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Detectability of a self-illuminating lifeline for self-escape in smoke conditions of an underground mine

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Lifelines are used to aid self-escape of underground miners, but they are difficult to find in low-visibility conditions of smoke, therefore a self-illuminating lifeline could facilitate miners in locating the lifeline. The detection distance, colour recognition, and miss rate for 10 subjects were determined for red-, green- and blue-lighted diffuse fibre-optic cables, used to create a lighted lifeline, and a traditional rope lifeline in a smoked-filled environment. The testing was conducted with and without a cap lamp. The use of a cap lamp resulted in all cases being undetected in 98.3% of trials. With the cap lamp off, there was no significant difference in the detection distance for blue- and green-lighted fibres; however, the miss rate for the green-lighted fibre was slightly higher. The red-lighted fibre was not detected in 93.3% of trials. The green- and blue-lighted fibres enabled the best visual performance, but subjects had difficulty correctly identifying the colour of the fibre. The lighted fibre-optic cable appears to have merit for improving self-escape from underground mines, and may have other mining and non-mining applications that include improving self-escape visibility.

1. Introduction

The mining industry provides energy resources and raw materials that have a direct impact on the US economy, producing $100 billion of the gross domestic product (GDP) and providing 1.7 million direct jobs in 2015.[1] Worldwide from 1900 to 2005, there were about 90 billion tons of materials extracted, with a world GDP of about 45 trillion international dollars.[2] The US mining industry has made positive strides in reducing the severity and frequency of mine accidents and decreasing the number of mine disasters (defined as incidents resulting in five or more deaths) through research, technology and preventive programmes.[3] However, during 2006, mine disasters occurred in the United States at the Darby Mine No. 1 Mine and Sago Mine that together claimed 17 lives. In response, the US Congress passed the Mine Improvement and New Emergency Response (MINER) Act[4] that includes the following provisions: underground coal mines must have at least two separate, distinct travelable passageways as escapeways that are clearly marked to show route and direction of travel to the surface, and a directional lifeline or equivalent device must be installed the entire length of each escapeway. While the MINER Act was a major piece of legislation to improve mine safety, efforts need to continue to improve miner safety and their ability to self-escape.

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A 2013 report by the National Research Council identified the need to empower miners to self-escape during a mine emergency; numerous recommendations were put forth, including the need to accelerate wayfinding technology efforts that enhance situational awareness and self-escape. The report recommended that the National Institute for Occupational Safety and Health (NIOSH) should '*accelerate efforts to develop technologies that enhance self-escape. These technologies should use human-centered design principles with specific attention to facilitating improved situational awareness and decision making...*'[5] Currently, passive self-escape technologies include signage, markers designating primary and secondary escapeways, and lifelines. Other self-escape aids have been evaluated that include a safety cane used to tap about the area in order to find the mine rib and a handheld laser pointer used as a flashlight to enable miners to better see objects in the mine. Miners had the most favourable opinion of the safety cane, but did not want to carry it. These devices proved useful, but they did not enable faster escape from a mine.[6] More sophisticated, active systems include the Mains Fail Operated Evacuation System (MOSES), which consists of a series of sound- and light-emitting units designed to help miners to self-escape in low or no visibility conditions.[7] MOSES was installed in 76 Australian and South African mine sites from 1994 to 1995. There were encouraging results when miners used the system in zero visibility conditions and they reported it was unlikely they could have reached safety without MOSES.[7]

The IMC Egress Beacon System, developed with the UK Health and Safety Executive and Mines Rescue Service, performs a similar function of sound and visual cues from red and green LEDs to alert miners if they are egressing in the proper direction. Tests were conducted and the system was found to have considerable value.[8] Another active system is the Miniguide Ultrasonic Mobility Aid developed by GDP Research in Australia, a handheld device that uses ultrasonic sounds to detect objects and then provides tactile and audio feedback through vibrations and sound when an object is near. Data from tests conducted by SIMTARS indicate that the Miniguide is effective in locating tripping hazards, but it did not significantly improve escape time travel in smoke.[6] Overall, these active systems provide varying degrees of improvement to egress from a smoke-filled mine, but are not without limitations. Depending on audible cues for wayfinding can be problematic because after an explosion a miner's hearing may be compromised. Furthermore, the absence of tactile feedback for indicating direction and locations can slow or inhibit evacuation, especially in low visibility where a miner's vision can be very limited.

Lifelines are required for anthracite, bituminous, and lignite mines.[9] Lifelines are used to aid the self-escape of miners by guiding them along the way out of the mine. They provide a tactile cue, given they are fitted with directional cones that are felt with a gloved hand to guide miners in low-visibility conditions. Additional tactile markers on the lifeline are positioned to identify other important locations in an emergency escape, including doors, branch lines, refuge alternatives, and self-contained self-rescuer (SCSR) caches that contain portable sources of breathable air. There are several types of lifelines that are approved by the Mine Safety and Health Administration (MSHA) for use in underground coal mines. The lifelines are constructed of polypropylene rope, aircraft cable, or two-conductor insulated wire housed in an outer jacket. However, in order for the lifeline to be effectively utilised, it must first be reached, which can be challenging in emergency conditions of limited visibility from smoke. Mines fires can produce either white or black smoke, the latter of which can worsen visibility further. The smoke density can vary greatly up to the point where a miner has zero visibility. During a mine fire, miners don a SCSR that isolates them from the smoke and provides breathable air. Additionally, miners typically experience disorientation after a mining incident that results in poor visibility conditions from an explosion or fire, so they may experience difficulty in locating a lifeline.[7]

