Virtual reality for mine safety training in South Africa

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Synopsis

The high incidence of accidents and fatalities in the South African mining industry, in particular those associated with falls of ground, is often attributed to ineffective and/or inappropriate training methods and material. Recently introduced mine health and safety legislation in South Africa also requires that all mine workers receive appropriate and effective training to enable them to operate safely in their given mining environment. There can, therefore, be no doubt that methods to provide effective training, in particular safety related training, are urgently required in the South African mining industry.

In the search for alternative and improved training approaches, attention has fallen on virtual reality (VR) technology as a possible solution. VR has found acceptance in a number of industries as an effective method of training for a variety of work place activities, including those of a safety related nature. VR has successfully been applied in a number of industries to improve the effectiveness of safety and hazard awareness training.

The CSIR: Division of Mining Technology (CSIR Miningtek), in conjunction with the Safety in Mines Research Advisory Committee (SIMRAC), therefore evaluated the potential of VR to be used as a training medium in the South African gold and platinum mining industry. Aspects of the evaluation included an assessment of the technical capability of VR to represent a typical underground mining environment with sufficient realism and the relevance of the VR training concept for a largely illiterate workforce. For these purposes, a prototype PC-based VR hazard awareness training simulator has been developed by CSIR Miningtek, and a series of evaluation sessions conducted at a typical deep level gold mine.

The conclusion from this evaluation work is that virtual reality technology has the potential to provide effective training systems that are relevant to the South African mining industry.

Keywords: Virtual reality, mine training, safety training.

Introduction

The need for improved worker safety training programmes, as a means to reduce accidents in South African mines, is being emphasized by all industry stakeholders and driven by legislation[1]. Accident statistics (cf. Table I) highlight the need to address falls of ground as the primary safety hazard in underground (gold) mining operations[2]. The high incidence of accidents and fatalities in the South African mining industry[3], in particular those associated with falls of ground in the gold and platinum mines, is often attributed to ineffective and/or inappropriate training methods and material[4].

The Leon Commission's[5] inquiry into safety and health in the South African mining industry identified four major hazard categories that it prioritised for urgent and immediate attention. The top two of these hazard categories being: falls of ground (noted by the Commission to be responsible for 61,7 per cent of deaths and 30,8 per cent of serious injuries in all gold mines in 1993); and mining equipment and transport (noted by the Commission to be responsible for 12,7 per cent of deaths and 21,4 per cent of serious injuries in all gold mines in 1993)[6].

Although the number of fatalities in gold mines (Table I) has dropped numerically by 60 per cent over the last decade, the rate per 1000 workers has remained largely unchanged due to a concomitant reduction in the workforce[7]. A similar picture also applies in the case of reportable accidents. A further indication of the seriousness of the situation is that the prevailing fatality rate is approximately five times higher than that recorded in the mining industries of developed nations[5].

The undoubted social and political consequences associated with such high accident rates cannot be ignored nor can the cost to the mining industry. For example, Schutte[8] notes that the average cost in 1993/94 of a fatal fall of ground accident was R462 872.00 and that of a reportable fall of ground accident was R233 398.00. The goal in the years to come should, therefore, be to address these unacceptably high accident rates in real terms through, amongst other strategies, the use of the improved training technologies and methods that are now available.

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Table I

Rock-related fatalities in Chamber of Mines of South Africa member gold mines 1990–1999[7]

Year	Total fatalities in all categ.	Fatality rate per 1000 p.a. for all categ.	Rock-related fatalities					
			Total rock-related		Pressure burst		Other fall of ground	
1990	522	1.24	285	54%	147	28%	138	26%
1991	443	1.18	277	62%	93	21%	184	41%
1992	400	1.12	263	66%	131	33%	132	33%
1993	398	1.16	255	64%	128	32%	127	32%
1994	357	1.03	209	58%	93	26%	116	32%
1995	401	1.20	181	45%	68	17%	109	27%
1996	304	1.09	183	60%	65	21%	118	39%
1997	265	0.97	151	57%	73	28%	78	29%
1998	240	1.07	138	58%	61	25%	77	32%
1999	202	1.06	103	51%	39	19%	64	32%

Traditionally, research into reducing fall of ground accidents has concentrated on providing improved support units and systems and improved mining layout design. An additional approach being promoted in the Mine Health & Safety Act 29 of 1996[1] is, however, to improve the level and effectiveness of training given to underground workers. This recently introduced legislation requires that all mine workers receive appropriate and effective training to enable them to operate safely in their given mining environment. In the context of rock-related accidents this training emphasis lies in the area of hazard identification and associated remedial safety action[9,10].

These developments in legislation have significant implications for employers who have to provide effective safety training of workers as a basic requirement[11]. From the employer's perspective, quoted by Dale, Davids[12] sees better educated and trained miners as a way of reducing accident numbers on mines.

Current training methods rely on repetitive classroom style learning with some instruction being given in a physical mock-up of an underground workplace followed by on the job training. If it is assumed that current methods are not adequate for training workers to operate safely underground, then a viable alternative or additional method is required. There can, therefore, be no doubt that methods to provide effective training, in particular safety related training, are urgently required in the South African mining industry. This paper addresses the application of virtual reality as an innovative approach to safety training in the mining industry and its potential for reducing accidents in the future.

