Evaluation of Underground Virtual Environment Training: Is a Mining Simulation or Conventional Power Point More Effective?

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Abstract. UNSW's Schools of Mining Engineering and Psychology have jointly developed high-fidelity simulations for training in the coal mining industry aimed at improving safety. These simulations have capitalised on advanced technology to move beyond replications of traditional class-room training and to implement best, evidence-based instructional practices. The present paper describes controlled experiments conducted as an initial, rigorous evaluation of the simulations by testing one small component. Specifically, a 3-D simulation of a coal mine was compared to a 2-D slide-based presentation in the acquisition, retention and transfer of a standardised operating procedure. Novices were trained to re-start an exhaust fan and were subsequently given a multiple-choice test immediately after training and then again after a retention interval of one week or more. In Experiment 1, training was conducted using the mining simulator (Group Sim) versus class-room slide presentations (Group PP). To maintain the participants' active attention, each step of the procedure was followed by a question and feedback. Experiment 2 included a third condition in which participants in the mining simulator were asked to collaborate in generating answers to the in-training questions (Group Sim+). Two weeks after the retention test in Experiment 2, the top five participants in Groups Sim+ and PP provided a hands-on demonstration of the exhaust-fan procedure. Across experiments, training in the simulator tended to yield better test scores than the class-room training, particularly in the practical, hands-on test. The positive effect of the mine simulation on acquisition, retention, and transfer of the procedure provides a foundation for further simulation-based modules, which can replicated across mine sites and provide consistent training that does not depend on the individual trainer. This replication and consistency will decrease the cost of development and ownership to a small fraction of the cost of mining.

1. INTRODUCTION

For introductory training in hazardous places such as underground mines, simulations provide an environment that, among other things, is completely safe, well-controlled for optimal instruction, and less expensive than taking trainees to the work site and interrupting production. However, high-resolution, high-fidelity simulations are themselves expensive to construct. They must be used at an optimal capacity to ensure a return on investment. Nevertheless, the cost of such facilities when compared to the loss of a human life or debilitating injury is insignificant. The key to all simulations is the interactive experience gained by the trainees. Unless the courses are carefully designed, there is no guarantee that they will efficiently or effectively engage the trainees' learning processes, especially for novices. For them, initial training in standardised procedures necessarily has to be didactic, with little scope for interaction with the environment featured in, for example, vehicle simulators. Moreover, individual training is often not feasible in terms of the availability of instructors and/or simulator time. So, the question is: does a simulation offer an advantage for introductory training over group lectures, sometimes called "death by Power Point."

Although a high-fidelity simulation may be very attractive to trainees, there is no guarantee that, in any one case, it will benefit the training. Particularly for novices, the complexity of an unfamiliar environment may hinder learning by making it difficult to identify and focus on the key features (Park, Lee, & Kim, 2009; Vermeulen, Corneille, & Niedenthal, 2008). Well-established findings concerning human information processing and memory strongly suggest that, for novices, the very limited span of human working memory and their lack of schemas in long-term memory for filtering and organising complex inputs makes their ability to learn highly vulnerable to becoming overloaded and inefficient (Owens & Sweller, 2008; Sweller, van Merrienboer, & Paas, 1998)

The present study was conducted to compare the effectiveness of a 3-D, 360^{o} simulation of a mine versus a 2-D Power-Point presentation in promoting the acquisition, retention, and transfer of a standardised operating procedure, specifically, restarting an exhaust fan and testing its operation after a power outage.

This study was aimed at identifying a worthwhile experimental procedure, and hence, the exhaust fan procedure was chosen as it is a relatively simple operation that must be performed in an exact sequence. In real life, the procedure would be performed by an experienced person as the consequences of an error could be significant. In general, the simulations developed for the mining industry present much more complex situations that require an understanding of spatial awareness and many concurrent processes, but for this experiment, the aim was to minimise complexity to ensure robustness in the research procedures.

2. METHODS

To ensure that the participants were indeed novices to mining, they recruited from university psychology courses. None was a mining student or former miner.

Thus, it was safe to assume that the participants would have no knowledge of degassing a mine ventilation exhaust fan.

2.1 Mine Simulation

The simulation of a real underground coal mine was conducted in a circular room at UNSW that had a diameter of 7.5 m and a height of 3 m. (On mine sites, the simulators are 10 m by 4 m.) The visual display was a 360° projection that, when polarised glasses were worn, appeared in 3-D. For this experiment, all the training was conducted in a square space in the mine. The location of the exhaust fan in the simulated mind was such that no other mining activities were simulated in this location during the experiment. The lighting was at a low level, consistent with the real mine. The visual projection depicted the ribs, floor and roof of the mine, including, among other things, the roof-supports and the ventilation system. Most important for this experiment, an exhaust fan was depicted in one corner of the virtual space. In addition to the visual display, a set of hidden speakers provided ambient mine noises. During the training, the steps of the exhaust fan procedure were demonstrated by an animated figure of a miner. Multiple-choice questions for the trainees were projected on a floating dialogue box near the exhaust fan.