The approach to improve miner self-escape was to focus on the lifeline given that it is a very effective passive navigational aid[10,11] and lifelines have been identified to be the most effective self-escape aid in low visibility.[10] Lifelines have an advantage over signage and escapeway markers that can be very hard to see in smoke.[12] Miners who had escaped a smoke-filled mine were interviewed and they reported that they had a difficult time seeing the escapeway markers located on the ceiling because they had to bend over to walk or crawl in the thick smoke.[13] The lifeline can be very useful even in zero visibility conditions because it can be located by feel. Lifeline visibility can be improved with the use of diffuse fibre optic technologies such as Fibrance, which ‘leaks’ light along its entire length, thus enabling an illuminated visual cue. Visual cues are critical given that 80% of human perception is visual.[14] Visual perception directly affects cognitive, task, and motor performance[15] all of which are essential for empowering a miner to escape or take actions to prevent accidents. NIOSH is developing a lighted lifeline, using the Fibrance diffuse fibre illuminated by red, green or blue lasers. These colours were selected because they are readily available commercially; however, it was unknown which colour would provide the best visual cue. Secondly, a miner’s cap lamp is a primary light source that is critical to aid in self-escape when visibility is good, but the cap lamp’s effect on visual performance in detecting a lighted lifeline is unknown in smoke conditions. Therefore, the objectives of the present study were to: (1) determine the fibre colour that enabled the best visual performance in terms of the detection distance, miss rate and the ability of people to identify the colour, and (2) determine the effect of the cap lamp light source on visual performance.

2. Method

2.1. Experimental layout and apparatus

The study that is the subject of this paper took place in the NIOSH Human Performance Laboratory (HPL), which simulates an underground coal mine environment. The HPL has a smoke chamber (Figure 1) that is 8.4 m long × 3.3 m wide. The chamber is sealed from the fresh air area such that the participant and researchers are never exposed to smoke during testing. The lights in the fresh air area are kept off during the testing, and the subject is isolated from the researcher by a black curtain to ensure stray light does not interfere with the experiment. The roof of the chamber was coated with a dark, rough-textured material having a spectrally-uniform reflectance of approximately 5%, which is typical of coal. The chamber walls were made of coalcrete – a combination of coal, cement and fly ash that closely resembles the texture, colour and reflectance of coal.

The smoke used in this study was from a water-based, food-grade, glycol (propylene glycol, 30%, and triethylene glycol, 30%) solution to generate a synthetic white smoke atmosphere. Two oscillating fans enabled a uniform mixing of the smoke in the chamber. To maintain consistent smoke levels during the study, a smoke density sensor measured the levels in the smoke chamber. The sensor data were used to remotely control the smoke machine to maintain an optical density of approximately $0.70\,\mathrm{m}^{-1} \pm 5\%$, as calculated from equation (1). Whenever the smoke was outside of the threshold, experimentation was paused until it was back within bounds.