Virtual reality and its role in training

Virtual reality (VR) can be defined as: *3-D computer generated representations of real, or imaginary, worlds with which a user can have real-time interaction and experience some feeling of being present in those worlds.* VR is often depicted as involving head-mounted displays (HMDs) and other 'high-tech' input/output devices that enable human interaction with the system, ultimately providing the feeling of immersion, or presence, inside the computer generated world. This, however, is not necessarily the case, as somewhat less sophisticated systems can be constructed at a significantly lower cost, in which, for example, a standard computer joystick and monitor are the input and output devices.

In the search for alternative and improved training approaches, attention has fallen on VR technology as a possible solution. VR has found acceptance in a number of industries as an effective method of training for a variety of work place activities, including those of a safety related nature. VR has successfully been applied in a number of industries to improve the effectiveness of safety and hazard awareness training.

Research Triangle Institute[13] (RTI) note that numerous conditions exist in which it is difficult for learners to practise and perfect their skills, and lists these conditions as occurring when:

- working conditions are hazardous
- interaction with equipment is required, but equipment is expensive, unavailable, or inaccessible
- down-time is costly
- changes need to be quickly incorporated.

Benefits of VR training simulators have been described in terms of training operators to operate valuable equipment without needing to expose the equipment to any damage; and training individuals how to operate hazardous equipment without exposing the individuals to any danger from the equipment[14]. Suggested situations for which VR might be productively used are as follows[15]:

- when training mistakes would be costly
- when the necessary environment cannot be experienced in the real world
- to build interfaces that are sensible and can be manipulated
- to make training situations really 'real'
- to make perceptible the imperceptible.

VR has been recognized as having relevance for training in a wide range of industries, e.g. aviation, construction, manufacturing, medical, military and space exploration. Documented advantages include[16–19]:

- low cost alternative to creating full-scale physical training scenarios
- flexible configuration and amenable to ongoing modification and customization
- opportunity to create a wide variety of scenarios including ones rarely, or never previously, encountered in 'real life'
- once constructed the training scenarios can be run repeatedly and to order
- built-in monitoring of progress during training sessions
- provision of appropriate levels of trainee interaction.

RTI[13] believes that VR offers a solution to difficulties encountered with conventional training, such that the equipment and actual working conditions can be conveniently brought to the learner for unlimited training at any location. RTI[20] cite the example of field maintenance mechanics who, requiring training on expensive equipment that is unavailable for trainee practice, showed a 4-to-1 factor improvement through the use of a VR-based training system. In terms of the time-saving aspect of VR-based training, RTI[20] also present results, shown in Figure 1,

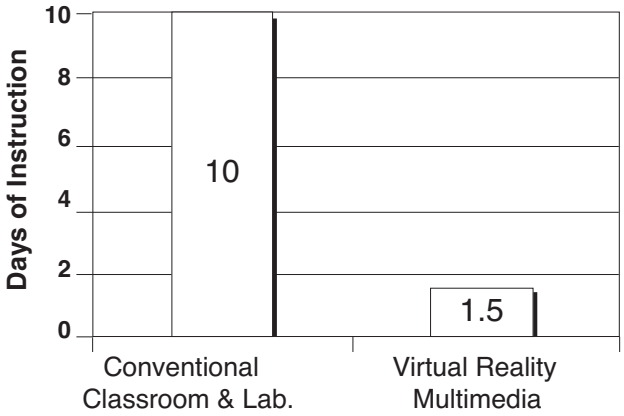

Figure 1—Comparison of learning time for conventional and VR-based training[20]

which reflect a markedly shorter time to achieve training with VR compared to a conventional approach. These advantages of VR training translate into significant cost savings. Further to this, Hall[21] quantifies the cost saving to be gained from computer-based training, compared to traditional instructor-led training, to be as much as 50 per cent. Hall's[21] research also indicates that computer-based training achieves an equal or higher quality level of learning, even though its content is typically delivered in 40–60 per cent less time than instructor-led training.

Beyond the obvious suitability of VR to meet the broad spectrum of training requirements, the benefits of VR would seem to make VR particularly appropriate in the field of safety training, wherein implications of hazardous situations need to be realistically portrayed and countered without exposure of the trainees to any real danger.

In light of these benefits and the increased attention currently being given to training, and in particular safety training, in the mining industry it is appropriate that these areas are investigated for the possible introduction of VR-based training methods.

The relevance of virtual reality for mine training

In the case of the mining industry, the low levels of education and literacy among mineworkers in South Africa are seen as a hindrance to effective safety training and as contributing to the poor safety record[4,22,23]. In addition, Schutte and van Graan[24] state that 'conventional classroom training techniques achieve little success, especially where the trainer has to compete with factors such as illiteracy and lack of employee enthusiasm to be trained'. A solution being proposed by Schutte and van Graan[24] to address this problem is, with the aid of various simulation techniques, to present the training in a 'fun-filled, exploratory and exciting manner'. This all fits in with the use of VR, which not only offers the potential for an exciting and consistent level of instruction material and quality in its presentation but also demands, and tests for, a certain level of understanding in the trainees. The trainees cannot successfully complete a training session unless they are correctly interpreting and reacting to the scenario and images being presented.

