Usability of Collaborative "VR Mine Rescue Training" Platform

Jennica L. Bellanca, Timothy J. Orr, Cassandra Hoebbel, William Helfrich, Brendan Macdonald, Jason Navoyski, Brendan Demich, Jessie J. Mechling, Paul E. Schmidt, Linda L. Chasko, Jessica Cohen
National Institute for Occupational Safety and Health, Pittsburgh Mining Research Division

ABSTRACT
The National Institute for Occupational Safety and Health (NIOSH) in partnership with the Mine Safety and Health Administration (MSHA) developed VR Mine Rescue Training (VR-MRT). It is a training platform that allows mine rescue team members to explore virtual emergency scenarios collaboratively. Team members use a head-mounted display to visualize and interact together with equipment, hazards, and dynamic ventilation. All player actions are recorded and displayed for debriefing. Researchers at NIOSH demonstrated the training platform at various mine rescue competitions, including the International Mine Rescue Competition, and collected feedback. Participants' responses were overwhelmingly positive. This paper describes the development of the software platform and the results of the usability surveys and interviews.

INTRODUCTION
Low-probability/high-severity events such as mine disasters create substantial human and economic costs to employers, workers, and communities. For example, the Upper Big Branch mine disaster in 2010 resulted in the loss of 29 lives, direct payments of over $200 million (Memmott 2011), criminal charges, and catastrophic damage to the community and all involved. Over 39,000 workers in underground (UG) mines across the U.S. (NIOSH 2022) face the risk of disaster every day. It is critical that the mining industry remains prepared. With just over 260 mine rescue teams (NMRA 2020) in the United States, the investment in high-quality training can be difficult, but proper emergency response can mean the difference between life or death and have far-reaching effects in mining communities.

All mineworkers must prepare for minor emergencies and evacuations, but mine rescue teams must be ready if mineworkers cannot escape on their own. Training for such events requires time and money that can be difficult to secure. Many mine rescue team members only receive the minimum 40 hours of training and are only able to participate in two mine rescue contests that are required by law for underground coal; for metal/nonmetal teams, it can be even less (30 CFR 49.8). Furthermore, these events are often in the form of low-fidelity drills in open fields or above-ground facilities and have limited evidence of effectiveness (Hoebbel et al. 2015). With scarce resources, it is critical that mine rescue training be as effective as possible.

Effective Training
Training is defined as the systematic acquisition of knowledge, skills, and abilities (KSAs) that are necessary for effective performance (Goldstein & Ford 2002). There are many ways to measure effectiveness including knowledge, retention, acceptability, and usability, but when focusing on

performance outcomes, several critical factors have been identified. Research has shown that effective training is engaging, authentic, and understandable (Burke et al. 2006; Burke and Hutchins 2007; Wilkins 2011). Training has also been shown to be more effective with additional context and realism (Kowalski-Trakofler & Barrett 2003). Lastly, effective training has been shown to include opportunities to demonstrate, practice, debrief, and assess (Salas & Cannon-Bowers 2001). Virtual reality (VR) is a mechanism that supports all these characteristics.

In addition to characteristics that improve performance, VR training also provides many opportunities to improve training logistics. VR can enhance traditional training with reduced space requirements, travel costs, and time (Bellanca et al. 2019; Shiva et al. 2021). Various scenarios can be run in quick succession without the additional set-up time, materials, and even personnel once the content is created. Additionally, VR training frees trainers to observe team interactions and decision making because the system tracks all the movements, actions, and events. The system data also helps trainers perform more robust after-action reviews. VR systems can provide detailed after-action data and playback, allowing for the comparison of multiple teams, which has been shown to improve learning (see Bauerle et al. 2016 for a summary of effective debriefing). Some examples of how VR has been effectively used to improve training include VR anesthesia training that improved performance and reduced anxiety compared to traditional instruction (Gaba 2017); manufacturing VR training was found to increase productivity and reduce errors (Kirsch 2018); and VR military training has long been used to train for combat situations, with studies showing that it can improve decision making and reaction times (Burdea & Coiffet 2003).

However, performance of critical KSAs in dangerous and dynamic environments can make training effectiveness difficult or impossible to safely assess. A large body of research suggests that “self-efficacy” can serve as a reliable proxy measurement for very specific competencies (Bandura 2006; Pajares 1996), like those required for mine rescue. Although self-efficacy is a complex construct and is not synonymous with confidence, it can be argued that both refer to “self-reflectiveness about one’s own capabilities” (Bandura 2001), and thus is often assessed by asking research participants to rate levels of confidence in their own KSAs (Pajares 1997). As a starting point to characterize the training need and effectiveness, mine rescue team members in this study were individually asked to rate their confidence in their preparedness to respond to an actual mine emergency.

Furthermore, before any training platform can improve KSAs, the training platform must first be usable and accepted. Brooke (1996) describes usability as “general quality of the appropriateness to a purpose.” More formally, usability has been defined as “the effectiveness, efficiency and satisfaction with which specified users achieve specified goals in particular environments” (ISO 2018). In either case, the question of usability focuses on whether it does what it is supposed to do, meets the needs of its users, and if the users are willing to use it. Usability is the focus of the current evaluation.

VR Mine Rescue Training

In 2020, NIOSH researchers at the Pittsburgh Mining Research Division (PMRD) partnered with MSHA to develop a VR mine rescue simulation to bring this promising technology to the industry

in the United States. The partnership built upon the NIOSH team's experience with implementing and researching VR in mine rescue and escape training, and MSHA's expertise in mine rescue and team training. Early NIOSH research showed success using virtual technologies for simulation, and preliminary data suggest these simulated environments offered both the realism and engagement levels critical for effective training (Hoebbel et al. 2015). Additional NIOSH research showed these environments can be used to observe and assess team dynamics relevant to successful emergency response team function (Connor et al. 2016). The partnership between NIOSH and MSHA resulted in the development of the VR Mine Rescue Training (VR-MRT) platform that was showcased at numerous events, but most notably the International Mine Rescue Competition (IMRC) held at the MSHA Training Academy in Beckley, WV in September 2022.
The goal of this paper is to introduce VR-MRT, assess the current training needs, and evaluate the usability and acceptability of VR-MRT.

