



Pre-implementation Evaluation of VR as a Mine Safety Training Tool

Jennica L. Bellanca¹ · Cassandra L. Hoebbel¹

Received: 19 March 2025 / Accepted: 3 November 2025 / Published online: 13 January 2026

This is a U.S. Government work and not under copyright protection in the US; foreign copyright protection may apply 2026

Abstract

High-fidelity, immersive training is known for its learning and logistical benefits. While other industries have been using virtual reality (VR) for decades, the same uptake has not been seen in mining. NIOSH recently developed an adaptable, scalable VR training platform, VR Mine Rescue Training (VR-MRT), which has attracted significant industry interest. NIOSH is using VR-MRT to understand the barriers to adoption and implementation of VR. As a part of a larger evaluation effort, researchers have conducted pre-implementation surveys and interviews from individuals at various implementation levels. In this paper, the authors use this feedback to formally evaluate VR-MRT's acceptability and appropriateness for mine rescue training and identify barriers to the implementation of VR training more generally. The results highlight a significant interest in using VR and preference towards using VR-MRT as a supplement to existing mine rescue training as opposed to a replacement. The results also identify potential implementation barriers for using VR for mine safety training in general including understanding how VR training fits in with compliance, getting external and internal IT support, and company and individual buy-in. Researchers describe ongoing efforts to overcome these barriers using VR-MRT as a case study.

Keywords Virtual reality · Training · Mine rescue · Implementation science

1 Introduction

1.1 Mine Rescue Training

Emergency preparedness is crucial in the mining industry, especially for underground mine rescue teams. These teams perform high-risk tasks in hazardous and rapidly changing environments, often requiring coordinated actions to be taken quickly and accurately. However, a recent survey found that more than 21%—more than one in every five—of mine rescue team members surveyed did not feel adequately prepared (i.e., 80% or more) to respond in the event of a mine emergency [1]. Furthermore, while there has been some investment in mine rescue technology [2], the mining industry has only minimally invested in new training

content and delivery. Moreover, many teams receive minimal training—only 96 hours annually—in compliance with U.S. federal regulations (30 CFR 49.18). Unfortunately, this training often lacks realism. As a part of this required training, underground coal mine rescue teams must participate in at least two contests annually. These competitions have traditionally been in the form of low-fidelity competitive drills in above-ground facilities or open fields. The rules and scenarios used in these competitions also often incorporate unrealistic aspects (e.g., no gas leakage). While these features allow the competitions to be more accessible and cover more hazards, they lack the context and realism that has been shown to improve training [3]. Other traditional training methods, such as full-scale Mine Emergency Response Drills (MERDs) are more immersive, but are expensive and resource-intensive, limiting their frequency and accessibility. Virtual reality (VR) training may be a promising alternative or supplement.

1.2 VR as Effective Training

Previous research has shown that effective training is engaging, authentic, and understandable and includes

✉ Jennica L. Bellanca
JBellanca@cdc.gov

¹ Pittsburgh Mining Research Division, National Institute for Occupational Safety and Health (NIOSH), Centers for Disease Control and Prevention (CDC), 626 Cochrans Mill Road, Pittsburgh, PA 15236, USA

opportunities to demonstrate, practice, debrief, and assess [4–6]. VR is a mechanism that supports all these characteristics. Research has shown that immersive VR training helps increase engagement, performance, and retention [7, 8]. Immersion and the added realism of the VR have also been shown to increase saliency by eliciting more emotional responses from the participants [9]. From a logistical standpoint, VR is a good training modality because it provides a safe means to simulate situations that would otherwise be too dangerous or expensive, and it provides a hands-on experience that allows objective performance measurement.

1.3 VR in the Mining Industry: Slow Adoption and Challenges

While VR has proven effective for training and assessment in various industries—such as the military [10]—its adoption within the mining industry has been slow. Research and development of VR applications for mining began about thirty years ago [11] with many specifically addressing mine safety training [12–14], but their scope and application was limited. Since then, new applications have been developed as summarized in a recent review and include incident reconstruction simulations, hazard awareness training, and equipment training [15]. These applications have ranged from non-immersive desktop programs [16, 17] to head mounted displays (HMDs) and treadmill setups [18], full-scale equipment simulators [19], and large theater implementations [20]. Why haven't these interventions been widely adopted?

Previous research has identified numerous barriers and challenges to the successful implementation of VR systems into mine safety training programs. These include content, cost, portability, user acceptance, program integration, and limited industry collaboration [21–28]. Many of the previously identified applications have limited content—potentially making them less engaging and impactful because sustained learning and engagement relies on fresh content. (i.e., the “one and done” problem) —which can make the resource investment needed less desirable as well. While VR equipment costs have come down significantly in recent years, hardware costs can still be prohibitive. Furthermore, the development costs for additional training content can be far greater than the hardware itself [29]. Travel is also another cost barrier, especially for permanent installations where trainees and trainers may have to travel long distances to get to the facility [25]. System design is another critical factor for successful implementation. System access, ease-of-use, comfort, and perceived benefits have all been previously identified as barriers to user acceptance [30]. Lastly, previous research identified the need for dedicated staff with some specialized training to set up, maintain, and operate

these systems [31], suggesting that the design of the interventions may have been too complex for the available implementation resources. To prevent inefficiencies and future failures, further research on VR implementation is essential.

1.4 Implementation Science

Implementation science (IS) is an expanding field that focuses on translating research findings into practical actions within community settings. IS research is defined as “the systematic investigation of the use of strategies to enhance adoption, integration, and sustainment of evidence-based health interventions in clinical and community settings to improve individual and population health” [32]. IS methodology asks researchers to consider how their findings could be used throughout the project cycle. The purpose of incorporating IS strategies into the development and dissemination of innovations is to clear and shorten the “pipeline” from research to practice. As summarized in Guerin et al., IS methods have been shown to be effective in hastening this translation in several disciplines, but critical gaps persist in the field of occupational safety and health (OSH) [32]. Furthermore, while IS frameworks have helped to facilitate and evaluate the translation of research into practice for several decades, such frameworks have been predominantly utilized for the post-hoc evaluation of implementation efforts [33]. Instead, Glasgow et al. advocate for the rapid and repeated use of IS strategies to inform iterative adjustments to the intervention and better facilitate the translation of research into practice [33]. This approach was successfully used in a rapid pre-implementation evaluation to identify key design factors and implementation strategies for a family engagement navigator program during COVID-19 [34]. Skivington et al. also highlight that engaging stakeholders and identifying uncertainties early can improve the feasibility and acceptability of an intervention [35]. They argue that early and continuous engagement enables iterative adaptations and refinements, ensuring the intervention better fits its intended context.

1.5 Consolidated Framework for Implementation Research

The Consolidated Framework for Implementation Research (CFIR) is a comprehensive IS framework designed to help identify factors that influence implementation success. CFIR was first introduced in 2009 [36] and has been used in a wide range of studies [37] and continues to be updated and used today [34, 38]. The CFIR 2.0 is made up of five domains—Innovation, Outer Setting, Inner Setting, Individuals, and Implementation Process—that each include a variety of constructs. Table 1 describes these domains through

Table 1 Consolidated framework for implementation research (CFIR) 2.0 domains^a, planning questions^b, and constructs^a

Innovation	Is this intervention superior to status quo?
Constructs	Source, Evidence-Based, Relative Advantage, Adaptability, Trialability, Complexity, Design, Cost
Outer Setting	Why is it important to implement this intervention now? Are there regulatory or environmental pressures?
Constructs	Critical Incidents, Local Attitudes, Local Conditions, Partnerships & Connections, Policies & Laws, Financing, External Pressure
Inner Setting	Will this intervention fit the system? Is it feasible?
Constructs	Physical Infrastructure, IT Infrastructure, Work Infrastructure, Relational Connections, Communications, Culture, Tension for Change, Compatibility, Relative Priority, Incentive Systems, Mission Alignment, Resources, Access to Knowledge and Information
Individuals	Does the staff have the skill and the will to deliver the intervention?
Constructs	High-level Leaders, Mid-level Leaders, Opinion Leaders, Implementation Facilitators, Implementation Leads, Implementation Team Members, Other Implementation Support, Innovation Deliverers, Innovation Recipients
Implementation Process	How is work affected by the intervention? What is needed to implement the intervention
Constructs	Teaming, Assessing Needs, Assessing Context, Planning, Tailoring Strategies, Engaging, Doing, Reflecting & Evaluating

^a As described in [39]; ^b Adapted from [40]

adapted planning questions [40] and lists the updated constructs [39]. The CFIR framework has been shown to be especially useful in identifying adoption and implementation barriers across each domain that can be directly mapped to implementation strategies [41]. Furthermore, Eaton et al. [38] suggested that an early structured pre-implementation evaluation can be beneficial in identifying actionable barriers and facilitators for future widespread adoption and implementation efforts. Some strategies identified from previous research include involving stakeholders at the outset, engaging subject matter experts to create meaningful content, piloting the intervention with subject matter experts, evaluating fidelity, usability, and acceptability with end users, and studying the effectiveness of the intervention. However, there are limited documented uses of IS frameworks in OSH. One of the few is Tinc et al.'s application of CFIR to identify barriers to and facilitators for the uptake of an evidence-based intervention in agriculture safety [42]. These researchers found that CFIR factors such as “access to knowledge and information,” “leadership engagement” (Inner Setting), and “engaging” and “reflecting and evaluating” (Implementation Process) were significantly associated

with positive intervention outcomes, suggesting the CFIR framework might be useful in other areas of occupational and public health.