Bise[25] summarizes the undeniable potential of applying VR for miner training thus:

> 'Virtual reality has the potential of becoming an effective tool for miner training by expanding the power of three-dimensional learning and involving more senses in the process. … it is a cost effective and safe alternative to real-world training under actual hazardous conditions. Further, as a component of new-miner and independent-contractor training programs, VR enables the users to experience virtual environments that are duplicates of a real world they have not yet experienced.'

Bise[25], however, qualifies this clear enthusiasm for the application of VR in miner training with the warning that 'care must be exercised so that VR is not promoted in situations that are considered to be neither appropriate nor cost effective as a training delivery method'. This point has particular relevance in the South African context, where, unlike the situation in other recognised training applications of VR, there exists a low level of education and exposure to technology among the potential trainees.

Lawrence[26] found the major underlying factor in underground accidents to be an inadequate perception of hazards. Thus, if training is to successfully combat the high incidence of accidents then the issue of hazard perception must be addressed. Blignaut[27] suggests that underground experience develops a worker's skills in the detection of loose rock by providing:

- exposure to a wide variety of loose rock
- exposure to a wide variety of levels of danger associated with loose rock
- feedback on detection performance (e.g. a detected rock falls, thus confirming the assessment).

However, Blignaut[27] also suggests that detection skills need not be developed through experience alone, but that these skills can also be developed through training and practice. For this training, Blignaut[28] proposes two approaches, *knowledge training* to provide a knowledge of the characteristics of loose rock and *skills training* to develop the skills of searching for and detecting loose rock. Blignaut *et al.*[29] had previously found that the prevailing safety training programmes were equipping trainees more with 'knowledge' for the job than with the necessary 'skills'. This prompted them to emphasize the merits of a period of training under actual working conditions, such as in an underground stope, during which trainees are given assistance in refining their skills. Blignaut[27] concludes that the success of his experimental skills training programme was due to the knowledge that it provided, the opportunity to practise and the prompt feedback given. This training exercise also made use of stereoscopic slides, to provide a three-dimensional view of loose rock, in order to overcome the deficiencies in conventional methods. A VR training system is capable of addressing these aspects, since it can graphically depict the various hazards, thus providing knowledge about the appearance of loose rocks, and through user interaction it allows detection skills to be developed, practised and tested, and it can provide immediate feedback. In addition, all this can be done in 3D.

A study into methods for teaching underground workers to evaluate dangerous conditions found that safety training should not only involve teaching the principles of safety but also the application of these principles[30]. Again, VR offers the opportunity for trainees to apply these principles in a controlled environment.

The workforce in the mining industry is now of a more permanent nature[31], which means that the investment in introducing the workforce to new technology, including VR, is not wasted through high personnel turnover and replacement. This has the benefit that, once a trainee has been exposed to a VR simulator and the effort made to teach the trainee its operation, this knowledge and effort is not lost to the industry. This knowledge can also be built on with each subsequent exposure to the technology and will raise the workforce's general technology level and competence. This increased level of familiarity with technology will have spin-off benefits for the mining industry in general when and where an increased use of technology occurs.

The indications are, therefore, in favour of VR having meaningful application to South African mine training, and make it worthwhile investigating its application for hazard awareness training. The CSIR: Division of Mining Technology (CSIR Miningtek), in conjunction with the Safety in Mines Research Advisory Committee (SIMRAC), therefore evaluated the potential of VR to be used as a training medium in the South African gold and platinum mining industry. Aspects of the evaluation included an assessment of the technical capability of VR to represent a typical underground mining environment with sufficient realism and the relevance of the VR training concept for a largely illiterate workforce. For these purposes, a prototype PC-based VR hazard awareness training simulator was developed by CSIR Miningtek, and a series of evaluation sessions conducted at a typical medium to deep level gold mine.

Exploring the training potential of virtual reality

During the period 1995 to 1997, CSIR Miningtek, in conjunction with SIMRAC, investigated the potential for VR to be used as a training medium in the mining industry, particularly in safety training[32]. A prototype VR training simulator, representing a stope in a typical South African gold mine, was developed with which to conduct the hazard awareness training exercises. In light of the statistics that show falls of ground being a primary cause of gold mine accidents (cf. Table I), emphasis was placed on this category of hazard in the stope environment.

The training simulator

Through the development of a pre-prototype VR mine model and an industry survey, the requirements and hence the features of a VR simulator deemed to be suitable for mine hazard awareness training were identified. Factors taken into account were the application purpose; target users; trainee interaction; trainee evaluation; and trainer/instructor interaction. Finally, the basic system components for a suitable VR simulator were assembled (Figure 2) and the necessary software programming undertaken.

The virtual environment created in the PC/Windows-based simulator represents a portion of a stope (Figure 3) in a typical medium to deep level gold mine, namely Elandsrand Gold Mine. The typical objects likely to be encountered are included in this VR stope, as are several major hazards. The main hazards take the form of loose pieces of rock that can fall as the trainee 'walks' underneath.