METHODS

VR Mine Rescue Training Development

The NIOSH VR-MRT platform is built upon the Unity game-engine framework that was previously developed by the NIOSH VR research team called VR Mine (Bellanca et al. 2019). VR Mine was designed to allow researchers the ability to create simulated underground mines to be used as virtual laboratory spaces to study various health and safety issues related to human system interactions. The simulation could be readily deployed using large theater spaces, head mounted displays (HMDs), and desktop computers, while adhering to the performance specifications required by a particular application or study. For this application, this framework was significantly adapted with numerous new features to provide both single and multiplayer configurations that can be both co-located and remote.

The VR-MRT platform was designed for individuals and teams of mine rescue trainees to explore an underground mine as a part of their mine rescue training. Specifically, the training objective was to improve mine rescue team members' procedural, collaborative, and problem-solving skills for an underground emergency response. The VR-MRT platform was developed with four main modules: the simulation, director, spectator, and debrief modules.

Simulation Module

Each trainee can join a VR-MRT simulation and interact with the virtual environment using an HMD and two controllers that immerses the wearer into the simulated environment. Trainees are assigned one of six roles: captain, vice-captain, gas man, map man, 2nd gas man, and tail captain. Each role has a different accent color (i.e., trim of gloves, hard hat, arm band) and has different tools and capabilities as described in Table 1 following that of a real mine rescue team.

Table 1. Mine rescue team member roles

Role	*Color*	*Tools*
Captain/ Vice-captain	Red/ Orange	Sounding stick, gas meter, smoke tube, chalk (to date and initial), multi-gas meter, smoke tube, BG4 sentinel, radio (nonfunctional)
Gas Man	Yellow	Multi-gas meter, smoke tube, BG4 sentinel, radio (nonfunctional)
Map Man	Green	Map board, smoke tube, BG4 sentinel, radio (nonfunctional)
2^{nd} Gas Man	Cyan	Multi-gas meter, smoke tube, BG4 sentinel, radio (nonfunctional)
Tail Captain	Purple	Multi-gas meter, smoke tube, BG4 sentinel, radio (nonfunctional)

The tools listed in Table 1 cannot be grabbed by any other player but can be viewed and used by others for collaboration (e.g., reviewing the map together to determine where the team should advance, viewing O_2 level of a teammate's rebreather during a team check). Trainees can interact with their own tools by using only the grip and trigger buttons on their controllers. Based on the position of the controllers, the trainees' gloves are visualized in the simulation. When their gloves are close enough to an object they can interact with, such as their tools or other objects in the mine, the object glows green. Upon grabbing the object (i.e., with the grip button), it snaps into their hand so that they can see it or use it (i.e., with the trigger button). Figure 1 displays various first-person perspectives of the tools available to trainees and how they look when trainees interact with them. The map board is a special case; trainees assigned the role of map man carry a map board in one of their hands at all times and are able to add and remove symbols using a simple drag and drop interface.

Equipment like the multi-gas meter is integrated into the simulation, displaying readings for values including methane (CH_4), oxygen (O_2) and carbon monoxide (CO) derived from the simulation at that point in the mine. In the simpler scenarios, gas readings can be defined to be specific values in certain zones and interpolated between these zones. Alternatively, VR-MRT can use the NIOSH MFIRE software (Zhou, Yuan, Cole 2020) to simulate ventilation in the mine including airflow, contaminant levels from fires, and methane levels from methane sources. In scenarios running MFIRE, the trainee can also use their smoke tube to create a smoke cloud that moves in the direction of the simulated airflow. The MFIRE simulation can also be interacted with in real time by placing and removing curtains to change the resistance of airways and by extinguishing fires. Additionally, the airflow and contaminant or methane levels can be visualized in first-person while in the VR simulation for added training impact.

During the simulation, players are primarily able to move through two mechanisms: physically walking around and teleporting. To reduce simulator sickness, to improve immersion, and to tap muscle memory, researchers thought it was important to have some part of the simulation walkable. Depending on the scenario and setup, trainees could explore a large portion of the mine by walking.

For this data collection, the playspace was 60' x 60'. This allowed participants to physically explore a full intersection up to half a block on either side since the entries were 20' wide and the pillars were 40' x 40'. Larger scale movements were completed by teleporting the team to the next "team stop," and the whole team would be moved to the next requested intersection. To ground this in mine rescue procedure, teams were instructed to "ask for permission to advance" when they wanted to teleport.