1.6 VR Mine Rescue Training (VR-MRT)

Bringing together their expertise in mine rescue, training, and immersive development, NIOSH researchers have developed a VR training framework—VR Mine Rescue Training (VR-MRT). VR-MRT is a single or multiplayer VR application designed to supplement current mine rescue training. The platform focuses on scenario-based training with the goal of improving mine rescue team members' procedural, collaborative, and problem-solving skills with a focus on decision making. The trainees can visualize and interact with a mine environment using a VR headset (e.g., Meta Quest 2 and 3) and work through scenarios together with their teammates. VR-MRT was initially described in Bellanca et al. [1], but now consists of five modules: Scenario Editor, Simulation Module, Director Module, Spectator Module, and Debrief Module. The Scenario Editor allows trainers to create their own content through a drag-and-drop interface. Trainers can either use the built-in room-and-pillar style tile sets (i.e., coal, stone) that snap together or import their own geometry (e.g., LiDAR, photogrammetry). In the mine geometry, trainers can place both built-in and custom objects and hazards. They are also able to set up static ventilation zones as well as a dynamic ventilation node network that runs on NIOSH's MFIRE [43]. The Simulation Module allows one or more trainees to experience the scenarios. Trainees are either co-located or remote. They can freely walk around and interact with the environment using their tools (e.g., sound the roof) or collected objects (e.g., hang curtains). The Director Module is a desktop-based mode that allows trainers to facilitate training sessions. Trainers can select which scenarios to run, set up player configurations, monitor trainees' progress, and make changes and additions in real time (e.g., add objects, change ventilation). Similarly, the Spectator Module is run on a desktop. The Spectator Module gives observers a birds-eye view of the simulation. This module is intended for mine rescue judging and other observers. Lastly, the Debrief Module enables playback of simulation sessions using the generated log file for an after-action review. The Debrief Module includes both a 2D and 3D view. The 2D view displays all the users' actions and movements, the map man's map, as well as the environmental conditions throughout the session (e.g., air flow, gas concentrations). The 3D perspective view depicts the trainee avatars, their motions, and their interactions to capture how and what they did. Both views can be played back continuously and scrubbed through. See Bellanca et al. for additional technical details [1].

NIOSH researchers are currently finalizing the development of VR-MRT through a multi-year evaluation effort using the RE-AIM evaluation framework as a case study for the use of implementation science [44]. The parent project of this study was conceptualized with the five dimensions—**Reach, Effectiveness, Adoption, Implementation, Maintenance**—to enhance the potential for successful translation of findings into a practical solution. In this case, researchers are using the VR-MRT platform to better understand barriers and challenges to VR training adoption and implementation in the mining industry, helping to facilitate the use of this program and inform the future design and implementation of other immersive applications for training. While RE-AIM can be useful during the implementation planning and execution stages, it emphasizes the evaluation of the overall impact and sustainability of the intervention. To better fit the current phase of the development and implementation process, researchers are utilizing a complimentary IS framework—the CFIR 2.0 [39]. Results of the first pre-implementation evaluation have captured the two antecedent assessments constructs “acceptability” and “appropriateness,” as recommended by Proctor et al. [45, 46]. These constructs are defined as [47]:

- Acceptability: the extent to which an innovation is perceived as agreeable, palatable, or satisfactory.
- Appropriateness: the perceived fit, relevance, or compatibility of the innovation and/or the perceived fit of the innovation to address a problem or issue.

As described in Bellanca et al., surveyed mine rescue team members were overwhelmingly positive and found VR-MRT to be acceptable, usable, and immersive with limited concerns about simulator sickness [1].

2 Objective

The objective of this study was to complement the previous study and complete the pre-implementation evaluation using the CFIR 2.0 framework. First, researchers aim to assess the acceptability and appropriateness of VR-MRT for mine rescue training. Secondly, researchers aim to identify actionable barriers and facilitators to the adoption and implementation of VR safety training more generally. These results are intended to allow NIOSH researchers to preemptively eliminate or mitigate identified challenges prior to the larger evaluation efforts of VR-MRT. These results can also be used to inform stakeholders of potential strategies that they can adopt to improve implementation of any immersive training. This paper builds upon earlier pre-implementation

efforts conducted by NIOSH to gather technical feedback from development partners such as the Mine Safety and Health Administration (MSHA), as well as end-user feedback evaluating VR-MRT’s acceptability, feasibility, and usability [1].

3 Methodology

3.1 Data Collection

As a part of a larger evaluation effort to better understand the barriers and challenges to implementing VR mine safety and health training, researchers conducted a pre-implementation, mixed methods study including surveys with mine rescue teams and two rounds of semi-structured interviews. The protocol was reviewed and approved by the Centers for Disease Control and Prevention (CDC) as exempt human subjects research¹ and reviewed for public burden and cleared by the Office of Management and Budget (OMB).

The surveys and first set of interviews were conducted with mine rescue team members and trainers respectively—would-be innovation recipients and deliverers—in August and September of 2022 following a technical demonstration of the VR-MRT platform. Part of this data set was previously published [1]. The second set of interviews was conducted across all levels of a large organization that was interested in adopting VR-MRT. These interviews were conducted in November 2022. Again, all participants participated in a demonstration of VR-MRT prior to the interview. Table 2 describes the breakdown of the participants’ demographics including their experience in their current positions, if they have ever responded to a mine emergency, if they had experience with VR, and whether they identified as a decision maker within their organizations.

3.1.1 Surveys

Following the completion of the technical demonstration of VR-MRT, mine rescue team members completed a survey about their experience. The survey included the following multiple choice and open-ended questions about acceptability and implementation strategy:

- Did you enjoy participating in today’s simulation and debrief exercise? (i.e., yes, no)
- Given the opportunity, would you be interested in participating in virtual mine rescue contests *in addition to*

¹ See 45 C.F.R. Part 46.104.

Table 2 Participant demographics and experience

	Count (N)	Median Position Exp. (yrs.)	Mine Rescue Experience		Virtual Reality Experience		Decision Maker	
			Yes	No	Yes	No	Yes	No
Mine Rescue Teams								
Recipients ^d	124	7.0	53%	47%	40%	60%	N/A	N/A
Deliverers	7	15.0	N/A	N/A	14%	86%	14%	86%
Organization								
Deliverers	4	8	N/A	N/A	0%	100%	50%	50%
Facilitators	3	11	N/A	N/A	0%	100%	67%	33%
Mid-Level Leaders	4	7	N/A	N/A	0%	100%	100%	0%
High-Level Leaders	2	2.75	N/A	N/A	0%	100%	100%	0%

N/A = not measured; d = survey participants

traveling to a physical location to participate? (i.e., yes, maybe, no) Why or why not?

- Given the opportunity, would you be interested in participating in virtual mine rescue contests *instead of* traveling to a physical location to participate? (i.e., yes, maybe, no) Why or why not?

The survey also included three yes or no questions about mine rescue experience and VR experience:

- Do you have any mine rescue experience in a real mine emergency underground and under apparatus?
- Have you ever responded to a real mine emergency as part of a mine rescue team, but your team did not go underground?
- Have you ever experienced VR using a head mounted display (HMD) before today?

3.1.2 Interviews

All interviews were conducted in person with a few follow-up phone calls due to scheduling conflicts. Prior to the start of the interview, all participants provided oral consent to participate in the research. Each interview was conducted individually. The interviews were conducted with one or two researchers where both researchers took notes. The interviews lasted between 20 and 60 min and contained questions to capture the participants' perspective about VR-MRT and its implementation. Example questions include:

- What, if any, value do you think VR simulations like VR-MRT bring to mine rescue training?
- What do you see as the biggest barriers to using training like VR-MRT?
- In your opinion, would your organization support the use of training like VR-MRT?
- In your opinion, does your organization have the resources to conduct training like VR-MRT?

- Do you have any suggestions to improve VR-MRT in terms of ease of adoption/use?