2.2 Power Point Presentation

The Power Point presentation was conducted in a conference room. Slides were projected from ceiling-mounted projectors (2.3 m x 1.7 m) on wall-mounted screens. The slides showed static 2-D photographs corresponding to the steps in the sequence demonstrated in the mine simulation. These photographs were interspersed with the same multiple-choice questions as used in the mine simulation.

2.3 General Procedure

After written consent was obtained, all participants were given a 5-min briefing on the importance of safety training and asked to imagine themselves as new miners undergoing introductory training. Then, the experimenter, acting as trainer, escorted the participants into either the mining simulator or the conference room. Training was conducted in groups of 12-17 (Experiment 1) and 3-5 (Experiment 2). In both training environments, the experimenter described each of 18 steps for restarting the fan in synchrony with the visual display. The step-by-step recipe-like description, with only a minimum of essential explanation, was based on recent findings concerning the optimal method of introducing a new procedure to novices to facilitate learning and avoid deleterious overload (Clarke, Ayres, & Sweller, 2005; Pollock, Chandler, & Sweller, 2002).

Prior to each step, the participants were presented with a relevant multiple-choice question intended to encourage their attention to the subsequent demonstration of the step. Each question was first presented with the four possible answers, which were visually displayed and read aloud by the experimenter. The participants were allowed 3-5 seconds for this task. At the end of this interval, the correct answer was highlighted and the appropriate step was demonstrated.

After training had ended, the participants were given a 10-min break outside their training environments. They then went to a testing room where they completed 18 multiple-choice questions similar to those used in training. This test was conducted on a PC with a 24-in flat screen display. Each question was accompanied by a static photograph of an alternate mine environment created by moving the exhaust fan to a different part of the space and changing the colour of the mine walls, making them lighter and brighter. Either four weeks later (Experiment 1) or one week later (Experiment 2), the participants were asked to complete a text-only version of the same multiple-choice test. Among the participants, 74% returned the second test.

3. RESULTS

3.1 Experiment 1

Figure 1 shows the mean percentage of correct answers on the two tests.

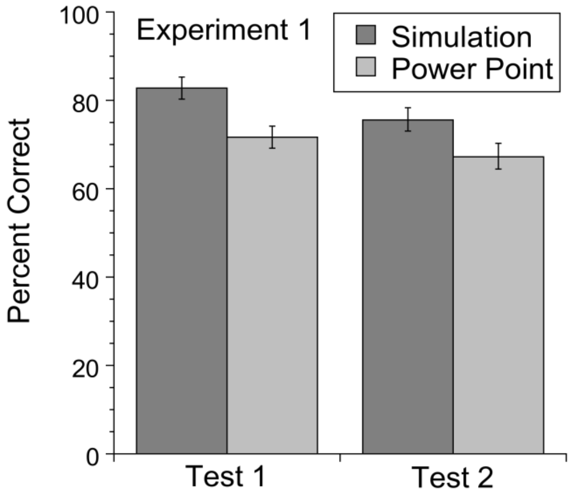

Figure 1: Mean percent correct (± 1 standard error).

Inspection of Figure 1 reveals that the novice participants had acquired and retained considerable knowledge of the procedure. Across both groups and both tests, the scores averaged 75% (SD = 13%). The simulation-trained group moderately but significantly outperformed the group that received the Power-Point presentation on both the Test 1, $F(1, 55) = 9.87$, $p < .01$, $\eta^2p = 0.152$, *n*s = 24, 33, and Test 2, $F(1, 40) = 4.91$, $p < .05$, $\eta^2p = 0.111$, *n*s = 19, 23. |Performance on Test 2 was lower than on Test 1, $F(1, 40) = 9.83$, $p < .01$, $\eta^2p = 0.197$. This decline may reflect a combination of a retention loss and change in context.

3.2 Experiment 2

Experiment 2 was conducted with three aims: (1) to replicate Experiment 1, (2) to test whether active engagement of the participants could be increased by encouraging them to collaborate, which, for example has been beneficial in medical training (Suebnukarn & Haddawy, 2006) and (3) to test transfer of training to a hands-on demonstration of the exhaust fan procedure by the participants.

To achieve these aims, Experiment 2 included a condition in which half the participants in the mining simulation were asked to collaborate amongst themselves in generating an answer to each question during the demonstration (Sim+). To enable collaboration in this condition, participants in all conditions were run in subgroups of three to five individuals. The other half of the participants in the mining simulation (Sim) and the participants in the PowerPoint condition (PP) were not allowed to discuss their answers.