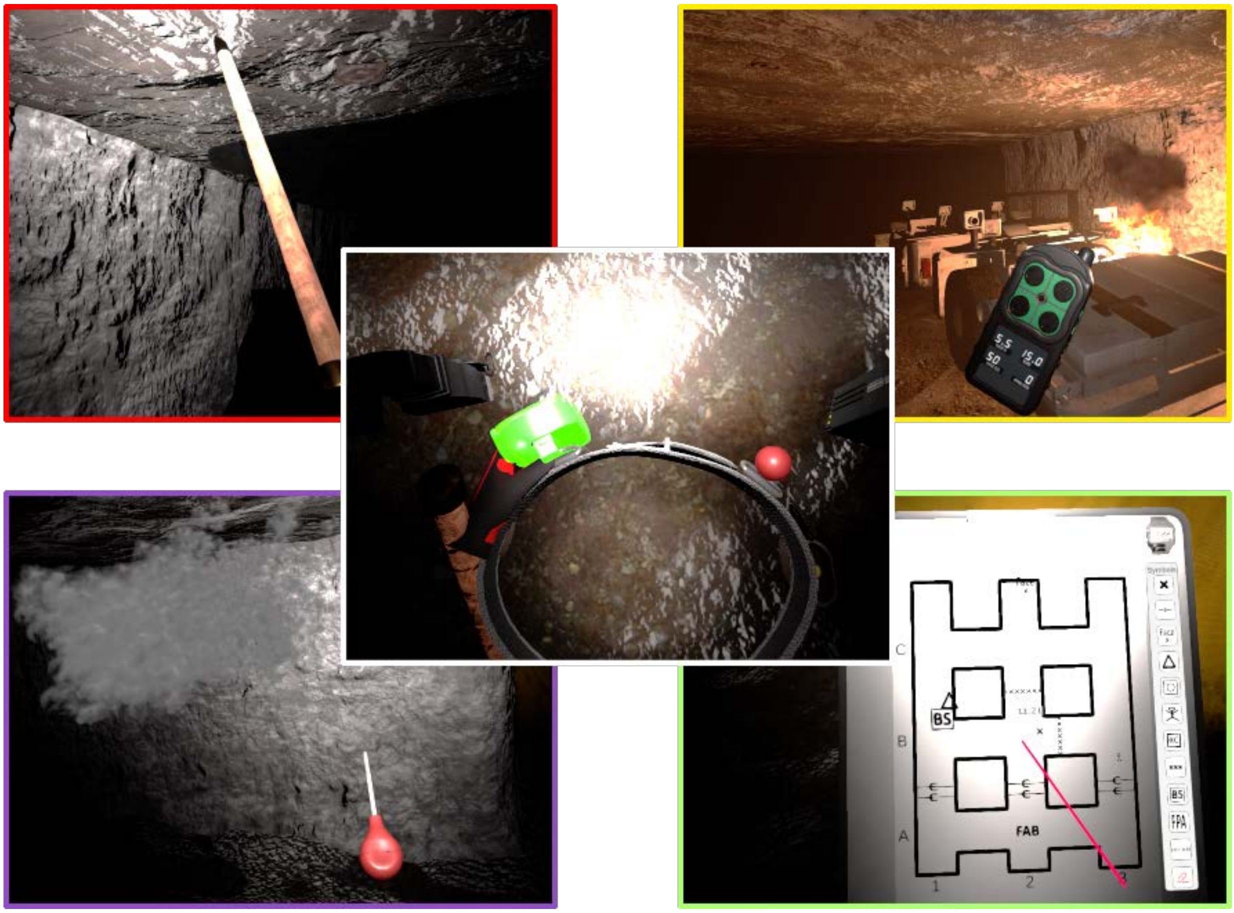

Figure 1. Screen captures from the first-person perspective of the tools available to various roles and how they are used. *Top left*: The captain is using their sounding stick to test the roof. Good and bad top are distinguished by different audio from an actual mine. *Top right*: The gas man is using their multi-gas detector to check for CH_4, O_2, and CO gases. *Bottom left*: The tail captain is using their smoke tube to check the direction of the ventilation. Smoke moves in the direction of the airflow. *Bottom right*: The map man is adding symbols to the map board representing objects in the mine. *Center:* A first-person view looking down at the captain's tool belt. The captain can see their gloved hand that is used to interact with objects that highlight green when the player comes close

Director and Spectator Modules

Multiplayer simulations are controlled by a desktop computer running VR-MRT in the "director module." In this module, the trainer can load new scenarios, record log files for the debrief, and teleport the trainees from one virtual location to another. The trainer can also manipulate the underlying ventilation, provide the team with additional resources (e.g., extra curtains, fire extinguishers), or refill or empty the oxygen in their rescue rebreather apparatuses (i.e., BG4 units). To accomplish this technical oversight of the trainees in simulation, the director module also includes a third-person perspective of the mine. Trainers can zoom, pan, and rotate the camera over any part of the simulation. For scenarios with MFIRE ventilation (i.e., not static gas zones), the trainer can also turn on visualizations of the velocity and concentration of various contaminants (e.g., CO, CH_4).

The spectator module also runs on a desktop computer. It provides an overhead and third-person chase camera view of the simulation. This module can either run on two screens or swap between the views on a single screen. There are no other controls in this mode as it is just intended to provide the audience with a visualization of the simulation.

Debrief Module

When the simulation is complete, the training continues via an after-action review tool, the debrief module. The debrief module loads the log file that was collected by the director module. The log file includes the necessary states, actions, and events from all players such as movement and interactions in order to recreate the events of the simulation. The debrief module can display a top-down orthographic plan view and/or a 3D perspective view. Figure 2 depicts the top-down view that displays important events such as a fire extinguisher discharge, sounding the roof, and more. It also displays the color-coded paths traveled by each team member. Visibility of all the events and traces including ventilation velocities and concentrations can be toggled on and off. In the lower right corner of the top-down view, trainers can also view the map man's map(s). The 3D perspective view shows a playback of events that occurred during the simulation as seen from within the virtual environment. Trainers can zoom, pan, and rotate the camera to examine what each team member did, where they went, and even the gestures they made with their arms (e.g., pointing in a specific direction or at the map board). Both views can be manually scrubbed through time or automatically played back at various speeds. As the time point changes, the content of the views change, including the map markers placed by the map man. Trainers can use this tool to isolate key decision points and sets of actions to highlight critical mistakes.