3.2 Data Analysis

3.2.1 Surveys

Quantitative analysis of the survey data was conducted using SPSS statistical software (version 26, IBM), where three main analyses were performed. First, a series of Chi-square tests of independence were performed to determine whether participants' responses (i.e., yes, maybe, no) to the implementation strategy (i.e., Instead of, In Addition to) varied as a function of their mine rescue experience or VR experience (i.e., yes, no). Participants were considered to have mine rescue experience if they answered "yes" to either of the mine rescue experience questions. Since no significant relationship was found, these covariates were excluded from further analyses. Secondly, a Chi-square test of independence was performed to determine if the participants were interested in VR (i.e., yes, maybe, no). General VR interest was determined by the highest level of interest in VR from both implementation strategy questions. For example, if a participant responded "no" to "instead of," but "yes" to "in addition to" it would be a "yes" for general VR interest. Lastly, a marginal homogeneity test was used to assess whether participants preferred one implementation strategy over the other. This within-subjects comparison examined the change in responses from "instead of" to "in addition to." Missing data were excluded on a case-by-case basis ($N=107$). Significance was set at $\alpha \leq 0.05$ for all tests. Because the qualitative survey responses were brief and sometimes incomplete, no formal analysis was conducted. Direct quotes are included as anecdotal support.

3.2.2 Interviews

Two researchers analyzed the interview notes from all 20 interviews using a combination of deductive and inductive

strategies. For this study, researchers deductively applied the five domains and 45 constructs (Table 1) of the CFIR 2.0 framework [39] to the data. The researchers used the framework guidance [47] and the planning questions from a previous study [40] as a basis for the codebook. From there, the researchers used a constant comparison method [48] to identify “themes” made up of actionable barriers and facilitators for each construct. To do so, the two researchers first coded two of the interviews together—one mine rescue trainer and one organizational representative. The researchers then divided up the remaining interviews and coded them independently. The researchers met periodically while coding to refine the construct and theme definitions. 100% agreement was achieved through discussion.

3.3 Other Pre-Implementation Activities

An important but sometimes overlooked aspect of IS is the criticality of ensuring that the innovation is well designed for implementation prior to deployment and dissemination at scale. In addition to the data collection described above, NIOSH has been engaging in additional antecedent assessment activities as defined in the CFIR 2.0 framework. These activities align with the constructs of acceptability and appropriateness proposed by Procter et al. [45, 46].

Since the project’s inception, NIOSH researchers have relied on internal and external subject matter experts to conceptualize and guide the development of VR-MRT. Development began as a partnership with the Mine Safety and Health Administration (MSHA) in 2020, and the two organizations have maintained a cooperative relationship throughout the development process. Additionally, NIOSH has developed and sustained strong relationships with multiple state agencies, mine operators, universities, mine rescue teams, and myriad other stakeholders.

Specifically, researchers engaged in several pilot activities to understand the feasibility of long-term implementation including a VR mine rescue contest, a university implementation, and a general safety training. Researchers recently co-hosted a VR mine rescue competition with collaborators from the Pennsylvania Department of Environmental Protection. The contest involved six teams completing at least one 90-minute mine rescue problem in VR-MRT. This contest was held at NIOSH’s Bruceton research facility and took place over a three-day period in September 2024. All teams were able to successfully complete the problem, and four of the six teams chose to extend their visit to complete a second 90-minute problem. NIOSH is also working with the West Virginia University Department of Mining Engineering to incorporate VR-MRT into their academic curriculum and outreach activities. University staff have helped improve the hardware specification,

documentation, and software design through their testing and suggestions. The staff have even become proficient at running the system on their own. Lastly, researchers collaborated with an underground stone mine to develop and run a VR hazard identification training for use during the mine’s “Stand-Down for Safety” day. The simulation demonstrated the utility of VR-MRT beyond mine rescue and the ability to provide site-specific training incorporating LiDAR scans of the mine.

4 Results and Discussion

4.1 Antecedent Assessment: Acceptability, Appropriateness

By talking directly to the mine rescue team members—the innovation recipients—researchers were able to gain a better understanding of the acceptability and appropriateness of VR-MRT for mine rescue training. 100% of the respondents indicated that they enjoyed the experience, suggesting that the demonstrated Simulation Module of VR-MRT was acceptable.

Results suggest that opinions about VR implementation strategy did not vary with mine rescue or VR experience. The Chi-square tests of independence revealed no significant association between participants’ mine rescue experience and their responses to either of the implementation strategies (Addition to: $\chi^2(2)=4.212$, $p=0.122$; Instead of: $\chi^2(2)=5.428$, $p=0.066$). This was also true of participants’ VR experience (Addition to: $\chi^2(2)=2.727$, $p=0.256$; Instead of: $\chi^2(2)=0.871$, $p=0.647$). Because of this result, the mine rescue and VR experience variables were not included in any further analysis.

Results also suggest that mine rescue team members are interested in VR. The Chi-square test of independence revealed that the responses were significantly different than chance ($\chi^2(2)=93.622$, $p<0.001$). As shown in Fig. 1, most of the participants reported that they were interested in VR (76.6%) compared to only 13.5% saying “maybe” and 9.9% saying “no.” These strongly positive responses also support the idea that VR training for mine rescue is both acceptable and appropriate.

Digging deeper into preferences, the data suggests that mine rescue team member participants prefer to use VR in addition to traditional training. The marginal homogeneity test indicated a significant difference in individual participant’s responses to each implementation strategy (MH=14.000, $p<0.001$). As shown in Table 3, 38.7% of participants preferred implementing VR in addition to traditional training as opposed to implementing it instead of traditional training.

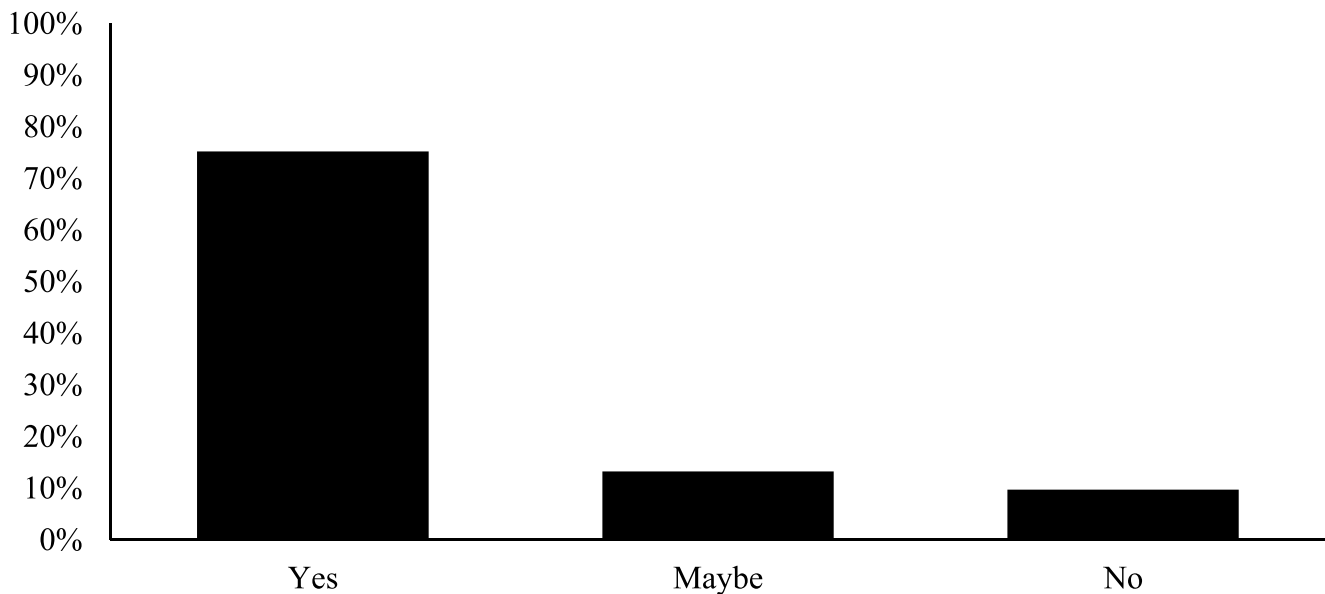


Fig. 1 Graph depicting the percentage of mine rescue team member respondents that would be interested in virtual reality in general ($\chi^2(2)=93.622$, $p<0.001$)

Table 3 Crosstab of responses by implementation strategy (marginal homogeneity (MH)=14.000, $p<0.001$)

		In Addition to		
		No	Maybe	Yes
Instead of	No	9.4%	0%	30.2%
	Maybe	0.9%	12.3%	8.5%
	Yes	0	1.9%	36.8%

N = 106

The positive quantitative data was supported by comments from the team members. For example, they stated that VR was quicker and more accessible because it did not require as much physical exertion and allowed participants to focus on their analytical skills. Many interviewees also stated that they really liked the idea that VR training could simulate dangerous situations while being “hazard free.” Lastly, participants discussed how they liked that the “virtual rescue simulation provides actual experience.” The respondents that were not interested in participating in a VR contest, especially instead of traditional training, cited concerns about how it would be implemented and how it might replace traditional contests. One team member said that “community is a huge part of mine rescue,” presumably concerned about not getting to travel and meet up with other teams if they switched to VR contests. Others were concerned that VR did not incorporate “the physical challenge” of mine rescue.