As seen in Experiment 1, all the participants acquired and retained knowledge of the procedure. In fact, overall, the scores averaged 83% (SD = 3%). Differences among the Sim+, Sim, and PP groups in either Test 1 (*n*s = 17, 18, 17) and Test 2 (*n*s = 16, 13, 11) were small (< 9%). Group Sim+ showed a higher level of performance than either Group Sim or PP on both Test1 and Test 2. However, the only difference among the three groups that attained statistical significance was between Group Sim+ (M = 86%, SE = 2%) and Group Sim (M = 77%, SE = 3%) on Test 1, $F(1, 49) = 4.17$, $p < .05$, $\eta^2 p = 0.02$. Group PP showed an intermediate level of performance (M = 82%, SE = 4%).

To determine the subjective engagement in the training, all participants were asked to complete a questionnaire after the completion of Test 2. Specifically, the participants were given seven items, e.g., "Please indicate the degree to which you felt the training was interactive," and asked to respond using a seven-point scale ranging from "1, not at all" and "7, extremely."

The seven responses were combined to obtain a total engagement score, the maximum being 49. Group Sim+ (M = 36.6, SE = 1.2) reported a higher level of engagement than Group Sim (M = 31.5, SE = 1.7), who in turn were more engaged than Group PP (M = 26.7, SE = 1.6), $Fs\ (1, 37) = 6.49, 4.56$, $ps < .05$, $\eta^2 p = 0.149, 0.110$, *n*s = 16, 13, 11. However, the engagement totals were not significantly correlated with the participants' performance on either Test 1 ($r = .04$) or Test 2 ($r = .13$).

3.3 Hands-on Transfer Test

To determine whether the training would be transfer to a hands-on test, a third test was conducted two weeks after Test 2 in Experiment 2. Participants were run individually in the mining simulator, with the exhaust fan presented on the 3-D display. Participants were given a hand-held device that represented a gas detector. Participants could also move around the exhaust fan by using a joystick. Participants were asked to perform the steps required to re-start the exhaust fan.

Correct sequences of action were displayed in the simulation. For example, to correctly open the fan box, the actions required were: pull out a retaining pin, pull the box toward the operator, and replace the pin. When this sequence was performed, the 3-D display would show the sequence. Participants were awarded a point for completing each appropriate action. A maximum of 25 points could be obtained. Testing stopped when a participant indicated that the fan was operating normally.

For the transfer test, the five top-performing participants in the simulation groups and the five top-performing participants in the Power Point group were recruited. In the former case, all the participants were from Group Sim+, who averaged 90% on Test 1 and 94% on Test 2. The participants from Group PP averaged 91% on Test 1 and 89% on Test 2.

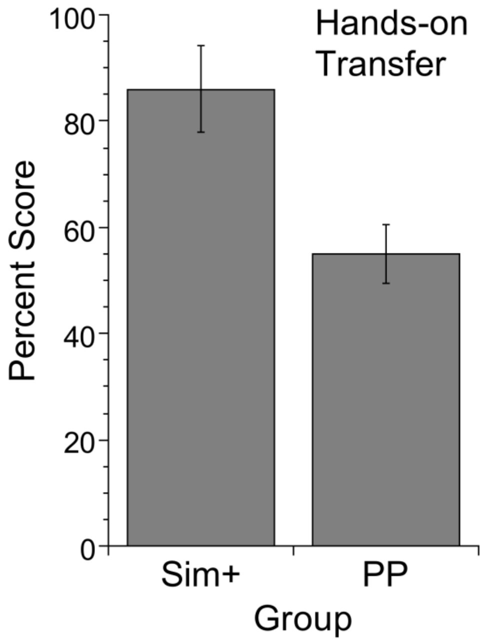

Figure 2: Mean percent score (± 1 standard error) for high performers on hands-on transfer test.

Figure 2 displays the means and standard errors expressed as a percentage of the maximum points. Inspection of the figure reveals that the Sim+ participants performed at a very high absolute level and significantly higher than the PP participants, who performed at a far lower level, $F\ (1, 8) = 14.49$, $p < .01$, $\eta^2 p = .644$.

4. DISCUSSION

The present experiments demonstrated that the 3-D simulation of a mine environment enhanced the acquisition, retention, and transfer of procedural knowledge relative to a conventional class-room presentation of the training. Although the sample for the transfer test was small, the benefit of the mining simulation appeared to be particularly large in promoting the hands-on application of the procedural knowledge.