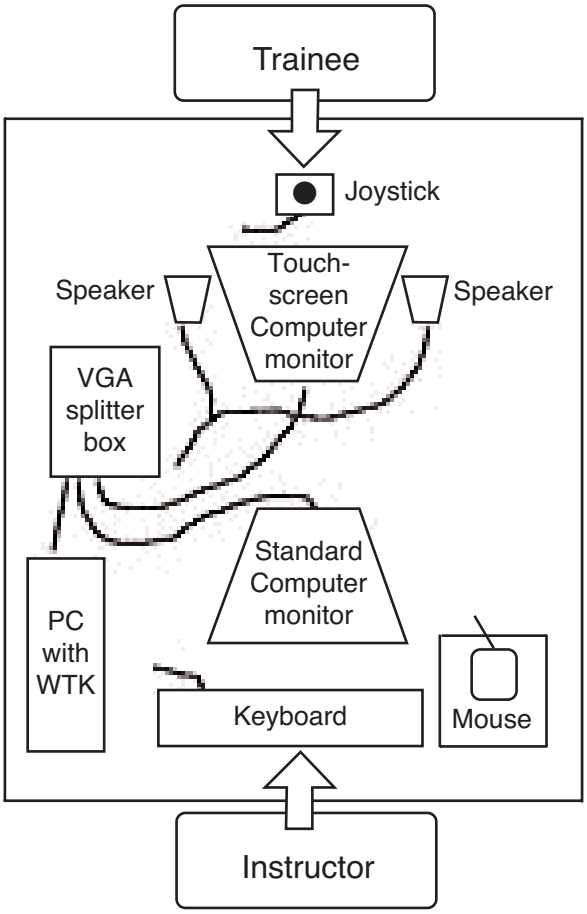

Figure 2—VR Simulator system in research configuration

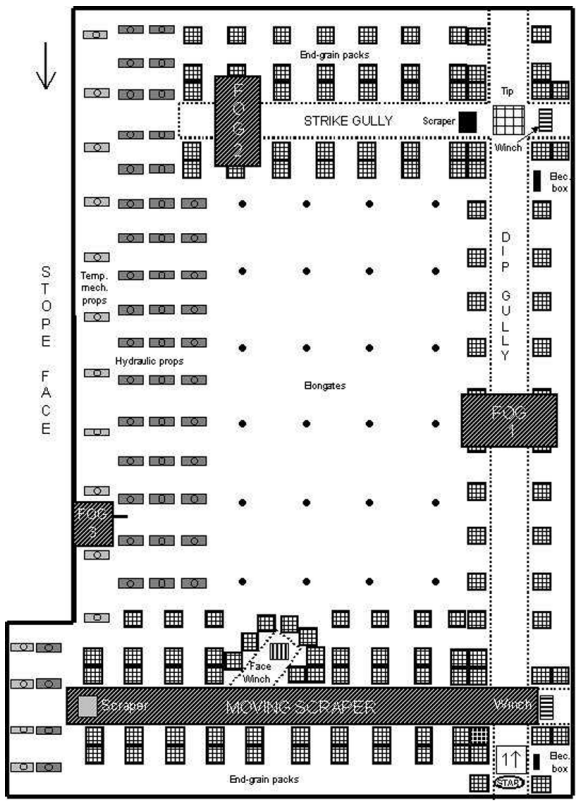

Figure 3—Schematic of the final VR stope model layout indicating the position and type of stope objects and hazards

The trainee's movement through the VR stope model (cf. Figure 4 and Figure 5) is achieved via a standard computer joystick, and interaction with the hazards and the selection of corrective actions are via a touch-screen monitor. The simulator has been designed to avoid the need for trainees to have any particular language or literacy abilities, the training content only being represented graphically. Additional functions and control sequences are available to the training instructor via the keyboard for the following:

- loading and resetting of hazards
- jumping to pre-set viewing positions
- activating scoring and evaluation module
- making other minor adjustments to the model.

After identifying one of the hazards (cf. Figure 6) the trainee is required to select the appropriate corrective action from on-screen button icons and indicate the hazardous item that needs attention (cf. Figure 7). After successfully correcting the situation the trainee is able to proceed safely. If, however, the hazard is not identified or correctly made safe and the trainee 'walks' underneath, then a series of visual and audio effects indicate the disastrous outcome and likely injury. A scoring feature is included to provide the evaluation and recording, to hard disk, of a trainee's session.

Evaluation of the training simulator

With a favourable result obtained from a preliminary evaluation, a detailed investigation was initiated at the Elandsrand Training Centre by CSIR Miningtek and SIMRAC[32]. This investigation set out to evaluate aspects of the VR simulator in detail and to make a comparison with equivalent aspects of the prevailing classroom training. To achieve this, two sample groups were drawn from the mine's workforce, one being exposed to the VR-based training programme and conventional video-based training programme (VR group), and the other experiencing only the conventional video-based training programme (Video group). The VR group was, therefore, in a position to give an opinion (and if required make a comparison) of the VR and video material, whereas the Video group could only give an opinion of the conventional video material. An independent occupational psychologist and an experienced African interviewer assisted with the interview and evaluation process involving these two separate groups. A selection of the results obtained from this evaluation exercise is presented and discussed below.