Overall, the quantitative and qualitative data suggests that mine rescue team members were excited about and interested in the scenario-based training offered by VR-MRT. They would prefer to see it as a supplement. Importantly,

these findings also add to the very positive fidelity, usability, and acceptability previously reported [1]. They also suggest that the platform would fit well into existing curricula, and that the mine rescue community accepts it.

4.2 Implementation Facilitators and Barriers

Diving deeper into stakeholders’ perspectives, the semi-structured interviews helped researchers identify many of the barriers and facilitators of implementing VR training using the CFIR 2.0 Framework. Researchers found all five CFIR domains and 26 of the 45 constructs to be relevant, and the thematic coding resulted in 37 unique barriers/facilitators. The following sections describe the results by domain (See Table 1).

4.2.1 Innovation: Is this Intervention Superior To Status quo?

Overall, there was excitement from participants of all types (e.g., mine rescue, organizational) and levels (e.g., high-level leaders, mid-level leaders, deliverers, team members) about the Source, Relative Advantage, Trialability, and Adaptability of VR-MRT. Most of the feedback was positive in support of the innovation. However, participants also mentioned barriers related to Adaptability, Complexity, and Cost. Table 4 lists the identified constructs and themes from the data with paraphrased examples and actions that researchers plan to or have already taken to support the facilitators and mitigate the barriers.

Table 4 Innovation domain constructs, facilitators/barriers, and supporting evidence

Construct	Facilitators/Barriers	Feedback	NIOSH Actions
Source	Trustworthiness	NIOSH is good.	History of effective training [20, 49]
Evidence-Base	Domain Effectiveness	Need to show value.	Future effectiveness research
Relative Advantage	Logistics	Can increase training repetitions. Offers options, flexibility to train remotely (e.g., COVID-19, other hazards). Could save time and we could do other things.	Built-in logging and debrief Future implementation research
	Cost	Long-term cost-savings.	Commercial hardware
	Content	There are one million uses for new people (e.g., basic mining principles). Allows mine-specific training.	Added ability to import custom content Including content from all commodities
	Safety	Can do [things] that would otherwise be dangerous, enhances training.	Adding accident recreations
	Appeal	Good for a new generation of students. VR means less classroom time.	Pilot university implementation (e.g., student outreach)
	Realism	VR allows trainees to see that actions make a difference.	
	Assessment	VR-MRT would be good for assessment (i.e., automatic scoring).	Adding automatic mine rescue scoring
	Physical Training	Team is not under apparatus.	Potential to adapt rebreather to fit with HMD
	Face to Face Interactions	Missing team unity, interaction, and camaraderie when not together. MERDs are better for BO to CC for training communication.	Future implementation research
	Equipment Availability	Class size might be an issue.	Future implementation research
Adaptability	Simulator Sickness	Sim sickness might be a concern (e.g., thought I would get motion sick, but didn't).	Modality proven [1]
	Content	Good for simulated inspections and different mining methods (e.g., longwall). VR-MRT can create site-specific training (e.g., custom assets, environments). Would want long (e.g., fatigue, stress) and short scenarios (e.g., small segments). VR is limited to what you can program; every operation is different.	Custom content import Added content from all commodities Added surface content Developed Scenario Editor
	Delivery Mechanism	Different modalities (e.g., desktop, cast to screen rather than HMD). Different set-up spaces (e.g., size, conditions). Add multiple entry searches (i.e., 2 × 2 exploration).	Updated Spectator Module Developed Scenario Editor
Trialability			Pilot safety training Pilot university implementation
Complexity	Technology Aversion	Resistance to the technology. Too much time to train the trainers and the trainees. Need contractor for tech modifications and maintenance. Needs to just work (e.g., there were technical issues with the calibration).	University collaboration (i.e., less tech resistance) Commercial hardware
	Scenario Creation	Need Unity training for building scenarios. Concerns about development time and getting content.	Developed Scenario Editor Incorporated easy file sharing
	Execution	Too much training time. Setup is a challenge, too much time. Would need tech support.	Future implementation research
Cost	Cost	Cost of equipment is general concern.	Commercial hardware VR-MRT public release

Table 4 (continued)

Construct	Facilitators/Barriers	Feedback	NIOSH Actions
Design	Additional Interactions	Add additional task training (e.g., W65 rebreathers, rock dusting, first aid). Add more instruments (e.g., anemometer, thermal imaging cameras).	Added smoke tube Added patient interaction (e.g., donning rebreather)
	Additional Features	Add fire suppression on UG equipment and components. Add smoke (e.g., idea of taking light off and could see better in smoke too).	
	Fidelity	4D interactions (e.g., heat, wind, weight of equipment).	
	Additional Instructions	Need better teleport instructions to avoid disorientation.	Future implementation research

NIOSH National Institute for Occupational Safety and Health; *VR-MRT* VR Mine Rescue Training; *BO* Briefing Officer; *CC* Command Center; *HMD* Head Mounted Display; *UG* Underground

As evidenced by previous publications and recognized by the interview participants, a sense of trust and understanding that VR has the potential to improve mine safety and health training was apparent. Though opinions about NIOSH as the developer of VR-MRT were not explicitly solicited—the only direct statement recorded was “NIOSH is good”—some level of trust in NIOSH can be inferred by the willingness of the teams to participate in the demonstration and the overwhelmingly positive responses to the surveys and interviews. Furthermore, NIOSH has been working on immersive training for decades, creating products that offer both the realism and engagement levels that are critical to be effective [1, 13, 20, 23, 26, 28, 49]. However, one participant underscored the need to have effectiveness data specifically for this training. Researchers plan to address this through additional effectiveness and implementation studies for mine rescue training and safety training in general.

Participants were also predominantly positive about the Relative Advantage of VR-MRT. Participants describe the benefits in terms of logistics, cost savings, content, realism, safety, appeal, and the ability to assess trainees. Many of the participants talked about how VR training is more efficient, allowing them to complete more repetitions and the possibility to do other training in the time saved. When compared to the field-based scenarios, there is minimal set-up time between problems; VR-MRT allows trainers to load a new scenario in seconds as opposed to the 30 + minutes it would take to reset a field. They also noted that the breadth and depth of the content could cover “one million things,” making it better than the fixed content of videos or presentations typically used during new miner or annual refresher training (30 C.F.R. Part 48/46). Almost all the participants also identified the realism of VR-MRT as a major benefit. One person specifically mentioned that VR is better because it “allows trainees to see actions make a difference.” Several other participants mentioned that the ability to “experience” things that would be dangerous to do or see in real life is important. This not only reduces risk for trainees but also increases the amount of practice they receive with

dangerous tasks, which the literature has shown to improve both learning and retention [5]. Another point that participants brought up was the appeal of VR as a medium that is good for the next generation of students that would rather be physically doing something as opposed to sitting in a classroom. NIOSH researchers are acting upon this sentiment in their university implementation pilot, where VR-MRT is being used in both classroom and outreach events. Lastly, participants acknowledged the advantage of being able to objectively assess trainees. Again, this is well documented in the literature as a critical component to effective training [4]. NIOSH researchers plan to further integrate quantitative assessment in VR-MRT through the automatic mine rescue scoring as the development is finalized.

Participants balanced their positive feedback to VR-MRT with a discussion of the potential implementation challenges as barriers to adoption. Participants discussed concerns around VR-MRT as a replacement for current training in that (1) remote contests would reduce team networking and team camaraderie and (2) VR-MRT lacked certain physical aspects such as being able to wear a breathing apparatus. Researchers plan to address these concerns in a few different ways. First, VR-MRT is intended to supplement existing mine rescue training with a focus on decision making. It is not intended to replace hands-on or in-person training. Additionally, the intended deployment mechanism for VR-MRT is for the team to be collocated (i.e., in the same physical space) and remote practice is intended as a backup, which incidentally, was mentioned as an important facilitator for adoption. Furthermore, the researchers would like to see VR-MRT added as an additional event at mine rescue competitions. This would still allow teams to get together and interact while also capturing the realism and experience of VR. Lastly, researchers have spoken to breathing apparatus manufacturers about the potential to make a half mask that would fit below the HMD. If completed, this would allow team members to get apparatus wear time during VR-MRT training and incorporate some of the physical aspects of mine rescue.

The complexity of the innovation was also identified as a potential adoption barrier for VR-MRT. Participants spoke about resistance to technology, concerns about execution and maintenance, and the difficulties of generating new content.