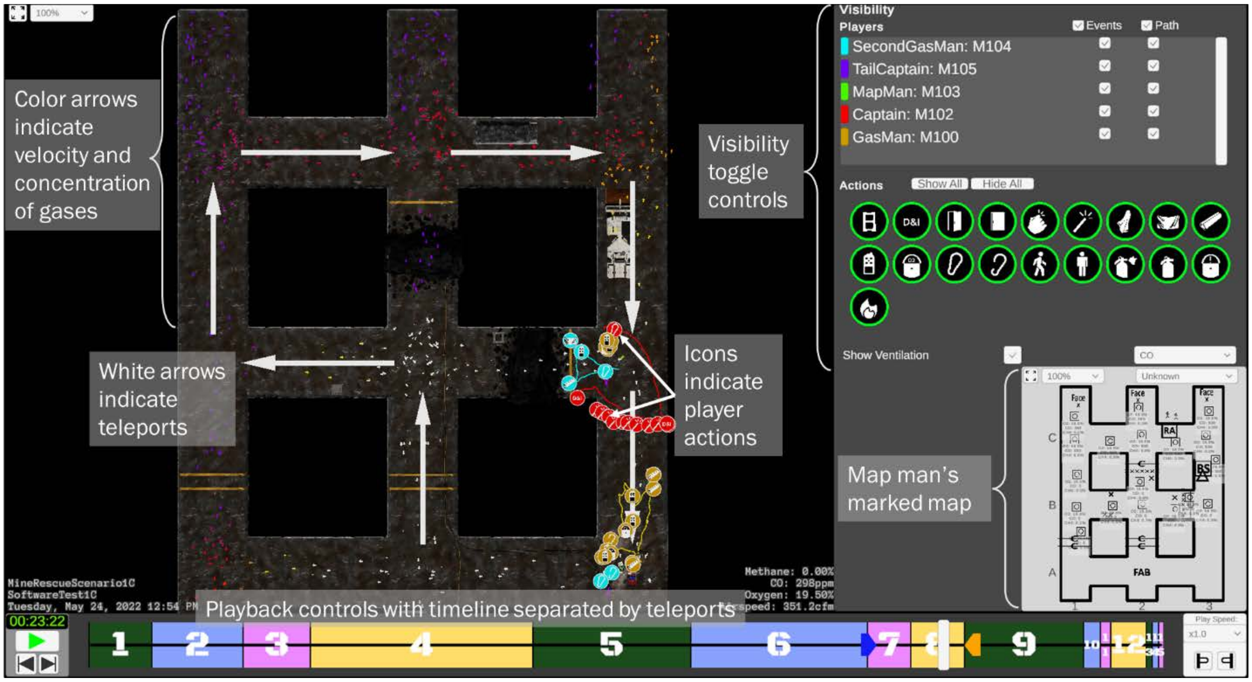

Figure 2. An annotated screenshot of the top-down view of the debrief module. The visibility controls are on the top right above the map man's map. The playback controls are located at the bottom of the screen, where the numbers indicate the teleport points

Hardware Setup

For this data collection, VR-MRT was deployed over a local wired network of VR gaming computers—one for each team member plus one computer running the director module and one running the spectator module. However, VR-MRT can be deployed over the internet in remote locations. The Meta Quest 2 HMDs for each team member were connected to their respective computers using Meta Quest Air Link over 5Ghz Wi-Fi. The HMD Wi-Fi connection was provided by a Wi-Fi router (TP-Link Archer AX11000) with two 5Ghz radios on different channels. This configuration provided sufficient bandwidth, acceptable graphical performance, and unrestricted movement within the playspace. Because of the size limit, the Meta guardian system was disabled during the simulation, but VR-MRT includes a configurable guardian to maintain safety.

Co-location and Calibration

For this data collection, all mine rescue team members were co-located in the same space. Therefore, it was critical that their positions were calibrated to ensure that their avatars in the virtual simulation matched their actual location in the real world. This was accomplished through a two-step calibration process followed by a validation measurement that was completed by the researchers prior to the participants' arrival. The researchers used 3D printed calibration puck to align the right controller of each system at three points. The first puck was placed at the center of the playspace to identify the origin. The second puck was placed just outside the playspace directly inby the origin to calculate the forward rotation vector. Lastly, the third puck was placed just outside the intersection at a common measurement point to calculate the accuracy of the calibration. Figure 3 depicts a schematic of the playspace with the three calibration locations as well as an image of a person calibrating and a drawing of the calibration puck. The use of the pucks makes this system quick and simple, allowing an entire team to calibrate in under five minutes.

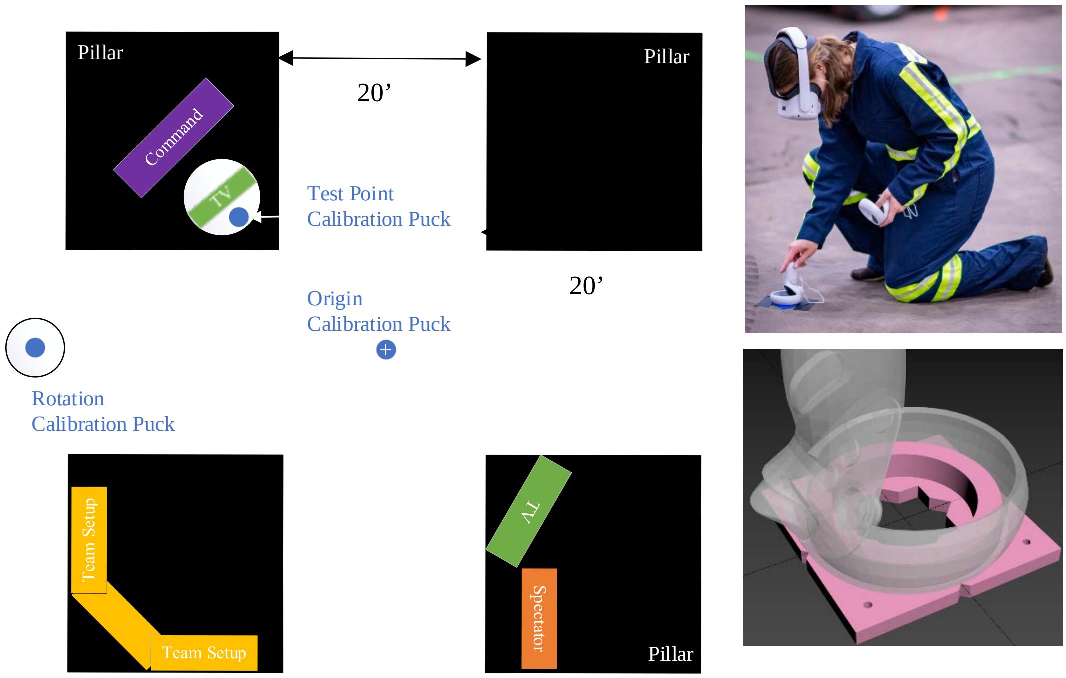

Figure 3. Schematic and pictures describing the calibration process. *Left:* Schematic of the playspace setup including the three calibration points marked by blue circles. *Top Right*: Photograph of a researcher calibrating a trainee system at the origin. *Bottom Right*: Rendering of a Meta Quest 2 controller sitting on a calibration puck