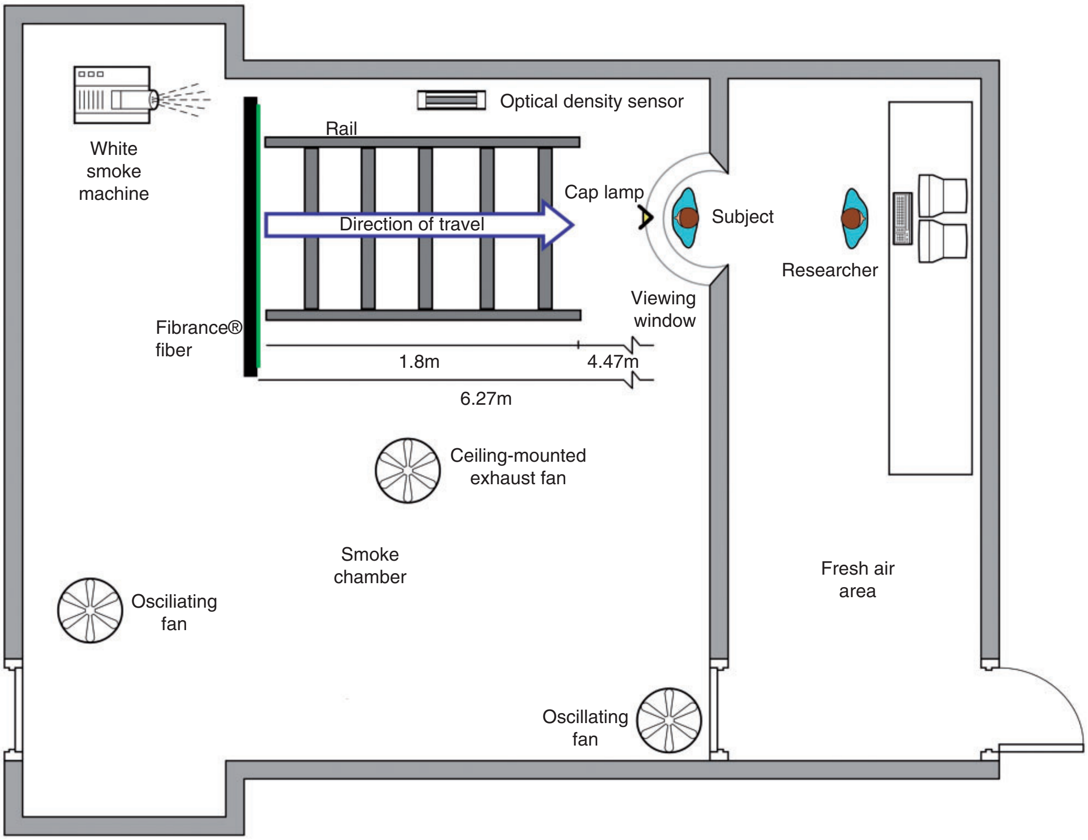

Figure 1 Experimental layout of the human participant tests conducted in the smoke chamber (not to scale) of the NIOSH Human Performance Laboratory

Smoke was gradually added into the chamber until the $0.70\,\text{m}^{-1} \pm 5\%$ was reached. The optical density was selected based on prior studies involving the visibility of underground mine escapeway markers in smoke.[16]

$$Optical\ Density = -\log\left(\frac{I}{I_{initial}}\right)\left(\frac{1}{d}\right) \qquad (1)$$

where I is the luminous intensity of the light, and d is the distance in metres.

The test apparatus (Figure 2) used a 2 m segment of Fibrance fibre mounted to a computer-controlled movable rail. A traditional rope lifeline, consisting of yellow nylon rope and tactile retro-reflective cones, was directly below the fibre. A rotating, computer-controlled, lightweight-foam shutter was placed directly in front of the rope lifeline such that the rope could be shown or hidden during a trial. The shutter and apparatus was painted with a matte black paint.

The test apparatus was mounted on a rail system (Figure 1) to enable moving the fibre and rope lifeline towards the participant. Both stimuli were securely mounted to the apparatus to prevent independent motion. A linear transducer attached to the apparatus enabled measurement of the distance traveled by the apparatus. A microcontroller with a Bluetooth Low-Energy transceiver-enabled wireless control of the apparatus.

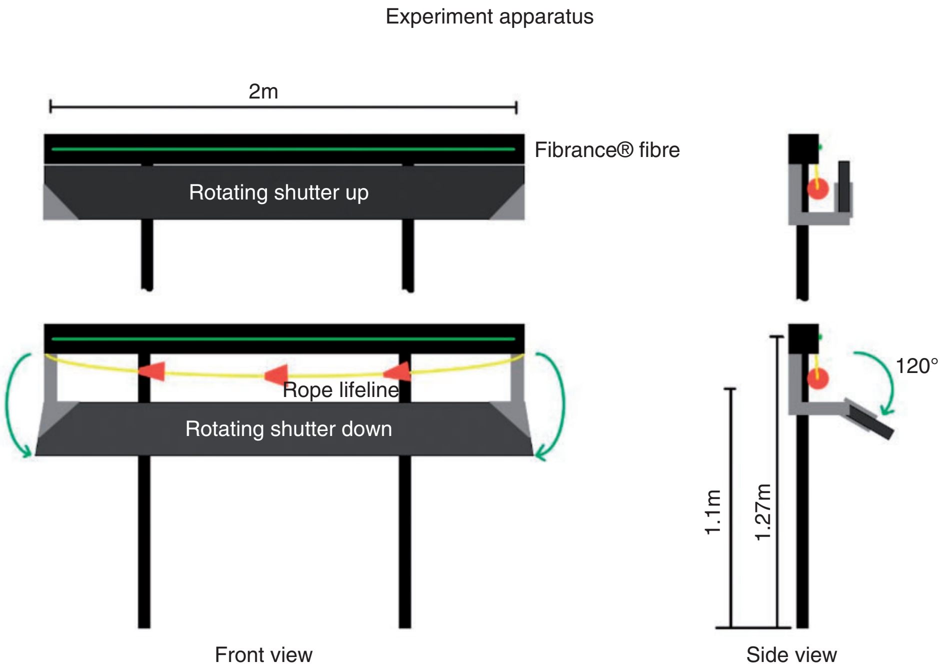

Figure 2 The lighted lifeline test apparatus (not to scale) used to test the Fibrance fibre and rope lifelines

The controller sent commands to a chain-driven door opener for moving the apparatus on the rail, the motor advanced at an average 0.165 m/s. Commands were also sent to two servomotors for operating the shutter and to a Versalume laser controller for controlling the fibre colour and luminous intensity. The controller would then send information to the experiment control workstation upon completing its actuation tasks for confirmation and time stamping.

2.2. Lighted lifeline

The lighted lifeline under development is an active system because it uses the electrical mains as a source of power during normal operating conditions and then reverts to battery power during emergency conditions that require the electrical mains to be shut down. Electrical power is needed for the lasers that illuminate the fibre, and the electrical power trickle charges the batteries.