Both groups of subjects were asked to evaluate, using a five-point scale, the ease with which they were able to understand the visual material in their respective training programmes. No extremes of view were recorded and both sample groups indicated high levels of ease of comprehension (Figure 8). The percentage (81 per cent) of the VR

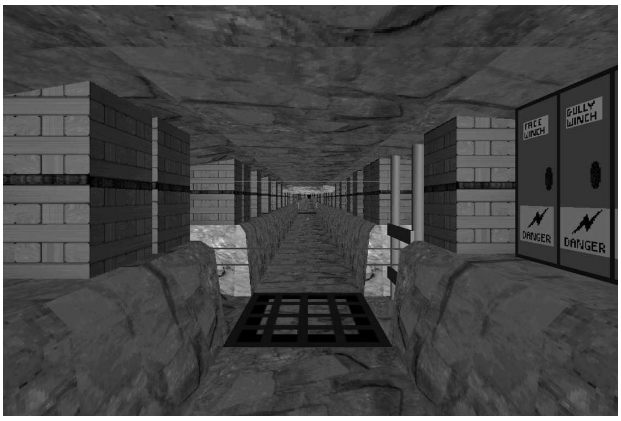

Figure 4—General view inside VR stope—main travelling way

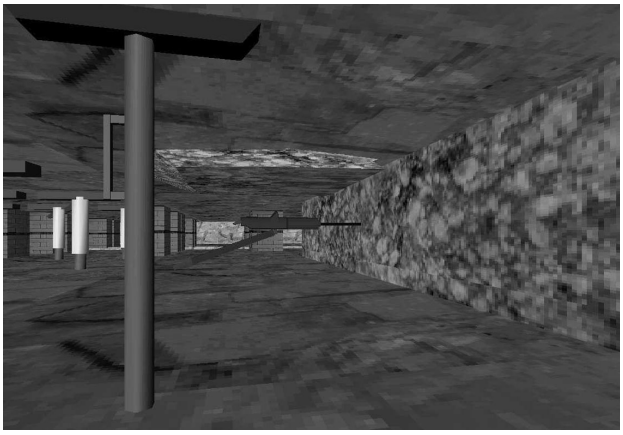

Figure 5—General view inside VR stope—working face

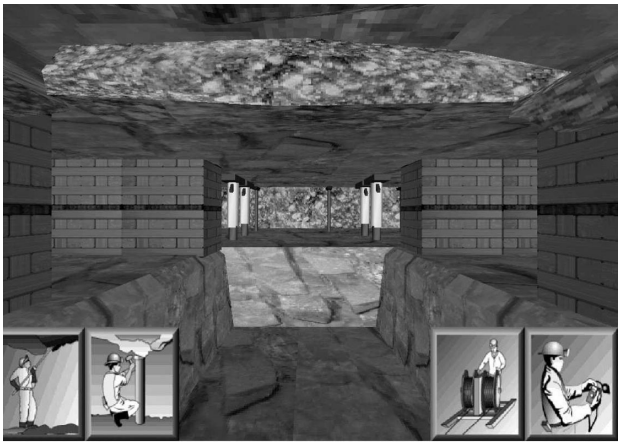

Figure 6—Loose rock waiting to 'fall' on the unsuspecting trainee

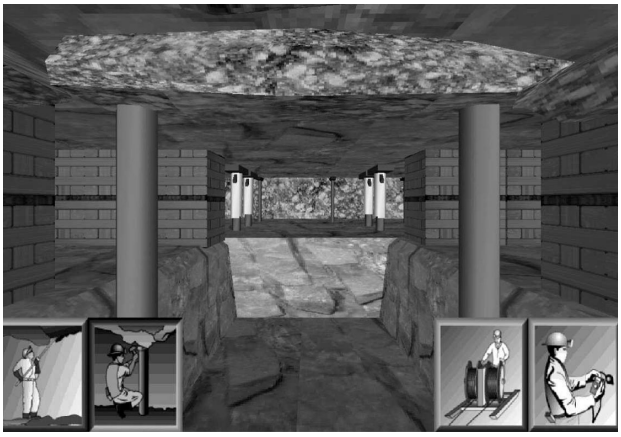

Figure 7—Loose rock safely supported

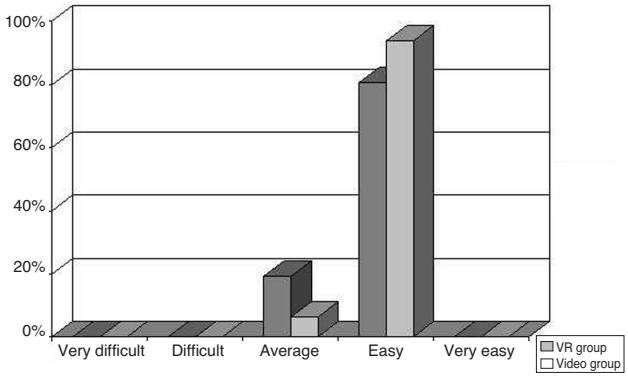

Figure 8—Ease of understanding visual material relevant to each sample group

group's 'easy to understand' rating for the VR material being almost as high as that of the Video group's (94 per cent) 'easy to understand' rating for the conventional video material. This indicates that VR is viable, in comparison to video, even where participants had little or no exposure to or experience with computers. Users do not require a high level of computer skills or literacy to benefit from VR.