Participants

Participant teams were recruited according to the Institutional Review Board (IRB)-approved protocol from two mine rescue competitions and 22 teams participated (10 international). Teams were approached during registration for the competitions. If they agreed to participate, teams were scheduled on a first-come first-served basis according to the competition schedule. Some teams fielded more than one team (i.e., with more than 5–6 individuals), but each participant completed at least one mine rescue scenario. This resulted in a total of 126 participants (3 females, 110 males, 13 omitted/preferred not to answer). Participants varied in their background and experience as detailed in Table 2.

Table 2. Participant demographics

	N	*Median*	*Interquartile Range*
Age (years)	125	36.0	32–43
Mining experience (years)	125	13.0	10–17
Mine rescue experience (years)	121	7.0	4–11
Mine rescue competitions (count)	121	9.0	3–28
	N	*No (count)*	*Yes (count)*
MR response experience (Y/N)	126	57	69
VR experience (Y/N)	126	77	49

Training

During their scheduled time slots, teams completed one or more of the three mine rescue scenarios. Depending on their availability, teams were offered a 5, 15, or 30-minute problem. Prior to the actual problem, teams completed 5–10 minutes of training on how to use the VR headsets and interact with the simulation. Teams were instructed on how to complete all interactions required for the scenarios including checking their oxygen levels, taking gas readings, sounding the roof, dating and initialing changes, using a smoke tube, hanging curtains, interacting with trapped miners, and moving through the scenario. All communication with any teams that were not native English speakers occurred through one or more translators that traveled with the team. Training was conducted in specially designed training scenes that provided opportunities to practice each skill along with pictorial descriptions of the actions required.

The mine rescue scenarios were completed with 5- or 6-man teams, where a vice captain was added for 6-man teams. Following the completion of the scenario, a NIOSH researcher debriefed the team on their performance during the simulation according to mine rescue competition rules as well as real-life emergencies.

Data Collection

Following the completion of the mine rescue training scenario and debrief, participants were asked to complete a survey about their experience. The survey included demographic questions to assess their experience in mining, mine rescue, and virtual reality. Then, participants were asked to rate their confidence in their ability to effectively respond to a real mine emergency. Next, participants were asked to rate their experience with VR-MRT using several modified scales measuring usability (Brooks, 1996), presence (Witmer and Singer 1998), ease of use, and simulator sickness (Kennedy et al., 1993). Lastly, participants were asked if they would be interested in using VR as a substitute or supplement for current mine rescue training.

Additionally, NIOSH researchers observed the participants during the simulation and debrief session. A structured reporting form was used to capture technical issues encountered by the research team or participants, engagement level, and the participants general behavior. The researchers also noted orientation, confusion, and any clarifying questions participants asked, as well as any other notes the researchers felt were relevant.

Analysis
Quantitative analysis of the survey responses was conducted using SPSS statistical software (version 2.6, IBM), where responses to all Likert scale questions were compared across participants with and without mine rescue and VR experience. Mine rescue (MR) experience (i.e., yes) was derived from positive participant responses to one or both of the following questions: "Do you have any MR experience in a real mine emergency underground and under apparatus?" or "Have you ever responded to a real mine emergency as part of a mine rescue team, but your team did not go underground?" VR experience was asked directly. Confidence was categorized into highly confident that they were prepared or not prepared, where highly confident or "prepared" followed the mastery learning convention and was set at 80% or higher (i.e., response ≥ 8) (Winget & Persky 2022). The overall usability score was calculated according to Brooks (1996) using the 10 subscales where any missing value was assumed to be neutral (i.e., response of 3). Any other missing values were excluded on an entry basis. A one-sample t-test was performed to compare the overall usability score to neutral (i.e., 50%) to determine significant positive result. All group comparison results were performed using the Mann-Whitney U test since the group samples violated the normality and homogeneity assumptions. Significance was set at alpha less than or equal to 0.05. Simulator sickness responses were reported as frequencies of mild, moderate, and severe symptoms.

RESULTS

Confidence
Of the 121 team members that responded, 26 (21.5%) rated themselves as not prepared (i.e., 7 or less out of 10) for a real emergency. This distribution was consistent across both mine rescue ($p = 0.424$) and VR ($p = 0.185$) experienced groups, signaling that on average more than one person on each team did not feel prepared to respond to a mine rescue emergency.

Usability
Mine rescue team members reported that the usability of VR-MRT was good. The overall usability score was 72.7 out of 100 (std 15.0) and was significantly higher than neutral (50%) ($t = 17.1$, $p < 0.0001$). In general, all the usability scores were good, but there were differences between VR-experienced team members and those who had not previously experienced VR. Figure 4 shows the normalized average responses to the System Usability Scale (SUS) and its 10 sub-scale questions (Brooks 1996). VR-experienced team members rated the usability higher than those without experience ($p = 0.003$), and the difference was significantly driven by the perceived need for tech support ($p = 0.001$), lack of consistency ($p = 0.016$), and prerequisites required ($p = 0.007$). There were no significant differences in SUS ratings between those with and without actual mine rescue experience.