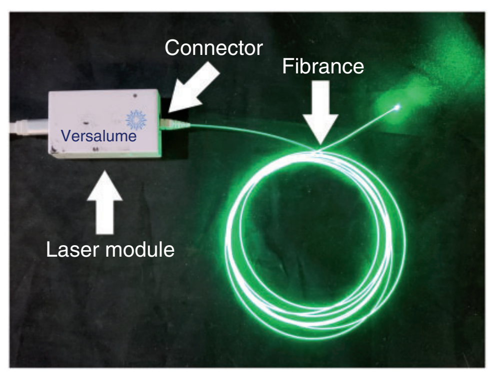

Figure 3 A section of Fibrance diffuse fibre optic cable illuminated by the Versalume Smart laser module

2.3. Lasers

The laser used for the experiment was a Versalume Multi-Colour Smart Module (Figure 3). The module contains three integrated lasers that are Center for Devices and

Radiological Health Class IIIa (IEC Class 3R). The module's lasers are red (639 nm) < 20 mW, green (515 nm) < 10 mW and blue (450 nm) < 20 mW. The module has the ability to control the laser intensities. Due to the varying powers of the different laser colours and the variability in sensitivity to colour of the human eye, each laser colour was set to a different intensity so that their measured luminance would be as close as possible to each other. By setting the intensity of the laser colour of red to 2%, green to 1% and blue to 5%, an average luminance value of 0.178 cd/m^2, 0.161 cd/m^2 and 0.146 cd/m^2 was achieved for each colour, respectively, in clear conditions, and 0.025 cd/m^2, 0.047 cd/m^2 and 0.041 cd/m^2, respectively, in smoke. These luminance values were verified using an imaging photometer and a spectroradiometer. Low intensity was selected for this experiment to accommodate the short distance traversed in the lab study, such that at the farthest point a participant would not likely be able to detect the lighted lifeline. Lower intensities were not possible using the Versalume module.

2.4. Fibrance fibre

Fibrance (Figure 3) is a flexible light-diffusing fibre that has a silica glass core with rings of non-periodically distributed (radially and axially) scattering sites that disperse light through the walls of the fibre.[17] The fibre is available in various diffusion lengths. A 5 m diffusion length was used that had a viewing angle >120° and an operating wavelength range of 422–700 nm. The fibre has a core diameter of 180 ± 3 μm and an outer diameter of 230 ± 10 μm. The core is clad in a clear PVC material that is flame resistant. It has a light diffusion capability of 90% over the 5 m length; therefore, there was an attenuation of 36% of light over the 2 m section of fibre exposed for the tests.

2.5. Rope lifeline

A rope lifeline was selected for the tests given that this type of lifeline is commonly found in mines. The rope lifeline was manufactured from quarter-inch-diameter, yellow, hollow-braid, flame-retardant polypropylene rope. A 2.1 m section was placed on the apparatus (Figure 2). Orange directional indicator cones, each having six green retro-reflective marker bands, were placed about 0.3 m apart. The indicator cones come standard with the lifeline.

2.6. Ambient light source

The primary light source for miners is their cap lamp,[18] which is worn on the hardhat. In many situations including self-escape, the cap lamp is a miner's only light source. A commercially available cap lamp approved by the MSHA was used for the testing in this study. The cap lamp has a single LED as the primary light source, along with an optical reflector to direct the light to a circular spot ranging from about 6° to 8°. It was placed inside the smoke chamber and in front of the subject in roughly the position it would be on a hardhat as seen in Figure 1. The cap lamp is characterised by the following colourimetric quantities: correlated colour temperature (CCT) = 7297 K; colour rendering index (CRI) $Ra = 79$; scotopic to photopic ratio $(S/P) = 2.26$; dominant wavelength $(\lambda_d) = 484$ nm.

2.7. Experimental design and statistical analysis

This study aims to evaluate the use of three different colours of the lighted fibre lifelines – red, green and blue – in comparison to the existing yellow nylon rope lifelines currently utilised in underground mines. A $2 \times 4 \times 1$ (2 lighting conditions × 4 lifelines × 1 age group) within-subjects design was used for the experiment. The two lighting conditions consisted of the same cap lamp being turned either on or off, and the only age group tested was that of >50 years.

Generalised estimating equations (GEE)[19] was the method used to analyse the effect of stimulus colour on lifeline detection and on the distance at which the lifeline was detected. An analysis was performed using PROC GENMOD in SAS version 9.4. GEE is a relatively recently developed method that can be applied to ordinal and categorical-dependent variables as well as to continuous dependent variables. Unlike the more common method of analysing categorical data, binary or multinomial logistic regression, GEE is not based on the assumption of independent observations. Therefore, it can accommodate data from repeated measures or clustered designs.

In the GEE analysis for lifeline detection, two conditions had to be dropped because of empty cells. When empty cells are present, standard errors of parameters cannot be computed. It was necessary to omit the nylon rope condition because no participants were able to detect the lifeline in that condition. Similarly, green- and blue-lighted fibres had to be combined into one category because all participants were able to detect the blue fibre, leaving the 'miss' category empty. It was necessary to drop the nylon rope condition from the GEE analysis of distance as well as from the analysis of detection because distance was coded as the timeout value for all participants. In addition, it was considered best to drop the red-lighted fibre condition because values other than the timeout value were only observed for two participants. Therefore, only the green- and blue-lighted fibre conditions were compared in the statistical analysis.