Resistance to change and difficulties in execution were discussed by all types and levels of participants. As excerpted in Table 4, the concerns focused on not wanting to use the technology, the technology being too difficult, the intervention being too time consuming, and concerns over the lack of support needed to implement and maintain its use. Resistance to technology occurs for many of the same reasons as resistance to organizational change in general: fear of loss, lack of trust, low tolerance for change, and differing perceptions [50]. However, these may differ between individuals as well as organizations. Techniques for reducing resistance to change vary widely. When implementing VR training it will be important to consider the use of these techniques based on the type and source of resistance. These techniques include both positive and negative reinforcement like education, communication, participation, facilitation, and support as well as negotiation, manipulation, co-optation, and coercion [51]. Education, communication, and participation may be particularly helpful in the case of VR-MRT. As seen in the usability data, users with VR experience felt that they would need significantly less support and prerequisites to use the system [1], suggesting that exposure and training could address some of the barriers. Familiarity and support are also some of the reasons that the development team has chosen to use commercially available hardware. In the second quarter of 2024, Meta had 74% of the global immersive hardware market share [52], increasing the likelihood that potential trainees and trainers have had exposure to the hardware. The large user base also provides a large support community which can be helpful in addressing maintenance and support concerns. Lastly, using commercial hardware has the greatest likelihood of reducing the overall system cost. Regardless of the change management strategies employed, effective planning and a realistic, achievable timeline is critical to successful implementation of an innovation [50].

To address the barrier of content creation, NIOSH researchers continue to make software improvements. Specifically, researchers have added a new Scenario Editor module. This functionality will allow users to create new scenarios quickly and easily with a drag-and-drop interface. Additionally, researchers have added the ability to add custom environments and objects. This expands the range of training scenarios that VR-MRT can cover. Lastly, researchers are working to include additional commodity-specific items (e.g., underground metal mining, surface). The Scenario Editor module has been piloted with great success,

where university staff have been able to make their own content for classroom activities.

4.2.2 Outer Setting: why now?

As shown in Table 5, interview participants discussed all the Outer Setting constructs except for External Pressure. They identified relevant points that can be both facilitators and barriers to the implementation of VR-MRT.

Related to the Policies and Laws construct, interviewees focused on compliance. They suggested that VR-MRT could be adapted to include general mine safety and health content for both new miner and annual refresher trainings required by law (30 C.F.R. Part 48/46). Many also expressed interest in incorporating a virtual mine rescue contest option to satisfy the 30 C.F.R. Part 49 contest requirement. This aligns with the 38.7% of mine rescue team members who also said they would be interested in using VR-MRT instead of traditional mine rescue training (Table 3). Since these interviews, NIOSH has successfully hosted a VR mine rescue contest, fully incorporating all the features needed to create and score scenario-based problems. At this event, the possibility of VR-MRT serving as a substitute for at least one traditional contest was raised by the participating teams, citing added benefits and greater applicability. As a first step towards adoption, NIOSH plans to work with mine rescue contest hosts to incorporate VR-MRT as an additional competitive event. Researchers are also exploring the development of automatic scoring for mine rescue problems. Both could enhance the likelihood that VR-MRT contests can be seen as a suitable, and in some ways, preferable alternative to traditional mine rescue contests.

NIOSH researchers have strong industry and academic partnerships and connections as exemplified by the pre-implementation efforts described above. However, interview participants discussed the need for more formal relationships and access to the technology. One participant talked about not knowing who to call or how to get the help they need to implement VR-MRT. NIOSH plans to combat this barrier by helping to establish and maintain VR working groups and connecting stakeholders.

Speaking about the Local Conditions construct, participants also identified barriers related to politics as well as software and hardware availability and accessibility. Politics often play an influential role in federal programs and initiatives because priorities can change as administrations change. Several interviewees mentioned that the changing of political priorities could affect uptake either positively or negatively. Interviewees also talked about barriers such as the technology's accessibility for all mineworkers (e.g., literacy, physical limitations) and the overall availability of the platform. Researchers are working to address these

Table 5 Outer setting domain constructs, facilitators/barriers, and supporting evidence

Construct	Facilitators/Barriers	Feedback	NIOSH Actions
Policy & Laws	Compliance	VR-MRT could be used to teach required training (e.g., 30 CFR parts 48, 46, & 49). MSHA might not accept VR training for contest compliance (e.g., we're stuck with physical contests). There is legislation in Queensland, Australia that requires this.	Working with MSHA for approval Conducted VR Mine Rescue Contest
Partnerships & Connections	Community	Need for relationships and access to the technology. Need to be able to call people and build relationships necessary to use VR.	Establishing VR working groups Building relationships with VR users
Local Conditions	Politics	Political appointees and other politics dictate federal support.	Conducted VR Mine Rescue Contest Adding automatic mine rescue scoring
	Accessibility	Aging workforce, those with literacy or other challenges might resist or be unable to use VR-MRT.	VR-MRT design review
	Availability	Haven't used VR yet because it is new and not yet available (e.g., nothing like that in Africa).	VR-MRT public release
Critical Incidents	Serious Event	COVID-19 delayed VR development in Australia. COVID-19 and other serious events can make remote training a necessity (e.g., it's a different world today).	Future implementation research
Financing	Funding	Might be a good avenue for states' grants. Some governments (e.g., New South Wales, Queensland) provide funding for mines rescue training.	Encourage stakeholders to apply for grants Future implementation research

NIOSH National Institute for Occupational Safety and Health; VR-MRT VR Mine Rescue Training; CFR Code of Federal Regulations; MSHA Mine Safety and Health Administration

concerns through the development of training scenes that could be included with the software. Researchers are also reviewing the software to ensure it follows good design practices such as making the interactions simple (e.g., only two buttons), consistent (e.g., green for “grab”) and clear (e.g., visual and audio confirmation for all actions). As for availability, following the completion of the larger evaluation effort, NIOSH plans to make VR-MRT freely available on their website. Ultimately, the goal is for stakeholders to be able to incorporate VR-MRT into their own training curriculum.

Finally, participants discussed how Critical Incidents like the COVID-19 pandemic served as both a facilitator and barrier to implementation efforts. Participants discussed how the pandemic made remote options for training more salient and acceptable, but they also noted the two-year delay in the demonstration of VR-MRT at the International Mine Rescue Contest. Since this data was collected in 2022 COVID-19 was still top of mind, but more generally, the comments identify the possibility that future external events could similarly impact the mining community's ability and resources to train. Therefore, it is critical that the community take advantage of the current technological boom. The commercial investment in hardware and software for immersive training as a result of the COVID-19 pandemic has made this technology more ubiquitous and accessible than ever. To prepare for future critical incidents, mining companies may consider adopting a holistic VR training

strategy that is expandable and adaptable to meet emergent training needs rather than commissioning trainings one at a time. As described in the background, one-off trainings are typically limited in content and may use incompatible hardware and software, resulting in inefficient use of the already scarce training resources. The developers of VR-MRT tried to address this concern with the Scenario Editor Module and the ability to import custom content. The flexibility of VR-MRT described in the innovation section makes it well suited to address far more than mine rescue and using VR-MRT for multiple training applications may give it a higher potential return on investment.

4.2.3 Inner Setting: Will this Intervention Fit the system?

Given this pre-implementation interview study was not site-specific, it is not surprising that responses to questions related to the Inner Setting varied widely among respondents (Table 6). Individual mine rescue trainers were more likely to point to lack of Resources such as equipment and funding as barriers to adoption, while the organizational participants reported that access to Resources was of less concern. As discussed previously, NIOSH chose to design the system with low-cost commercially available hardware to reduce the costs, and the VR-MRT software will be free when it is released.

During the interviews, participants from the organization focused on issues of prioritization and action. They

Table 6 Inner setting domain constructs, facilitators/barriers, and supporting evidence

Construct	Facilitators/Barriers	Feedback	NIOSH Actions
Resources	Funding	Believes company has the resources.	Commercial hardware VR-MRT public release
		Funding could be a problem for some companies.	
Work Infrastructure	Equipment Availability	Have funding, but VR technology is not available. Lack of resources to acquire equipment to do this type of training.	Commercial hardware
	Personnel	Lack personnel in general. (e.g., short-staffed, as it is. I don't see how we can do all of this). Need a bigger team of personnel with dedicated time. A lot of turnover and attrition.	Future implementation research
	Bureaucracy	Procurement is difficult (i.e., it's hard to get things). Major alterations to training curriculum require different levels of approval (could be 3 months to a year).	Future implementation research
IT Infrastructure	Personnel	Need dedicated IT support for network and troubleshooting. Organization wants in-house expertise, but VR talent is hard to find in this location.	VR-MRT design review Future implementation research
	Bureaucracy	Purchase of software requires approval from IT department.	Future implementation research
Physical Infrastructure	Logistics	A lot to figure out (e.g., rooms, scheduling). Tradeoff between available space and proximity to training facilities.	Future implementation research
Communications	Transparency	Organization is siloed – no communication across levels and roles. Lack of transparency from high-level leaders (e.g., say what you mean, mean what you say). Biggest barrier is taking and accepting feedback.	Future implementation research
Relative Priority	Lack of Action	Interest in VR training is there, need to act. Organization wants to be leader in technology, but VR is not prioritized over other initiatives.	Future implementation research
	Resource Allocation	Concerns about trainer training time (e.g., trainers need time to practice with system). Need time to train the team on the tech before the actual training (i.e., lose a day of work). Hiring can be dependent upon administration priorities.	Future implementation research
Knowledge & Information	POC	Need to know who to contact from NIOSH and how	Future implementation research VR-MRT documentation
	Train the Trainer	We would need training on the system and technology. We're good in tech but need hands-on training. (e.g., better training on how to wear headset).	