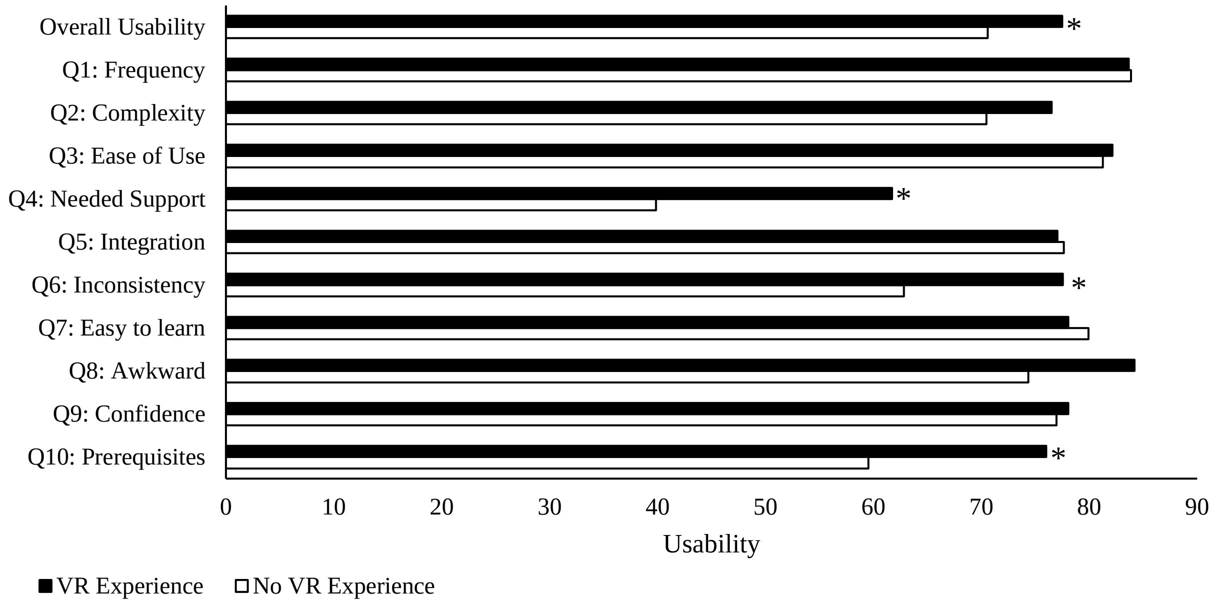

Figure 4. Graph depicting the average responses to 10 individual subscales of the System Usability Scale (SUS) as well as the overall score for participants with and without VR experience. All subscales are normalized to 100 from to 1 to 5 Likert ratings to align with the Overall System Usability Score. An asterisk indicates a significant difference between participants with (black) and without (white) VR experience ($\alpha \leq 0.05$)

Presence and Ease-of-use

Overall, participants rated their presence in the simulation as high. As depicted in Figure 5, the average normalized score for all the scales was greater than 70, and all but two scores were greater than 80. Participants rated consistency with the real world the lowest at 72.1 out of 100 (i.e., How much did your experience in the simulation seem consistent with your real-world experiences in an actual mine?), followed by the naturalness of moving at 78.4 out of 100 (i.e., How natural did moving through the simulation seem?). Participants rated immersion in the simulation the highest with a normalized average rating of 88.4 out of 100.

The presence ratings were only significantly different between those with VR experience and those with no experience on three dimensions: sound identification, sound origin, and realism. Those with VR experience rated the ability to identify sounds and locate the origin of sounds significantly lower (identify: 82.7 versus 90.7, $p = 0.001$; locate: 78.6 versus 88.3, $p = 0.001$). Those with VR experience also rated the realism of the simulation lower (76.9 versus 84.4, $p = 0.037$).

Similarly, there were only two dimensions that had significant differences between participants with and without mine rescue experience: sound identification and realism. However, the opposite relationship as compared to VR experience was found to be true. Participants with mine rescue experience rated the ability to identify sounds (90.6 versus 83.9, $p = 0.010$) and the realism of the simulation (85.3 versus 76.9, $p = 0.001$) significantly higher than that of participants without mine rescue experience.

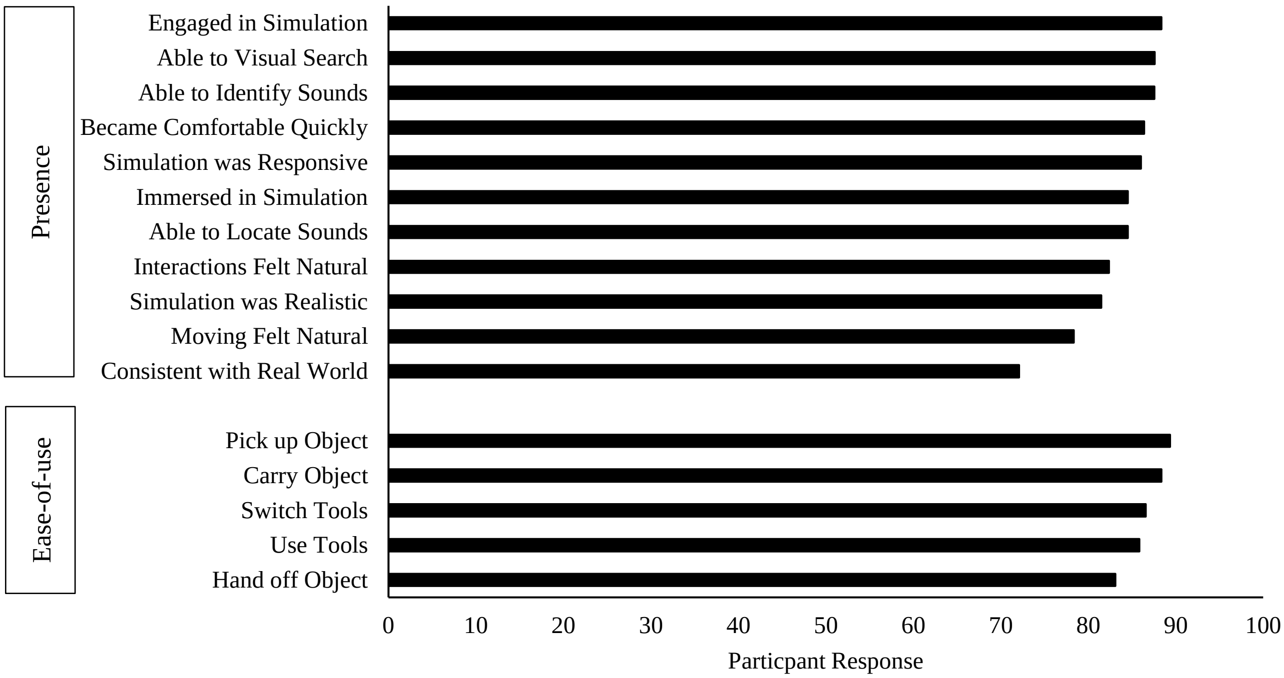

Figure 5. Graph depicting the average responses to the presence and ease-of-use questions from all participants. Responses are normalized to 100 from 1 to 7 Likert scale responses for the presence questions and 1 to 10 for the ease of use questions