2.8. Signal detection analysis

Signal detection theory (SDT) can indicate decision quality under conditions of uncertainty.[20] SDT defines four categories: a 'hit' is correctly identifying that a signal was present; a 'miss' is a failure to identify a signal; a 'false alarm' is identifying a signal when none was present; a 'correct rejection' is correctly identifying the absence of a signal. The sensitivity index (d') statistic, shown in equation (2), is commonly used in SDT to quantify the detectability of a signal that is present or not present.[21] Detectability increases as d' increases, while d' near zero indicates chance detection, or no detectability.

$$d' = Z(hit\,rate) - Z(false\,alarm\,rate) \quad (2)$$

where Z is the Z-transform.

SDT also considers bias, β, shown in equation (3), which shows the tendency towards avoiding an error type, either false alarms or misses.

$$\beta = \frac{probability\ ordinate\ of\ misses}{probability\ ordinate\ of\ false\ alarms} \quad (3)$$

In this analysis, 'hit' and 'miss' refer to the participant's response to identifying the lighted fibre, which is considered the signal. A miss occurs when the lifeline reaches the end of the rail without a response from the subject. A 'false alarm' would occur if the participant identified the lifeline when it was not present. In this scenario, there would be no case for 'correct rejection,' as there is always a signal present at some point in each trial. The results from the SDT analysis are listed in Table 3.

2.9. Participants

The participants were federal employees. Ten participants completed all testing and their data were used for the study. The average age was 57.8 years (St. Dev. = 4.6).

There were no exclusions based on sex, race, or ethnicity. Only the participants that passed vision tests for distance visual acuity, contrast sensitivity, and peripheral vision were accepted. The visual acuity and peripheral vision tests were conducted using the Titmus V4 vision screener, and contrast sensitivity tests were conducted using the

Mars Letter Contrast Sensitivity charts. Participants were required to have: normal or corrected vision with an acuity of 20/40 or better; contrast sensitivity values of 1.60 to 1.92 for participants ≤60 years and 1.52 to 1.76 for participants >60 years; peripheral vision of at least 80 degrees for each eye. Participants that had self-reported radial keratotomy, monocular vision, glaucoma, or macular degeneration were excluded.

The NIOSH Institutional Review Board approved the protocol. Informed consent was obtained from all participants in the study. Participants could withdraw from the study at any time.

2.10. Procedure

Participants underwent a 20-minute dark adaptation time to adapt to the reduced illumination of the smoke chamber. Prior to the experiment, the smoke chamber was filled with smoke to the desired 25% opacity level. The experiment consisted of four practice trials to familiarise the participants with the test, followed by 12 trials with the cap lamp turned off, and another 12 trials with the cap lamp turned on. Each colour was presented three times for each experimental set, selecting between red, green, blue and a nylon yellow rope. The order was randomised by performing a Fischer–Yates shuffle algorithm. The set of twelve experimental trials were performed with the cap lamp off and then repeated, in a different randomised order, with the cap lamp turned on.

Each trial began with the lifeline bar at its farthest position away from the participant. The participant was then informed to press and hold a mouse button. Between 3 and 5 seconds later, determined randomly by the software, the command was sent to the lifeline controller to present the colour stimulus and immediately to begin moving the test platform closer to the participant. Participants were informed to let go of the mouse button once they were able to perceive any visual presence of a lifeline. Upon letting go of the mouse button, the position of the lifeline was recorded. Participants were then asked what colour they saw, which was recorded by the researcher. If the participant did not release the mouse button, it was recorded as a miss.

The same procedure was repeated with the lifeline at its closest point on the experiment track. The lifeline stimulus remained active at this time, with the participant pressing and holding the mouse button to send the lifeline away. Participants were informed to let go of the mouse button once they lost sight of the lifeline. Once the participant let go of the mouse button, the position of the lifeline was recorded. If the participant never responded during the first half of the trial, however, the apparatus would automatically return back to the starting position for the next trial and a miss was likewise recorded for the return trip task.

3. Results

3.1. Lifeline detection and colour recognition

Cross tabulations of stimuli and participant responses for lifeline detection and colour recognition are presented in Tables 1 and 2 when the cap lamp was on and off, respectively. The results are only presented for the case of the lifeline moving towards the subject and the results do not include the practice trials. It can be seen in Table 1 both types of lifeline were hardly ever detected when the cap lamp was on, and when the lifeline was detected, the colour and type were not correctly identified. From Table 2, it can be seen that the colour of the green fibre was correctly identified in 36.7% of the trials, incorrectly identified as blue in 26.7%, and identified as rope in 23.3% (Figure 4). The colour of the blue-lighted fibre was correctly identified in 6.7% of the trials, identified as green in 46.7% of the trials, and identified as rope in 40% of the trials. Both the red-lighted