NIOSH National Institute for Occupational Safety and Health; VR-MRT VR Mine Rescue Training; POC Point of contact

emphasized deficiencies in the Work Infrastructure (e.g., lack of dedicated personnel, procurement red tape), IT Infrastructure (e.g., lack of expertise, IT procurement red tape), Physical Infrastructure (e.g., space, set-up configuration), Communications (e.g., lack of transparency), and Relative Priority (e.g., time to take actions). As one participant put it, leaders talked a lot, but “you have to walk the walk.” While VR training was very attractive to this organization, the employees felt there was no clear path forward. They lacked clarity about the next steps largely because the organization was not set up to easily support a technology-heavy innovation, and for them organizational change is difficult (e.g., hiring, reallocation of space, purchasing). Researchers plan to study the implementation process further at various sites to better understand if this is a challenge across the industry. One possible solution to these barriers is following an

implementation model such as the one proposed by Endsley [53]. Using this model, an organization would intentionally step through the implementation process in a logical and open way, where feedback is continually sought and integrated into the change management process. Another possible solution would be to identify and empower an organizational change champion—“a person at any level of the organization who is skilled at initiating, facilitating, and implementing change” [54].

Common across all participants were concerns about having Access to Knowledge and Information. This pertains to a stated need by all the participants for support from NIOSH throughout the implementation process, specifically system-user guidance and train-the-trainer content were requested as well as establishing lines of communication for support. As a part of NIOSH's future implementation

research, researchers plan to take an active role in the planning and execution of implementation strategies at individual sites willing to adopt the platform. As a part of the study, researchers will offer ongoing support while evaluating the process from pre-implementation through maintenance. These initial implementation efforts will further inform future efforts and the development of supporting documentation and software updates until NIOSH support becomes less critical to successful implementation. As VR-MRT becomes more widely available, it is possible that NIOSH or other entities could offer training sessions in central locations such as mine rescue contests. Another possibility is that groups implement VR-MRT in existing regional training facilities open to all teams, enabling resources and expertise to be widely shared.

4.2.4 Individuals: Do They Have the Will and the Skill To Deliver?

If individuals will not or cannot implement an intervention, the design, pressures, and fit are irrelevant—and it will fail. Despite some concerns related to lack of IT personnel earlier, most participants focused on a lack of will to implement VR-MRT as can be seen in Table 7. Concerns related to Individual Buy-In spanned across all organizational levels including High-Level Leaders, Mid-Level Leaders, Implementation Leads, Innovation Deliverers, Implementation Team Members, and Innovation Recipients. Individual mine rescue team trainers only identified High-Level Leaders' (i.e., Corporate) support as an issue. Organizational participants were far more mixed in their responses. In general, there was an impression that High- and Mid-Level Leaders were bought-in to VR training, but only about 50% of the Deliverers were bought-in. There were also concerns that the Recipients would be hesitant to try it.

Despite the organizational leadership strongly expressing support for the adoption and implementation of VR-MRT, there were some concerns about what could be described as Lack of Action. In addition to organizational inertia, many of these concerns were attributed to competing priorities, long-term commitment, high expectations, and a lack of understanding of what it would take for successful adoption and implementation of VR-MRT (i.e., leadership was “out of touch with reality”).

To combat the organizational inertia, lack of a common vision, and lack of shared expectations, many interviewees expressed the need for champions. However, none of the organizational interviewees felt they could fill this role. They all suggested other individuals. As discussed by Warlick [54], a change champion needs to have specific skills to be successful. When looking to implement VR-MRT in the future, organizations may consider identifying and

training individual(s) to fill this role. It may also be possible for NIOSH to include some of this training in their future implementation research.

Related to Individual Buy-In, many participants also talked about Technology Aversion with both the Deliverers and Recipients. As discussed with respect to the Complexity of the Innovation, resistance to technology and change in general is a common issue. In this case, participants felt that the Deliverers and Recipients could be swayed with time and exposure, like how they eventually accepted other IT innovations (e.g., computer-based tools for mapping).

Lastly, the organizational participants discussed the need to Build the Implementation Team. They underscored the need to find the right people, align their roles, and give them time to develop working relationships to be successful.

4.2.5 Implementation Process: What Is Needed To Implement?

Although the Implementation Process domain is more applicable to site-specific implementation efforts, it contains many of the same strategies required for the appropriate design, development, and pre-implementation evaluation of the innovation. Constructs such as Teaming, Planning, Tailoring, Engaging, Reflecting and Evaluating, and Adapting all strongly align with strategies that have been employed by NIOSH during the conceptualization and development of VR-MRT. These same strategies will also be applied throughout future evaluation research to not only enhance the chances of success, but to define and measure implementation progress. One general suggestion that emerged from the responses of several interviewees across roles was the belief that for something like VR-MRT to be widely adopted and implemented, its deployment should be gradual and incremental. It was suggested that this approach could help to alleviate several of the barriers that were identified across interviewees, including Technology Aversion and Individual Buy-In as well as concerns around Resources and Personnel. This concept is captured under the Doing construct.

5 Limitations

While this pre-implementation research provides an important step in the larger implementation evaluation of the VR-MRT platform, there are some limitations of the study. First, the surveys and interviews were conducted with a relatively small sample size and may not reflect the opinions of the entire mining industry. Similarly, the sample was one of convenience and self-selected which might have caused the perceived barriers of a less motivated group to go

Table 7 Individuals domain constructs, facilitators/barriers, and supporting evidence

Construct	Facilitators/Barriers	Feedback	NIOSH Actions
High-level Leaders	Individual Buy-In	High-level leaders support it (e.g., they've all seen it and are on board). Not much corporate support (e.g., this is the biggest barrier). ^e	Community outreach (e.g., competitions) Future implementation research
	Expectations	High-level leaders need to check their expectations (e.g., Need to have vision and mutual understanding). It's overwhelming for everyone that they are trying to do everything at once.	
	Lack of Action	The organization has been talking about it for a while, but there's always been something [else]. Need a high-level champion to get money and people to make it happen. Maintenance will be a problem; management will drop the ball.	Establishing VR working groups Building relationships with VR users
Mid-level Leaders	Individual Buy-In	Mid-level leaders say they bought in, but they don't support it.	Community outreach (e.g., competitions) Future implementation research
	Lack of Action	Maintenance (i.e., upkeep) could just disappear without support from mid-level leaders.	Establishing VR working groups Building relationships with VR users
Implementation Leads	Champion	Many interviewees suggested that other individuals (i.e., not themselves) at other levels need to be champions. Individual team trainers will champion the effort but are concerned about corporate push-back/trade-offs. ^e	Future implementation research
Innovation Deliverers	Individual Buy-In	Mixed support (e.g., it's a great tool for mine rescue and mining, in general, but we have other things to do). Need to convince the trainers of VR-MRT's usefulness (e.g., maybe 50% of our instructors are into it). It's important to keep the trainers involved in implementation and seek recommendations from them. Already low morale and burnout; trainers will resist unless there is some reward. Pressure comes from outside, not from instructors (i.e., no self-motivation).	Community outreach (e.g., competitions) Future implementation research Establishing VR working groups Building relationships with VR users
	Technology Aversion	Resistance to the technology (e.g., trainers want to be technology hands-off, fear of breaking the technology). Resistance to change. (e.g., concerns about being replaced by technology). There is/was resistance to other VR trainings. Many, but not all, eventually bought in.	Community outreach (e.g., competitions) Commercial hardware
Implementation Team Members	Individual Buy-In	Need key people to be bought in across the board. The team needs to be enthusiastic about the product and process. Everyone is overwhelmed, and they need an incentive to adopt.	Community outreach (e.g., competitions) Planned future implementation research
	Building the Team	Need to get the right people involved and have an understanding of it. Need to shift roles and responsibilities across the organization. Need development group (e.g., needs to be a team effort, need time for group relationship building).	Future implementation research Establishing VR working groups Building relationships with VR users
Innovation Recipients	Individual Buy-In	Trainees aren't going to do it unless there is a reward.	Community outreach (e.g., competitions)
	Technology Aversion	Need time to get accustomed to technology (e.g., it's different). Trainees might accept it (e.g., they resisted Visio but liked it when they saw it).	Community outreach (e.g., competitions)

^eMine Rescue trainer comment; *NIOSH* National Institute for Occupational Safety and Health; *VR-MRT* VR Mine Rescue Training

undetected. Furthermore, this analysis was conceptualized exclusively across the CFIR 2.0 domains, which may have precluded the emergence of themes that exist outside the framework. However, the goal of this pre-implementation

study was to identify potential facilitators and barriers early in the process to better prepare researchers and stakeholders for future widespread implementation efforts where these limitations will be addressed. Lastly, though the barriers

and facilitators are intended to be general to VR mine safety training, the lack of exposure to other VR applications may bias the results towards VR-MRT specifically. Further study may be needed to support the generalization of the concepts identified here.