Subjects in both sample groups were also asked to indicate the level of realism they felt to be depicted in the visual material contained in their respective programmes, the evaluations again being made against a five-point scale (Figure 9). Again, no extreme views were expressed and both sample groups indicated that they considered the respective visual material to be a realistic representation. The percentage (77 per cent) of the VR group's 'good level of realism' rating for the VR material being comparable to that of the Video group's (94 per cent) 'good level of realism' rating for the conventional video material. These results indicate that VR has the capacity to present visual content that is not markedly less understandable or realistic than that shown with the video medium. This, together with VR's greater flexibility of construction, indicates VR's potential to replace, or at the very least supplement, the video medium.

Despite the low previous exposure to the computer, the medium received overwhelming support from the VR group as a good training tool (Figure 10). This was despite the fact that the VR sample comprised, on average, an older group of subjects, who might have reasonably been expected to resist the new technology. Also, none of the subjects expressed any fear of the equipment. These positive opinions bode well for the successful implementation of VR as a training medium.

Almost all (94 per cent) of the subjects in the VR group preferred VR as a teaching medium compared to the other methods (including video) to which they had been exposed (Figure 11). A matching percentage (94 per cent) of the Video group preferred video as a teaching medium compared to other methods to which they had been exposed (i.e. excluding VR) (Figure 11). In addition, the open-ended responses of the VR group indicated that their self-esteem and opinion of mine management were raised by exposure to the VR medium. This is illustrated in the following responses made by the VR group:

> 'I like it very much although it needs some improvements. It makes me feel that the mine treats me like an intelligent person. The mine is empowering me.'
>
> 'With the computer you can see, hear and do as if you are walking underground.'
>
> 'We get scared to ask questions in a class because sometimes the trainer can embarrass you in front of others. The computer makes you feel at ease.'
>
> 'The computer has actual underground pictures and sounds, so it takes your mind to underground. The computer is practical and about reality. In classes we rely on few practicals, just theory only.'
>
> 'It is a more practical and up-to-date method of training us about our work situations and how to control them. The mine shows that it is highly concerned with our lives and treats us as human beings.'

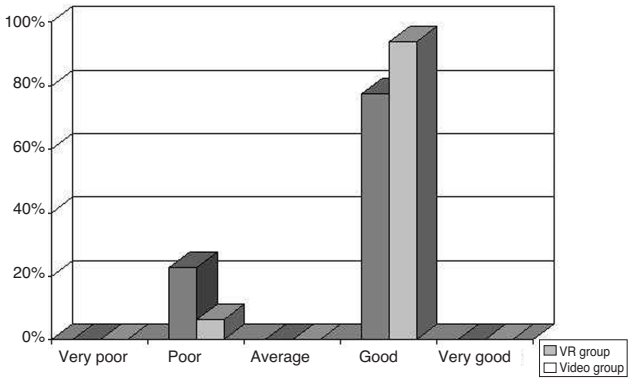

Figure 9—Perceived level of realism in visual material relevant to each sample group

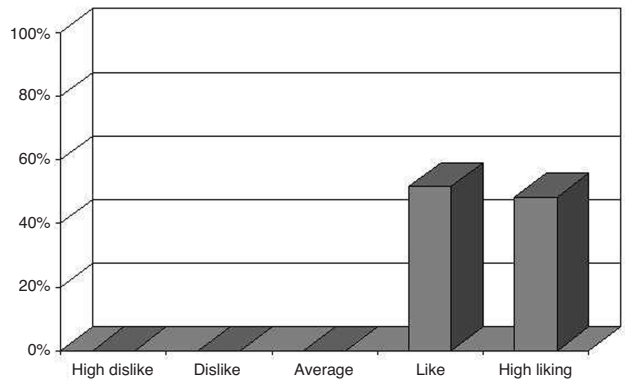

Figure 10—Opinion of computer as a training tool by VR sample group

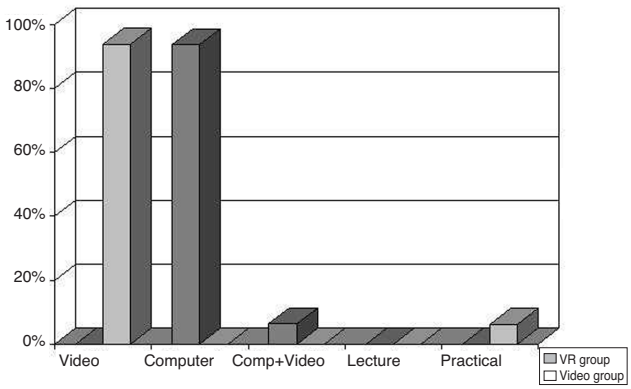

Figure 11—Preferred method of teaching for each sample group

Nearly all the subjects in the video sample expressed satisfaction with the video medium as a teaching method (Figure 11). However, observation of the subjects during the video training period revealed seven subjects (22 per cent) to be asleep during the screening of the videos; and a further nine (28 per cent) not to be paying attention to the screen. This is in direct contrast to the subjects in the VR sample whose attention and participation are inherent to the VR medium. While video-based training is passive, VR training requires hands-on interaction from the participants.