Table 1 Cross tabulation of the lifeline detection and colour recognition as well as misses for the condition when the cap lamp was on

Participant colour response	Lifeline stimulus				Total
	Green	Red	Blue	Rope	
Green	0	0	0	1	1
Red	0	0	0	0	0
Blue	0	0	0	0	0
Rope	0	0	1	0	1
Missed	30	30	29	29	118
Total	30	30	30	30	120

Table 2 Cross tabulation of the lifeline detection and colour recognition as well as misses for the condition when the cap lamp was off. Note that 'No colour identified' signifies the lifeline was detected but the participant abstained from identifying a particular colour

Participant colour response	Lifeline stimulus				Total
	Green	Red	Blue	Rope	
Green	11	0	14	0	25
Red	0	1	0	2	3
Blue	8	0	2	0	10
Rope	7	0	12	0	19
No colour identified	1	1	2	0	4
Missed	3	28	0	28	59
Total	30	30	30	30	120

fibre and the nylon rope lifeline were missed in 93.3% of the trials.

For the purpose of GEE analysis, responses when the cap lamp was off were collapsed into three categories of response: missed, colour incorrectly identified and colour correctly identified (see Figure 4). In this reclassification, the cases where rope was incorrectly identified as red were considered false positives and were treated as missing data.

Figure 4 indicates that all coloured fibre lifelines were detected more frequently than the nylon rope, and that the green- and blue-lighted fibres were detected more frequently than the red-lighted fibre. The blue-lighted fibre was detected in 100% of the cases whereas the green-lighted fibre was detected in 90% of the cases. On the other hand, the colour of the green-lighted fibre was correctly identified in 36.7% of the cases, but the colour of the blue-lighted fibre was correctly identified in only 6.7% of the cases.

3.2. Signal detection analysis

Table 3 lists the miss rates, P(H); false alarm rates, P(FA); detectability (d′); and bias

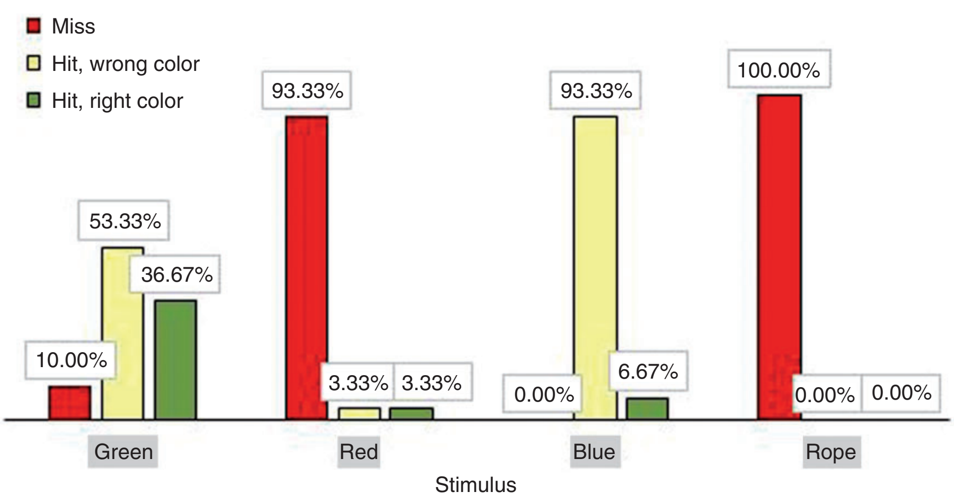

Figure 4 Misses, hits but identified as the wrong colour, and hits and identified as the correct colour, by lifeline type

(β) for the SDT analysis of the lighting conditions. There were very significant differences between the lighting conditions. A *d'* value of >1.0 indicates a reasonably high detectability for the cap lamp off condition, suggesting that the results are most likely not by chance. For the same condition, a β considerably >1.0 shows a strong bias towards avoiding false alarms. For the cap lamp on condition, a $d' = 0.0$ shows that detectability, if any, was entirely by chance, and a $\beta = 1.0$ indicates an equal bias towards avoiding all error types.

Table 3 Results from the signal detection theory analysis of the detection of the lifeline for the cap lamp off and on

	Cap lamp off	Cap lamp on
False alarm, P(FA)	0.9917	1.0
Miss, P(H)	0.8833	1.0
Detectability, d'	1.21	0.0
Bias, β	8.8914	1.0

3.3. Visual performance

The results of the GEE analysis on lifeline detection and colour recognition are reported in Table 4. The effect of stimulus was significant at $p < 0.0001$. Based on the parameter estimate, the odds of detecting a blue- or green-lighted fibre are 5.28 times greater than the odds of detecting a red-lighted fibre. The bounds of the 95% confidence interval indicate that there is a 95% probability that if the experiment were repeated an infinite number of times, the odds ratio would fall between 3.53 and 7.02.