The results were by no means preordained. Three features of the experiment could have masked the relative effectiveness of the simulation: (a) the use of participants who were utter novices to mines risked that they would experience cognitive overload in the simulation, which appears not to have been the case; (b) the use of current optimal methods for sequencing the instructions may have yielded a ceiling effect, which appears to have been partially true, as seen in the high level of performance on both Test 1 and Test 2 in all groups in both experiments; (c) the instruction in the simulated mine did not require that the participants interact with the environment, namely, by performing themselves the steps in the exhaust fan procedure. Thus, the simulation did not take advantage of the possibility of interaction with the environment, which is a key potential of simulator-based training. Nevertheless, being taken into a mine environment, the participants may have been engaged more than in a passive classroom.

In the absence of interaction with the environment, the substantial transfer from the demonstration of the exhaust fan procedure in the 3-D simulation to the hands-on application of the procedure was impressive. Although this result needs replication, the odds were stacked against this transfer from occurring for two reasons. First, the transfer test was conducted three weeks after the single demonstration of the procedure. Even well-rehearsed procedures of similar complexity to the exhaust fan procedure can show substantial losses over retention intervals of a few weeks (Jones, et al., 1993; McKenna & Glendon, 1985). Other mine procedures and rules are extremely complex and require the knowledge of many interacting components, thus making them even more vulnerable to retention losses. Second, the transfer test was conducted in a different portion of the simulated mine. Although the differences in context might seem to be trivial, transfer of new knowledge and skills, particularly in novices who have a limited range of experience, is reduced by even minor changes in the superficial features of a task, which has been labeled "encoding specificity" (Tulving & Thomson, 1973; Whittiesea, 1987). Psychomotor performance (e.g., control of a robotic arm) declines if the response requirements are changed (Healy, Wohldmann, Parker, & Bourne Jr., 2005; Mattar & Ostry, 2007). Cognitive skills such as categorisation and problem-solving also diminish when tested outside their original context (Chen & Mo, 2004; Cheng & Holyoak, 1985).

In contrast to the substantial transfer shown by the Sim+ participants, the modest transfer shown by the PP participants may have reflected a combination of retention loss and/or encoding specificity. Recall that the PP participants were all high performers on the multiple-choice tests. Hence, they had demonstrably encoded the procedure in at least a declarative manner. However, for them, there was a substantial change in context from the 2-D representation to the transfer test in the simulated mine. In fact, most of the PP participants skipped steps when performing the procedure.

In hazardous environments such as underground mining, a failure to remember even one step of a procedure can be extremely serious. In restarting an exhaust fan, such a failure could lead to a build-up of methane gas. Where the costs of failure are so high, the costs of high-fidelity simulation can be justified. Simulation is already in use in the industry and the present results warrant the further examination of at least four factors, suggested by current theories of instructional design:

First, different levels of fidelity simulation may worthwhile as trainees gain experience, likewise for fully-qualified personnel undergoing refresher training. For example, there are now findings in several domains indicating that instructional methods that are worthwhile for novices can diminish or even become counterproductive as personnel become more proficient (Kalyuga, 2008; Kalyuga, Ayres, Chandler, & Sweller, 2003). Thus, the level of fidelity required may change across levels of proficiency.

Second, reducing encoding specificity – or, more aptly, increasing the breadth of transfer – relies on the range of scenarios in which practice occurs (Paas & van Merriënboer, 1994), which in turn interacts with the complexity of the task (Van Merriënboer, Kester, & Paas, 2006). Thus, staging the variability and complexity of the training scenarios needs to be investigated and optimised, regardless of the level of fidelity in the training.

Third, the efficient use of the simulated mine seems to require group-based training. Both the time required for each individual trainee and the cost of the trainers' time militate against individualised instruction. The present results indicated that encouraging collaboration among the trainees raised the level of engagement and potentially the level of learning and transfer. From the perspective of current theories of instructional design, such collaborations help encourage attention and organisation of long-term memory by the trainees (Van Merriënboer, et al., 2006).

Fourth, increasing the level of interaction of the learner with the environment may foster faster learning, greater retention, and greater transfer (Van Merriënboer, et al., 2006). Mine personnel work in teams and replication of this environment seems logical. In the present case, this hypothesis could be tested by asking participants to navigate their way around the mining simulation using the joystick and spot hazardous situations. The benefit of such interactions could be tested with any level of fidelity, including perhaps a 2-D display on a desktop computer.

In conclusion, the present results plus the factors just described suggest that a one-size-fits-all-solution is unlikely to yield the greatest ratio of benefits to costs in the use of simulators in training. Immersive simulations can be designed to present complex training scenarios. These scenarios can train mine workers, even novices, in safe operating procedures. The key is consistency in training. When many trainees can be simultaneously exposed to high-resolution simulation of the mine environment that is also safe and forgiving, the cost of developing and owning the simulator can be justified. Mining is a multi-billion dollar industry. The cost of simulators in comparison is small.

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