, A., 2004. A proposed unified system of photometry. Lighting Research and Technology 36, 41–47.
Sanders, M.S., McCormick, E.J., 1993. Human Factors in Engineering and Design, seventh ed. McGraw-Hill, Inc., New York.
Schiffbauer, W., 2002. Active Proximity Warning System for Surface and Underground Mining Applications.
U. S. Bureau of Labor Statistics (BLS), 2009. Table 16. Employed persons by detailed industry, sex, and age, Annual Average 2009.
Wierwille, W.W.L., Lee, S.E., DeHart, M.C., Perel, M., 2006. Test road experiment on imminent warning rear lighting and signaling. Human Factors 48.