The areas in the mosaic plots shown in Figure 5 represent the estimated relative

Table 4 Results of GEE analysis of the effect of stimulus on fibre lifeline detection. Response categories: 0 = did not see fibre; 1 = saw fibre, incorrectly identified colour; 2 = saw fibre, correctly identified colour

Parameter	Estimate	Standard error	95% Confidence limits		*Z*	*p*
			Lower	Upper		
Response 2 vs 1 or 0	−6.49	0.91	−8.28	−4.69	−7.09	<0.0001
Response 1 vs 0	−2.60	−0.72	−4.02	−1.19	−3.61	0.0003
Green- or blue-lighted fibre	5.28	0.89	3.53	7.02	5.93	<0.0001

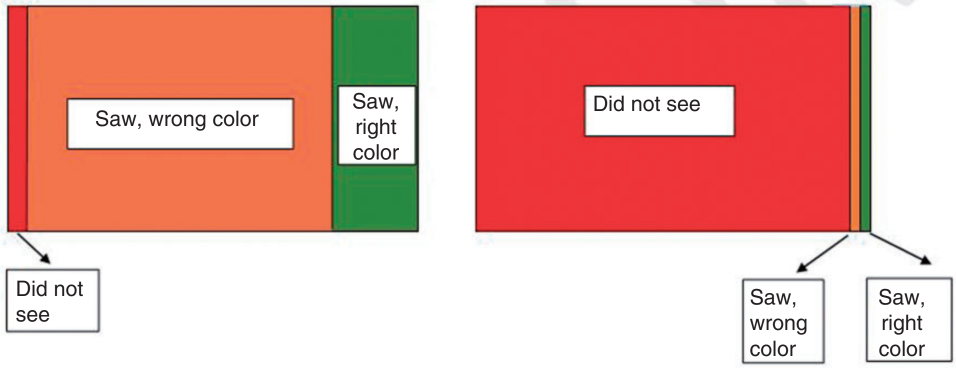

Figure 5 (Left) Relative probabilities of response categories for blue- or green-lighted fibre lifelines with the cap lamp off. (Right) Relative probabilities of response categories for red-lighted fibre lifeline with the cap lamp off

Table 5 Results of a GEE analysis comparing distance (*m*) at which green- and blue-lighted fibre lifelines can be detected

Parameter	Estimate	Standard error	95% Confidence limits		*Z*	*p*
			Lower	Upper		
Intercept	5.36	0.16	5.05	5.66	34.45	<.0001
Green- vs blue-lighted fibre lifelines	0.07	0.21	−0.35	0.49	0.33	0.7402

probabilities of the three response categories for blue- or green- versus red-lighted fibres.

The average distances at which green- and blue-lighted fibre lifelines could be detected were 5.36 and 5.43 m, respectively; the standard deviations were 0.77 and 0.84 m, respectively. The results of the GEE analysis on distance are reported in Table 5. The effect for fibre colour was not significant, indicating that there is no difference in the average distance at which blue- and green-lighted fibre lifelines can be detected.

4. Discussion

The results of this study clearly indicate that having a cap lamp on severely limits the ability to detect the fibre lifeline, regardless of colour. The cap lamp produces luminances in smoke ranging from 1.5 to 30 cd/m^2, which are orders of magnitude greater than the luminance of the lighted lifeline. The contrast between the fibre and surrounding area becomes very limited when the cap lamp is on because the light illuminates the smoke and a veiling of the fibre takes place that inhibits visibility.[15] Other research has shown that ambient light scattering in smoke creates a veil of light that can greatly reduce visibility of emergency exit signs.[22] Using a cap lamp resulted in the lifeline not being detected 98.3% of the time compared to 49.2% without the cap lamp on. The latter result is somewhat misleading given it includes false positives from the rope lifeline, which cannot be seen without a light source. Eliminating the rope lifeline reduces the miss rate to 25.8%, of which 90% of those misses occurred with the red-lighted fibre. These descriptive statistics provide compelling evidence that it is better to have the cap lamp off. SDT was used to analyse miss data for the conditions of the cap lamp on and off. The SDT analysis results (Table 3) clearly indicates that detectability $d' = 0.0$ with the cap lamp on was merely by chance, while detectability $d' = 1.21$ with the cap lamp off indicating detectability was most likely not by chance.

The miss rate is of prime importance given detection of a lifeline is more critical for self-escape than recognising the lifeline colour. The colour recognition data do provide some useful information. First, it is important to understand that the average spectral sensitivity of the eye changes depending upon the general light levels. For daylight conditions (photopic) the peak sensitivity is about 555 nm (yellow–green), and for moonlight conditions (scotopic) the peak sensitivity is about 507 nm (blue–green). The mesopic state is between the photopic (>10 cd/m^2) and scotopic (<0.001 cd/m^2) states, where the peak mesopic sensitively of the eye is between 555 nm (photopic) to 507 nm (scotopic).[23] The spectral sensitivity of the eye shifts from green towards blue as the light level decreases. Although the lighting conditions were mesopic, the conditions were much closer to scotopic than photopic given the fibre luminance in smoke was 0.025 cd/m^2, 0.047 cd/m^2 and 0.041 cd/m^2, for the red, green and blue, respectively. The poor visibility of the red-lighted fibre was likely because the wavelength of 639 nm was further from the peak wavelength of scotopic conditions and because it had a much lower value of luminance in smoke. Further investigation is needed to determine why the luminance of the red fibre lifeline was much lower in smoke even though the luminance was higher than the green or blue fibre lifelines in clear conditions.