Similar to usability and presence, participants rated the ease-of-use of specific simulation tasks very highly. As shown in Figure 5, on average participants rated all tasks between 83 and 90 out of 100. The only group difference for the ease-of-use questions was that participants without VR experience rated the task of picking up objects as easier than those with VR experience (91.4 versus 86.1, $p = 0.019$).

Simulator Sickness

Simulator sickness reports from the simulation were generally mild and rare. Table 3 shows the percentage of participants reporting mild, moderate, and severe symptoms in the standard categories. The most common symptom, experienced by less than one-quarter of the participants, was mild eyestrain. Discomfort and difficulty focusing were also reported by 20% and 29% of participants, respectively. There was only one participant that reported severe symptoms. However, none of the participants experienced severe enough symptoms that they needed to stop the simulation nor required any assistance from researchers. Table 3 also shows that the overwhelming majority of participants reported no motion sickness when performing the key actions.

Table 3. Percentage of participants reporting simulator sickness

Symptom/Action	*N*	*None*	*Mild*	*Moderate*	*Severe*
Discomfort	125	79.2%	15.2%	4.8%	0.8%
Eye strain	124	69.4%	23.4%	6.5%	0.8%
Difficulty focusing	125	70.4%	20.8%	8.0%	0.8%
Nausea	125	93.6%	5.6%	0%	0.8%
Dizziness	125	91.2%	8.0%	0%	0.8%
Stomach	125	95.2%	3.2%	0.8%	0.8%
Moving down a long entry	123	92.7%	4.1%	2.4%	0.8%
Sudden movement	122	93.4%	2.5%	3.3%	0.8%
Turning quickly	123	88.6%	8.1%	1.6%	1.6%
Looking around while moving	121	91.7%	5.0%	2.5%	0.8%
Looking into RA*	117	90.6%	5.1%	2.6%	1.7%
During teleporting	120	93.3%	3.3%	2.5%	0.8%

*RA = Refuge alternative

DISCUSSION

The overall results of this study indicate that the VR-MRT platform was well received by the industry. Participant ratings suggest that it is an acceptable, usable, and immersive training platform, and there are limited simulator sickness concerns. The confidence responses also suggest that additional training is needed. With more than one in five mine rescue team members reporting less than 8 of 10 on the preparedness scale, additional industry investment in training is required. VR-MRT has the potential to help close that gap. The usability data gives a clearer picture on how this platform could be implemented.

The difference in usability scores between those with and without VR experience suggests that any remaining concerns related to usability may decrease with exposure to VR. The main concern according to the data was the need for technical support to use the VR-MRT. However, those with VR experience were not nearly as concerned. This result suggests that initial training is probably required, but continued intensive technical support is probably not needed. This appears to be similarly true for user prerequisite knowledge (i.e., I needed to learn a lot of things before I could get going in this simulation.). Those with VR experience in general found it easier to pick up VR-MRT and get started. Both of these points are good news for the implementation of this training, in that the ultimate personnel resource investment is expected to decrease over time.

Interestingly, experienced VR users also indicated that the simulation was more internally consistent than those without experience. This suggests that any inconsistency within VR-MRT is still within the variation of VR interactions in general, and it is not a large concern for experienced users. Therefore, additional development efforts in this area are probably not required.

The high presence ratings suggest that this training is indeed immersive and engaging. Many of the participants mentioned that VR-MRT looked great and felt real. Researchers also observed that all of the teams and almost all of the team members were actively engaged in the simulation. Participants were so engaged that they routinely stepped up over the lip on the refuge alternative in the scenarios even though it wasn’t physically present. Despite the fact that realism was the lowest of the subscales, based on the observations, the level of fidelity achieved appears to be more than sufficient to achieve the stated purpose. As seen in other studies, participant engagement increased when they perceived that the training was consistent with reality (Shiva et al. 2021). This is further supported by the group differences. Participants with actual mine rescue experience rated VR-MRT as more realistic and better able to identify sounds, suggesting that inexperienced team members might not know what to expect. The difference in VR experience is harder to explain. One possible explanation is that frequent VR users have more inflated expectations. As VR games are becoming more cinematic and realistic, so are their expectations for immersive training. While this is something that immersive training designers should take into consideration, more evidence is needed to clarify the small differences seen here.

The positive ease-of-use ratings suggest that the training mechanics have good affordances and are matched to the purpose. It is critical that these aspects are not distracting from the purpose. In this implementation, the user controls were intentionally selected to minimize the complexity of controls (e.g., only two interaction buttons), to provide natural movements for interaction wherever possible (e.g., object hand off), and to incorporate the physicality of actual mine rescue tasks when practical (e.g., walk the curtain across the entry to hang it). For this application, this strategy appears to have been successful.

Simulator sickness for VR-MRT was low. This result matches the expected and desired outcome. The movement scheme used in VR-MRT was specifically chosen to reduce simulator sickness. In this movement scheme, the user's physical motions matched the virtual motions one-to-one in both translation and rotation as opposed to controller-based movement (Chance et al. 1998). Regardless, previous research suggests that a small amount of simulator sickness does not detract from the learning. Shiva et al. (2021) reported that "getting slightly sick did not appear to prevent trainees from benefiting from the 360 VR training." It appears that this is similarly true for VR-MRT given the positive response.