The detailed evaluation confirmed that the application of VR has relevance and potential in the field of mine hazard training. Aspects finding particular favour were the interactive and practical 'hands-on' nature of the VR system, acceptable realism of visuals and sounds, and the implied message that mine management is treating the workforce with more respect. The use of the joystick provided the only real difficulty in the use of the VR system and this was limited to only a few of the subjects. However, none of the subjects rejected the ongoing use of the joystick, saying only that they required more time to become familiar with the device, which is not unreasonable to expect.

The application of virtual reality in the mining industry

Given the current high accident rates in the mining industry and the apparently inadequate training methods, it is necessary to consider other training options if the situation is to be rectified in the years to come. To this end, the technology that is now available can be better utilized. VR, for instance, has proven itself in flight training and given the opportunity it can be as effective in mining. A low level of education and literacy among mineworkers is not seen as a valid reason against the application of VR. On the contrary, the visual, hands-on nature of VR is seen as a feature of the technology that is ideally suited to this situation. In addition, the interactive nature of the VR medium lends itself to the Outcomes-Based Education and Training (OBET) approach currently being pursued for mine training, wherein competencies can be generated in appropriate skill areas and effectively evaluated in accordance with the desired outcomes. A role for VR is also envisaged in Adult Basic Education and Training (ABET) where interactive and more intuitive programmes can be developed, in particular as the natural evolution of the current computer-based ABET media.

It is strongly believed that the application of VR training systems could have significant impact on the quality, relevance and effectiveness of safety training in the mining industry. The prototype training simulator developed for concept evaluation purposes is but a small example of what areas and aspects of training can be covered. Although the 'fall of ground in a gold mine stope' hazard scenario was chosen for the prototype simulator, the same techniques could equally be applied to other hazard types, e.g. transport hazards, to other commodities and environments, e.g. coal mining, and to accident/incident reconstructions.

Although the experimental configuration of the prototype system required the trainee to have one-on-one interaction with the PC it is envisaged that this may only be appropriate for certain situations. A more appropriate arrangement might be in the form of group or team interaction where the display is not a small PC screen but a large wall-mounted screen. In this configuration either the training instructor or a nominated member of the team will, using suitable VR devices, interact with the system on behalf of the group.

While the response from training personnel in the mining industry to the prototype VR training simulator was enthusiastic, this has not yet been translated into any significant take-up of the concept. It is believed, however, that given further exposure and investment this situation will change. A large mining group in South Africa is, for example, currently evaluating a customized and significantly modified and improved version of the original simulator to determine for themselves the suitability of the VR training approach for their workforce. The customization and evaluation work is being done at the group's own expense, and is evidence of their commitment to exploring more effective training methods and VR in particular.

Substantial investment is, however, still required in order to utilize the available VR technology to create a robust, fully featured and customizable training simulator that will serve the diverse needs of the wider mining industry. The AIMS Group at the University of Nottingham in the UK have taken the initiative in this respect and made a considerable contribution in the development of an appropriate generic VR application, but as yet there has been no significant commitment in the South African arena to fully realise the potential of VR for mine training.

Conclusions

The unacceptably high rate of fatalities and injuries in the mining industry, in particular those caused by falls of ground, and recent changes in mine legislation are placing increasing emphasis on improving safety training on mines. Research into the reasons for and the solutions to combat fall of ground accidents in the South African mining industry over the past three decades highlights shortcomings in the conventional training approach. These shortcomings indicate that there is an opportunity for an innovative approach to be taken to improve safety and hazard awareness training in the next decade. VR appears to have the potential to provide more meaningful and effective training systems to address the identified safety needs in the South African mining industry. An industry commitment is now required to turn this opportunity into more than just a *virtual reality.*

Research to date has demonstrated the following:

- the successful development of a VR underground simulator is possible and has demonstrated the potential for the application of VR training systems in the mining industry over the next decade
- an encouragingly high level of acceptance and understanding was shown by the target group of underground workers for the concept and the imagery of the VR underground simulator
- indications are that VR-based simulators can be successfully applied to raise the level of hazard awareness training in the mining industry and thereby reduce underground accident and fatality rates
- VR-based simulators can be integrated with conven-

tional training techniques and thereby provide an enhancement to current training methods

- further investment is required to develop VR training systems that will meet the diverse needs that exist across the mining industry.