Colour recognition in the mesopic state will become more difficult as the luminance decreases and approaches the scotopic state. This is because as luminance decreases, the rod photoreceptors of the eye become increasingly dominant over the cone photoreceptors that enable colour perception.[23] This helps explain the relatively low percentages of correct colour recognition for the green and blue fibre lifelines, these being only 36.7% and 6.7%, respectively. These results indicate that using colour to convey useful information for miners would not be very effective in mesopic luminance conditions, especially in smoke, which would further reduce luminance.

Although the blue fibre lifeline had a lower correct colour recognition (6.7%), it was detected 100% of the time compared to the 90% detection for the green fibre lifeline. From this, one could infer that blue had an advantage. However, the results for visual performance, which were based on the detection distance, indicate that there is not a statistically significant difference between green and blue fibre lifeline detection distances, although the green-lighted fibre lifeline had a slightly better average detection distance of 5.36 m compared to the average detection of 5.43 m for blue.

Overall, the results indicate that the blue fibre lifeline performed slightly better than the green fibre lifeline given it had a 100% detection rate, but there was not a statistically significant difference in visual performance between the blue- and green-fibre lifelines. Therefore, additional measurements were made to determine if one of the colours had an advantage not evident from the tests conducted.

It is important to determine the extent of luminance attenuation as a function of the fibre length. It is desirable to have a smaller luminance decrease as length is increased. A 105 m length of fibre was illuminated with green and blue lasers. The luminance of the green fibre decreased 39% between the 25% to the 50% length location, while the blue fibre luminance decreased 68% for the same locations. Given this additional information, green appears to be the most desirable colour for the lighted lifeline.

5. Limitations

The testing was conducted in a clean and controlled laboratory environment that minimised the effects from confounding variables likely to be encountered in a mine environment, such as the accumulation of dust on the lifeline that would partially reduce the luminance. More investigation is needed to determine differences between the laboratory results using artificial smoke described by the present paper and those from testing done in the field using real smoke. The testing was in a somewhat benign situation; thus, results might vary in an actual self-escape emergency where people would be under duress. In addition, the testing scope was limited to the detection of the lighted fibre. It would be very useful to conduct field-testing in smoke to determine if the lighted fibre improves the speed of egress, especially given that some evaluations of devices for self-escape did not significantly improve egress speed.[6,8]

The lighted fibres were tested at a constant luminance. Flashing the lighted fibre on and off might improve detectability given that participants would see a somewhat abrupt variation compared to a gradual increase in light intensity that was afforded as the lighted fibre apparatus came closer to the participant.

A 4-Hz flashing visual warning system developed for mining machines enabled the fastest detection in comparison to multiple visual modes used for warning participants of machine movements.[24] A study of automotive rear warning lights indicated that a light flashing rate of 4 Hz was optimal[25] and another study indicated that a flashing brake system significantly improved drivers' response time.[26]

Lastly, the study targeted an older age group with normal vision so it is unknown how younger age groups would perform with respect to the detection and recognition of the lighted fibre colour. Age is the most common cause of limited visual capabilities that include declines in visual acuity, contrast sensitivity, colour discrimination and sensitivity to glare.[27] We assume that younger age groups would perform better. Similar research that evaluated a person's ability to detect coloured escapeway markers in a simulated mine of smoke determined that the youngest age group had the best visual performance.[16]

6. Concluding remarks

A lighted lifeline is being developed in response to the 2013 National Research Council report recommendation that NIOSH should '*accelerate efforts to develop technologies that enhance self-escape. These technologies should use human-centered design principles....*'[5] The human factors of lighting drove the selection of a green-lighted fibre for the lighted lifeline based on visual performance data concerning detection distance, miss rate, colour recognition and data that indicated the green-lighted fibre lifeline could allow a longer length to be used given the luminance decrease of 39% versus 68% for the blue fibre lifeline over a distance of 105 m. It should be noted that the green laser tested in the experiment had a peak wavelength of 515 nm, putting it in the blue–green region and close to the peak scotopic sensitivity of 507 nm. The blue laser had a peak wavelength of 450 nm – closer to the violet part of the spectrum and well below the peak sensitivity of scotopic vision, though, very interestingly, the blue lighted fibre lifeline performed slightly better than the green lighted fibre lifeline with respect to miss rate. The rods in the eye, which are the only photoreceptors involved in scotopic vision, are more sensitive to the blue region and are highly sensitive to movement, which may explain the increased detectability of the blue-lighted fibre lifeline as participants could be perceiving the motion of the apparatus travelling towards them. An optimum laser colour for detectability could be possible, though commercial availability of more specific laser wavelengths may be limited and costly.

The research also indicated that visual performance in smoke was much better with the cap lamp off, which might be counter-intuitive to miners. The lighted lifeline appears to have merit for improving self-escape from underground mines based on the visual performance data that were far superior for the lighted fibre compared to the traditional rope lifeline. The technology could have other mining applications that include outlining mining machines to improve their visibility to miners and thus empower them to avoid moving machinery hazards. The technology could potentially be used for non-mining applications that include escape from rail and roadway tunnels and buildings.

Declaration of conflicting interests

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