6 Conclusion

As the mining industry continues to evolve, it is critical to maintain and enhance emergency preparedness efforts, particularly in the realm of mine rescue training. VR training offers a promising avenue to supplement traditional training, making it more realistic, accessible, and effective. To better understand the challenges and barriers to implementing VR training, NIOSH researchers developed the VR Mine Rescue Training platform (VR-MRT). As a part of the pre-implementation phase of the innovation's evaluation, researchers talked to individuals at various implementation levels to assess the acceptability and appropriateness of VR-MRT and to identify actionable barriers and facilitators to the implementation of VR mine safety training in general. Researchers employed an inductive and deductive strategy based on the IS framework, CFIR 2.0. This framework helped to make potential solutions more obvious by grouping the concerns in the domain where they were most applicable.

The results suggest that VR-MRT may be acceptable and appropriate for use in mine rescue training. Mine rescue team members surveyed expressed a strong interest in using the scenario-based training offered by VR-MRT. There was also a significant preference to implement it in addition to their current training as opposed to as a substitute. Trainers and organizational employees interviewed recognized the relative advantage, trialability, and adaptability of this specific platform citing improved logistics, reduced cost, increased content, safety, appeal, and realism, and the inclusion of assessment as facilitators. However, participants also highlighted the lack of the physical aspects, reduction in face-to-face interactions, and equipment availability concerns as potential barriers to successful implementation that should be considered in the VR-MRT implementation process.

Participants also identified barriers to successful implementation of VR mine safety training more generally. Industry level potential barriers (i.e., Outer Domain) included uncertainty whether and how VR training can be used for compliance, the need for industry partnerships and support, and a need for additional funding. On the organizational level potential barriers related to work structures, specifically IT support, prioritization of VR training over other

initiatives, and ensuring personnel with the right training were available. Lastly, on the individual level, potential barriers were alignment of expectations, individual buy-in, resistance to technology, and a lack of action. These barriers reaffirmed the important role of change management strategies, good documentation and training, and establishing and building communities to support VR's continued use. Table 8 summarizes the facilitators and barriers at each level and the primary mitigating actions that NIOSH and others can take. More generally, the results also underscore the need for additional implementation research at all levels to confirm the effectiveness and the generalizability of the results as well as to empower organizations to implement VR training themselves.

Table 8 Barriers/Facilitators to VR implementation and the primary mitigating actions

Domain	Facilitators/Barriers	Mitigating Actions
Innovation	Trustworthiness, Domain Effectiveness, Logistics, Cost, Content, Safety Appeal, Realism, Assessment, Physical Training, Face to Face Interactions, Equipment Availability, Simulator Sickness	Custom content import/generation Easy file sharing Built-in logging and debrief Add automatic scoring Commercial hardware Pilot testing Identify grants/funding sources Future effectiveness research
Outer Setting	Compliance, Community, Politics, Accessibility, Availability, Serious Event, Funding	Work with MSHA for approval Conducted VR Mine Rescue Contest Establish VR working groups Build relationships with VR users Freely available software
Inner Setting	Funding, Equipment Availability, Personnel, Bureaucracy, Personnel, Bureaucracy, Logistics, Transparency, Lack of Action, Resource Allocation, Point of Contact, Train the Trainer	Documentation/Training Establish VR working groups Commercial hardware Freely available software
Individuals	Individual Buy-In, Expectations, Lack of Action, Champion, Technology Aversion, Building the Team	Community outreach Establish VR working groups Build relationships with VR users
Implementation Process	Implementation Strategies	Incremental implementation Future implementation research

Declarations

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 (NIOSH), Centers for Disease Control and Prevention (CDC). Mention of any company name or product does not constitute endorsement by NIOSH, CDC.

Conflict of interest The authors declare no competing interests.

References

- Bellanca JL, Orr TJ, Helfrich W, Macdonald B, Navoyski J, Demich B, Mechling JJ, Hoebbel C, Schmidt PE, Chasko LL (2023) Usability of Collaborative ‘VR Mine Rescue Training’ Platform. In: Application of Computers and Operations Research in the Mineral Industry (APCOM), Rapid City
- Deuel J, Salton J, Hobart C, Garretson J, Callow D (2018) Mine rescue robotics: gemini-scout – 18507. U.S. Department of Energy, Office of Scientific and Technical Information. <https://www.osti.gov/biblio/1648665>. Accessed 1 Aug 2024
- Kowalski-Trakofler KM, Barrett EA (2003) The concept of degraded images applied to hazard recognition training in mining for reduction of lost-time injuries. *J Saf Res* 34(5):515–525. <https://doi.org/10.1016/j.jsr.2003.05.004>
- Salas E, Cannon-Bowers JA (2001) The science of training: a decade of progress. *Ann Rev Psychol* 52(1):471–499. <https://doi.org/10.1146/annurev.psych.52.1.471>
- Burke LA, Hutchins HM (2007) Training transfer: an integrative literature review. *Hum Resour Dev Rev* 6(3):263–296. <https://doi.org/10.1177/1534484307303035>
- Wilkins JR (2011) Construction workers’ perceptions of health and safety training programmes. *Constr Manage Econ* 29(10):1017–1026. <https://doi.org/10.1080/01446193.2011.633538>
- Farra S, Miller E, Timm N, Schafer J (2013) Improved training for disasters using 3-D virtual reality simulation. *West J Nurs Res* 35(5):655–671. <https://doi.org/10.1177/0193945912471735>
- Allcoat D, von Mühlenen A (2018) Learning in virtual reality: effects on performance, emotion and engagement. *Res Learn Technol* 26. <https://doi.org/10.25304/rlt.v26.2140>
- Pucher PH, Batrick N, Taylor D, Chaudery M, Cohen D, Darzi A (2014) Virtual-world hospital simulation for real-world disaster response: design and validation of a virtual reality simulator for mass casualty incident management. *J Trauma Acute Care Surg* 77(2):315–321. <https://doi.org/10.1097/ta.0000000000000308>
- Burdea GC, Coiffet P (2003) Virtual reality technology. Presence Teleoperators Virtual Environ. <https://doi.org/10.1162/105474603322955950>
- Schofield D, Denby B, McClarnon D (1995) Computer graphics and virtual reality in the mining industry. *Int J Rock Mech Min Sci Geomech Abstracts* 4(32):167A. [https://doi.org/10.1016/0148-9062\(95\)97048-N](https://doi.org/10.1016/0148-9062(95)97048-N)
- Denby B, Schofield D (1999) Role of virtual reality in safety training of mine personnel. *Min Eng* 51:59–64
- Filigenzi MT, Orr TJ, Ruff TM (2000) Virtual reality for mine safety training. *Appl Occup Environ Hyg* 15(6):65–469. <https://doi.org/10.1080/104732200301232>
- Van Wyk E, De Villiers R (2009) Virtual reality training applications for the mining industry. Proceedings of the 6th international conference on computer graphics, virtual reality, visualization, and interaction in Africa, pp 53–63. <https://doi.org/10.1145/1503454.1503465>
- Van Wyk E, De Villiers R (2019) An evaluation framework for virtual reality safety training systems in the South African mining industry. *J South Afr Inst Min Metall* 119(5):427–436. <https://doi.org/10.17159/2411-9717/53/2019>
- Brown LD, Poulton MM (2018) Improving safety training through gamification: an analysis of gaming attributes and design prototypes. In: Cassenti D (ed) Advances in human factors in simulation and Modeling. AHFE 2018. Advances in intelligent systems and computing, vol 780. Springer, Cham. https://doi.org/10.1007/978-3-319-94223-0_37
- Zujovic L, Kecojec V, Bogunovic D (2021) Interactive mobile equipment safety task-training in surface mining. *Int J Min Sci Technol* 31(4):743–751. <https://doi.org/10.1016/j.ijmst.2021.05.011>
- Andersen K, Gaab SJ, Sattarvand J, Harris FC (2020) METS VR: mining evacuation training simulator in virtual reality for underground mines. In: Latifi S (eds) 17th International Conference on Information Technology–New Generations (ITNG 2020). Advances in intelligent systems and computing, vol 1134. Springer, Cham. https://doi.org/10.1007/978-3-030-43020-7_43
- Tichon J, Burgess-Limerick R (2011) A review of virtual reality as a medium for safety related training in mining. *J Health Saf Res Pract* 3(1):33–40
- Hoebbel C, Bauerle T, Macdonald B, Mallett L (2015) Assessing the effects of virtual emergency training on mine rescue team efficacy. In: Conference proceeding, Interservice/Industry Training, Simulation and Education Conference (IITSEC) Conference Proceeding. Orlando
- Stothard P (2008) Developing an enhanced VR simulation capability for the coal mining industry. UNSW School of Mining Engineering
- Stothard P, Swadling P (2010) Assessment of maturity of mining industry simulation. *Min Technol* 119(2):102–109. <https://doi.org/10.1179/037178410X12780655704806>
- Navoyski J, Brnich MJ Jr., Bauerle T (2015) BG 4 benching training software for mine rescue teams. *Coal Age* 120(12):50–55
- Bauerle T, Bellanca JL, Orr TJ, Helfrich W, Brnich M (2016) Improving simulation training debriefs: mine emergency escape training case study. In: The Interservice/Industry Training, Simulation and Education Conference (IITSEC), Orlando, 16319
- Pedram S, Perez P, Palmisano S, Farrelly M (2017) Evaluating 360-Virtual reality for mining industry’s safety training. In: Stephanidis C (ed) HCI international 2017 – Posters’ extended Abstracts. HCI 2017. Communications in Computer and Information Science, vol 713. Springer, Cham. https://doi.org/10.1007/978-3-319-58750-9_77
- Bellanca JL, Orr TJ, Helfrich WJ, Macdonald B, Navoyski J, Demich B (2019) Developing a virtual reality environment for mining research. *Min Metall Explor* 36:597–606. <https://doi.org/10.1007/s42461-018-0046-2>
- Orr TJ, Bellanca JL, Navoyski J, Macdonald B, Helfrich W, Demich B (2020) Development of visual elements for accurate simulation. In: Cassenti D (ed) Advances in human factors and Simulation. AHFE 2019. Advances in intelligent systems and computing, vol 958. Springer, Cham. https://doi.org/10.1007/978-3-030-20148-7_26
- Hoebbel CL, Bellanca JL, Ryan ME, Brnich MJ (2023) Advancing self-escape training: a needs analysis based on the National Academy of Sciences report, Improving Self-escape from Underground Coal Mines. By Pittsburgh PA: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 2023–134 (revised 06/2023). <https://doi.org/10.26616/NIOSH PUB2023134revised062023>
- Day N (2022) Cost of custom full virtual reality training. Roundtablelearning.com. <https://roundtablelearning.com/cost-custom>