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References

1. Mine Health and Safety Act (Act No. 29 of 1996). *Government Gazette* No. 967 (14 June 1996). Government Printer. Pretoria.
2. MALALA, J. and LAMBERTI, T. 532 died in rockfalls and other accidents on SA mines last year. *The STAR Newspaper*, Friday 8 March 1996. Johannesburg. p. 1.
3. KRIGE, B. Leon Commission: A dismal record. *SA Mining, Coal, Gold & Base Minerals*, May 1995. pp. 9–13.
4. PLIMMER, F. Worker's perceptions and rock mechanics—what does the future hold? Proceedings: *The Human Element in Rock Engineering*. SANGORM, Johannesburg, 1996. pp. 5–7.
5. Leon Commission of Inquiry into Safety and Health in the Mining Industry. Johannesburg, 1995.
6. BARRY, B. Shifting the balance: the Leon Commission of Enquiry into health and safety in the mining industry. *SA Labour Bulletin*, vol. 19, no. 2, May 1995. Johannesburg. pp. 65–70.
7. Chamber of Mines of South Africa: Analysis of Annual Accident Statistics. Internet WWW, URL: <http://www.bullion.org.za/panl/genrl/accianal.htm> (accessed on 7 July 2000).
8. SCHUTTE, P. The human factor in safety: A behaviour-based approach enhancing empowered, valued, and safety committed employees. Proceedings *MINESAFE International* 1998, September 1998, Sun City, South Africa. pp 219–228.
9. MILAZI, A. Making mining safer. *The Sowetan Newspaper*, Tuesday 7 January 1997. Johannesburg.
10. MILAZI, A. Act makes mines safer. *The Sowetan Newspaper*, Monday 20 January 1997. Johannesburg.
11. DE KOCK, C. Internationally acceptable safety statistics are achievable—Bakker. *Mine Safety Digest*, vol. 8, no. 4. 1996. Mine Safety Division of Chamber of Mines Services (Pty) Ltd, Johannesburg. pp 22–30 & 43.
12. DAVIDS, F. A new generation of qualified miners emerges. *Mail & Guardian Newspaper*, February 21 to 27, 1997. Johannesburg.
13. Research Triangle Institute. Virtual reality multimedia training. Research Triangle Institute, North Carolina. Internet WWW, URL: <http://webtest.rti.org/vr/w/vrtrain.html> (accessed on 15 April 1997).
14. LEVY, J.R. and BJELLAND, H. *Create your own virtual reality system.* Windcrest®,/ McGraw-Hill Inc., New York, 1995.
15. CARR, C. Is virtual reality virtually here? *Training and Development,* October 1992. pp. 37–41.
16. VINCE, J. *Virtual Reality Systems*. ACM SIGGRAPH Book Series, Addison-Wesley Publishing Company, Wokingham, UK, 1995.
17. IOVINE, J. *Step into Virtual Reality*. Windcrest®,/ McGraw-Hill Inc., New York, 1995.
18. WITTENBERG, G. Training with virtual reality. *Assembly Automation*, vol. 15, no. 3, 1995. MCB University Press, 1995. pp. 12–14.
19. KOZAK, J.J., HANCOCK, P.A., ARTHUR, E. J., and CHRYSLER, S.T. Transfer of training from virtual reality. *Ergonomics*, vol. 36, no. 7, 1993. Taylor and Francis Ltd. pp. 777-784.
20. Research Triangle Institute. Virtual reality training results. Research Triangle Institute, North Carolina. Internet WWW, URL: <http://webtest.rti.org/vr/w/results.html> (accessed on 15 April 1997).
21. HALL, B. Return on investment: ROI and multimedia training. Internet WWW, URL: <http://www.multimediatraining.com/roi.html>. 1995. (accessed on 15 April 1997).
22. Safety in Mines: Change by Commission. *S.A. Mining World*, July 1995, Special Feature: Mine Safety. Johannesburg. pp. 20-21.
23. HILTON-BARBER, B. Government pins underground health as a priority. *Strategic Health Review*, Tuesday 1 July 1997. Internet WWW, URL: <http://www.web-abs.co.za/strathealth/19970601-121616-18003.html> (accessed on 3 July 1997).
24. SCHUTTE, P. and VAN GRAAN, J. The art of managing risk: Extraordinary results through ordinary people. *Mine Safety Digest,* vol. 8, no. 4, 1996. Mine Safety Division of Chamber of Mines Services (Pty) Ltd, Johannesburg. pp. 32–36.
25. BISE, C. J. Virtual reality: Emerging technology for training of miners. *Mining Engineering*, vol. 49, no. 1, January 1997. SME, Littleton, CO, USA. pp. 37–41.
26. LAWRENCE, A. C. Human error as a cause of accidents in gold mining. Research Report 21/73. Chamber of Mines of South Africa Research Organisation, Johannesburg, 1973.
27. BLIGNAUT, C. J. H. The development of a method to train mineworkers in the detection of loose rock: a laboratory study. Research Report 9/77. Chamber of Mines of South Africa Research Organisation, Johannesburg, 1977.
28. BLIGNAUT, C. J. H. A survey of the loose rock experiences of machine crews in gold mining in terms of visual search and detection. Research Report 105/76. Chamber of Mines of South Africa Research Organisation, Johannesburg, 1977.
29. BLIGNAUT, C. J. H., MAUER, K. F., and GRIFFITHS, J. A. An evaluation of the effectiveness of safety training for non-supervisory job categories. Research Report 58/75. Chamber of Mines of South Africa Research Organisation, Johannesburg, 1975.
30. MELAMED, L., LEDERMAN, S. T., and PHETHA, P. T. Learning to recognise hazardous conditions underground. Research Report 104/76. Chamber of Mines of South Africa Research Organisation, Johannesburg, 1976.
31. BAKKER, D. Safety at the stope face. *Mine Safety Digest,* Vol. 7, No. 2, 1995. Mine Safety Division of Chamber of Mines Services (Pty) Ltd, Johannesburg. pp. 24-32.
32. SQUELCH, A.P. Application of virtual reality for hazard awareness training in South African gold mines. PhD thesis, University of Nottingham, Nottingham, UK, 1998. ◆