Given the overwhelmingly positive response and high usability scores, NIOSH researchers plan to take the next step to implement the VR-MRT platform at training facilities and mine sites. To do so, the role of the instructor must first be considered. NIOSH is currently working to package VR-MRT as a stand-alone training package that can be used by individuals and organizations without programming knowledge. This software release would not only allow for the greater development and sharing of training materials but enable adoption at smaller operations. The availability of less expensive HMDs allows VR to be accessed by small or remote operations, promoting the adoption of this and other VR content.

ACKNOWLEDGMENTS
The authors would like to thank the numerous individuals from the MSHA Mine Emergency Operations for their collaboration and support in developing the mine rescue scenarios and testing VR-MRT as well as the surveys described in this paper.

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 any company name or product does not constitute endorsement by NIOSH.

REFERENCES

Bandura, A. 2001. Social cognitive theory: An agentic perspective. Annual review of psychology 52(1):1-26.

Bandura, A. 2006. Guide for constructing self-efficacy scales. Self-efficacy Bel Adol 5(1):307–337.

Bauerle, T., Bellanca, J., Orr, T., Helfrich, W., and Brnich, M. 2016. Improving Simulation Training Debriefs: Mine Emergency Escape Training Case Study. In 2016 Interservice/Industry Training, Simulation, and Education Conference (I/ITSEC). Dec 2, 2016. Orlando, FL.

Bellanca, J.L., Orr, T.J., Helfrich, W.J., Macdonald, B., Navoyski, J., and Demich, B. 2019. Developing a virtual reality environment for mining research. Mining, Metallurgy & Exploration, 36:597-606.

Brooke, J.B. 1996. SUS – a quick and dirty usability scale. In Usability Evaluation in Industry. Edited by P. Jordan, B. Thomas, B. Weerdmeester, and I. McLelland. London: Taylor and Francis.

Burdea, G., and Coiffet, P. 2003. Virtual reality technology. John Wiley & Sons.

Burke, C.S., Stagl, K.C., Salas, E., Pierce, L., and Kendall D. 2006. Understanding team adaptation: A

conceptual analysis and model. J of Appl Psychol 91(6):1189–1207.

Burke, L.A., and Hutchins, H.M 2007. Training transfer: An integrative literature review. Hum Res De Rev 6:263–296.

Chance, S.S., Gaunet, F., Beall, A.C., and Loomis, J.M. 1998. Locomotion mode affects the updating of objects encountered during travel: the contribution of vestibular and proprioceptive inputs to path integration. Presence Teleop Virt Environ 7:168–178.

Connor B.P., Brnich M.J., Mallett, L.G., and Orr, T.J. 2016. Mining Publication: Effective Group Training with Computer-Based Virtual Environments. Coal Age 121(6):44-51.

Gaba, D.M. 2017. The future of anesthesia simulation: Virtual reality. Journal of medical education and training 3(2):1-7.

Goldstein, I.L., and Ford, J.K. 2002. Training in organizations: Needs assessment. Development and Evaluation, 4th ed. Belmont, CA: Wadsworth.

Hoebbel, C., Bauerle, T., Macdonald, B., and Mallett, L. 2015. Assessing the Effects of Virtual Emergency Training on Mine Rescue Team Efficacy. In 2015 Interservice/Industry Training, Simulation and Education Conference. Dec. 2, 2015. Orlando, FL.

International Standards Organization (ISO). 2018. Ergonomics of human-system interaction — Part 11: Usability: Definitions and concepts. ISO 9241-11. https://www.iso.org/standard/63500.html.

Kennedy, R.S., Lane, N.E., Berbaum, K.S., and Lilienthal, M.G. 1993. Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. The International Journal of Aviation Psychology 3:203–220.

Kirsch, B. 2018. Virtual Reality in Industry 4.0: How VR Technology is Changing the Manufacturing Landscape. Journal of Virtual Reality and Broadcasting 15(3):1–13.
Kowalski-Trakofler, K.M., and Barrett, E.A. 2003. The concept of degraded images applied to hazard recognition training in mining for reduction of lost-time injuries. J Safety Res 34(5):515–525.
Memmott, M. 2011. Coal Company To Pay More Than $200 Million In W. Va. Disaster. NPR: The Two Way. https://www.npr.org/. Retrieved: January 3, 2023.
NIOSH. 2022. Mine operator employees, underground mines, 2021. https://wwwn.cdc.gov/NIOSH-Mining. Retrieved January 3, 2021.
National Mine Rescue Association (NMRA). 2020. Survey of U.S. Mine Rescue Teams. Pittsburgh, PA.
Pajares, F. 1996. Self-efficacy beliefs in academic settings. Rev Ed Res 66(4):543–578.
Pajares, F. 1997. Current directions in self-efficacy research. Adv Motiv Ach 10(149):1–49.
Salas, E., and Cannon-Bowers, J.A. 2001. The science of training: A decade of progress. Ann Rev Psych 52(1):471–499.
Shiva, P., Ogie, R., Palmisano, S., Farrelly, M., and Perez, P. 2021. Cost-benefit analysis of virtual reality-based training for emergency rescue workers: A socio-technical systems approach. Virtual Reality 25(4):1071-1086.
Training for mine rescue teams. 30 C.F.R. § 49.8. 2015. https://www.ecfr.gov.
Wilkins, J.R. 2011. Construction workers' perceptions of health and safety training programmes. Constr Manage Econ 29(10):1017–1026.
Winget, M., and Persky, A.M. 2022. A practical review of mastery learning. American Journal of Pharmaceutical Education 86(10):ajpe8906.
Witmer, B.G., and Singer, M.J. 1998. Measuring presence in virtual environments: A presence questionnaire. Presence 7:225–240.
Zhou, L., Yuan, L., and Cole, G. 2020. MFIRE software (version 4.0). U.S. Pittsburgh, PA: Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health.