- virtual-reality-training-full-vr-price-cost-factors-benefits-2022/ Accessed 1 Aug 2024
30. Engelbrecht H, Lindeman RW, Hoermann S (2019) A SWOT analysis of the field of virtual reality for firefighter training. *Front Robot AI* 6:101. <https://doi.org/10.3389/frobt.2019.00101>
 31. Gasteiger N, van der Veer SN, Wilson P, Dowding D (2022) How, for Whom, and in which contexts or conditions augmented and virtual reality training works. *Upskilling Health Care Workers: Realist Synthesis JMIR Serious Games* 10(1):e31644. <https://doi.org/10.2196/31644>
 32. Guerin RJ, Glasgow RE, Tyler A, Rabin B, Huebshmann AG (2022) Methods to improve the translation of Evidence-Based interventions: A primer on dissemination and implementation science for occupational safety and health researchers and practitioners. *Saf Sci* 152:105763. <https://doi.org/10.1016/j.ssci.2022.105763>
 33. Glasgow RE, Battaglia C, McCreight M, Ayele MA, Rabin BA (2020) Making implementation science more rapid: use of the RE-AIM framework for Mid-Course adaptations across five health services research Projects, in the veterans health administration. *Front Public Health* 8:194. <https://doi.org/10.3389/fpubh.2020.00194>
 34. Taylor SP, Short RT, Asher AM, Taylor B, Beidas RS (2020) A rapid Pre-implementation evaluation to inform a family engagement navigator program during COVID-19. *Implement Sci Commun* 1:1–10. <https://doi.org/10.1186/s43058-020-00098-2>
 35. Skivington K, Matthews L, Simpson SA, Craig P, Baird J, Blazeby JM, Boyd KM, Craig N, French DP, McIntosh E, Petticrew M, Rycroft-Malone J, White M, Moore L (2021) A new framework for developing and evaluating complex interventions: update of medical research Council guidance. *Br Med J* 374(n2061):1–11. <https://doi.org/10.1136/bmj.n2061>
 36. Damschroder LJ, Aron DC, Keith RE, Kirsh SR, Alexander JA, Lowery JC (2009) Fostering implementation of health services research findings into practice: a consolidated framework for advancing implementation science. *Implement Sci* 4:50. <https://doi.org/10.1186/1748-5908-4-50>
 37. Kirk MA, Kelley C, Yankey N, Birken SA, Abadie B, Damschroder L (2015) A systematic review of the use of the consolidated framework for implementation research. *Implement Sci* 11:72. <https://doi.org/10.1186/s13012-016-0437-z>
 38. Eaton TA, Kowalkowski M, Burns R, Tapp H, O'Hare K, Taylor SP (2024) Pre-implementation planning for a sepsis intervention in a large learning health system: a qualitative study. *BMC Health Serv Res* 24(1):996. <https://doi.org/10.1186/s12913-024-11344-x>
 39. Damschroder LJ, Reardon CM, Widerquist MAO, Lowery J (2022) The updated consolidated framework for implementation research based on user feedback. *Implement Sci* 17:75. <https://doi.org/10.1186/s13012-022-01245-0>
 40. King DK, Shoup JA, Raebel MA, Anderson CB, Wagner NM, Ritzwoller DP, Bender BG (2020) Planning for implementation success using RE-AIM and CFIR frameworks: a qualitative study. *Front Public Health* 8:59. <https://doi.org/10.3389/fpubh.2020.00059>
 41. Powell BJ, Waltz TJ, Chinman MJ, Damschroder LJ, Smith JL, Matthieu MM, Proctor EK, Kirchner JE (2015) A refined compilation of implementation strategies: results from the expert recommendations for implementing change (ERIC) project. *Implement Sci* 10:21. <https://doi.org/10.1186/s13012-015-0209-1>
 42. Tinc PJ, Jenkins P, Sorensen JA, Weinehall L, Gadowski A, Lindvall K (2020) Key factors for successful implementation of the National rollover protection structure rebate program. *Scand J Work Environ Health* 46(1):85–95. <https://doi.org/10.5271/sjweh.3844>
 43. Zhou L, Yuan L, 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
 44. Glasgow RE, Vogt TM, Boles SM (1999) Evaluating the public health impact of health promotion interventions: the RE-AIM framework. *Am J Public Health* 89(9):1322–1327. <https://doi.org/10.2105/ajph.89.9.1322>
 45. Proctor EK, Landsverk J, Aarons G, Chambers D, Glisson C, Mittman B (2009) Implementation research in mental health services: an emerging science with conceptual, methodological, and training challenges. *Adm Policy Ment Health* 36:24–34. <https://doi.org/10.1007/s10488-008-0197-4>
 46. Proctor E, Silmere H, Raghavan R, Hovmand P, Aarons G, Bunger A, Griffey R, Hensley M (2011) Outcomes for implementation research: conceptual distinctions, measurement challenges, and research agenda. *Adm Policy Ment Health* 38:65–76. <https://doi.org/10.1007/s10488-010-0319-7>
 47. CFIR Research Team-Center for Clinical Management Research (2022) The consolidated framework for implementation research. <https://cfirguide.org/> Accessed 2 Oct 2024
 48. Bradley EH, Curry LA, Devers KJ (2007) Qualitative data analysis for health services research: developing taxonomy, themes, and theory. *Health Serv Res* 42(4):1758–1772. <https://doi.org/10.1111/j.1475-6773.2006.00684.x>
 49. Connor BP, Brnich MJ, Mallett LG, Orr TJ (2016) Effective group training with computer-based virtual. *Environ Coal Age* 121(6):44–51
 50. Burchell J (2011) Anticipating and managing resistance in organizational information technology (IT) change initiatives. *Int J Acad Bus World* 5(1):19–28
 51. Robbins SP, Coulter MA (2018) Management, 14th global edition. Pearson Education, Inc., United States of America
 52. Counterpoint (2024) Global XR (AR & VR Headsets). Market share: quarterly. <https://www.counterpointresearch.com/insight/global-xr-ar-vr-headsets-market-share-quarterly> Accessed 1 Aug 2024
 53. Endsley MR (1994) An implementation model for reducing resistance to technological change. *Int J Hum Factors Manuf* 4(1):65–80. <https://doi.org/10.1002/hfm.4530040107>
 54. Warrick DD (2009) Developing organization change champions. *OD Practitioner* 41(1):14–19

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.