The validity of a simulator for training of shotcrete operators

Håkan Alm
Division of Engineering Psychology, Luleå University of Technology, Sweden

Förord

Rapporten redovisar en studie av validiteten hos en simulator avsedd för träning av sprutbetong operatörer, utvecklad av företaget Edvirt AB. Studien har genomförts i samarbete med en referensgrupp bestående av Tommy Ellison, Besab, Henrik Eriksson, Besab, Petter Börjesson, Edvirt AB, Eric Göransson, Edvirt AB, Benjamin Krutrök, LKAB, Magnus Pohjanen, LKAB. Författaren till denna rapport riktar ett varmt tack till referensgruppen för värdefullt stöd under projektets genomförande. Ansvarig för kvaliteten i det vetenskapliga arbetet har varit Håkan Alm, professor i Teknisk psykologi vid Luleå tekniska universitet.

Projektet har genomflörts med stöd från Bygginnovationen/VINNOVA, Svenska Byggbranschens Utvecklings Fond/SBUF samt Innovationskontoret Väst

Foreword

The report presents a study of the validity of a simulator for training of shotcrete operators, developed by the company Edvirt AB. The study has been performed with the support of a reference group consisting of Tommy Ellison, Besab, Henrik Eriksson, Besab, Petter Börjesson, Edvirt AB, Eric Göransson, Edvirt AB, Benjamin Krutrök, LKAB, Magnus Pohjanen, LKAB. The author expresses his gratitude to the reference group for valuable input during the performance of the study. The responsibility for the scientific quality of this study has been Håkan Alm, Professor at Luleå University of Technology.

The project was financially supported by Bygginnovationen/VINNOVA, Svenska Byggbranschens Utvecklings Fond/SBUF and Innovationskontoret Väst

SBUF® LULEÅ UNIVERSITY OF TECHNOLOGY VINNOVA

ABSTRACT

The aim of this study was to test the validity of a simulator developed by the company Edvirt AB for the training of shotcrete operators. Thirteen experienced and six inexperienced operators participated in an empirical study. The inexperienced operators were exposed to a training program for two weeks. In the beginning of the training they performed one task, and by the end of the training program they performed three additional tasks. The experienced operators were given a short introduction to the simulator and after that performed the same four tasks as the inexperienced operators with the help of the simulator. The performance on the four tasks showed that the experienced operators showed a better performance initially but that difference disappeared when the inexperienced operators had completed their training in the simulator. The mental workload was lower for the experienced operators after performing all four tasks. Ratings of similarity between the simulator and a similar real equipment showed acceptable levels, and a number of suggestions for improvement of the simulator was produced by the experienced operators. All experienced operators considered the simulator to be a useful tool for the training of shotcrete operators. The conclusion from the study is that the simulator, as it was designed during the study, has an acceptable level of validity and can be used in the training of shotcrete operators.

Keywords: Constructions underground, rock support, shotcrete, simulation, training

SAMMANFATTNING

Syftet med denna studie var att testa validiteten hos en simulator, utvecklad av företaget Edvirt AB, med syfte att kunna träna operatörer som arbetar med bergförstärkning med hjälp av betong. Tretton erfarna och sex oerfarna operatörer deltog i en empirisk studie. De oerfarna operatörerna deltog i ett två veckor långt träningsprogram, I början av träningsprogrammet genomförde de en uppgift och i slutet av programmet genomförde de tre ytterligare uppgifter. De erfarna operatörerna fick en kort introduktion om simulatorn och genomförde därefter samma fyra uppgifter som de oerfarna operatörerna. Mätningar av prestationen på de fyra uppgifterna visade att de erfarna operatörerna presterade bättre initialt men att skillnaden försvann efter att de oerfarna hade genomgått träningsprogrammet. Mätningar av mental arbetsbelastning efter genomförande av alla fyra uppgifter visade på lägre värden för de erfarna operatörerna. Bedömningar av likheter mellan simulatorn och en verklig utrustning visade på acceptabla värden och de erfarna operatörerna producerade ett antal förslag till förbättringar av simulatorn. Samtliga erfarna operatörer ansåg att simulatorn, i dess dåvarande utförande, kan vara ett användbart verktyg för att träna operatörer som arbetar med bergförstärkning med sprutbetong. Slutsatserna av studien är att simulatorn, i dess dåvarande utförande, har en tillräckligt hög validitet för att användas vid träning av sprutbetongsoperatörer.

Nyckelord: Byggnader under marknivå, berg förstärkning, betong, simulering, träning

INTRODUCTION

Constructions underground, such as tunnels for transportation and other premises must be designed in a way that ensures safety. A common risk in underground facilities is that, due to geological reasons, as rock strain and fractured rock mass, parts of the surrounding structure may loosen and, in the worst case, fall down on people and machines. From a safety perspective, one important concern is to stop smaller and larger parts of the surrounding structure from falling down on workers and users of these premises. This is even more challenging in the perspective of the tunnels operation time of at least 120 years. A common strategy to reduce the level of risk in any type of construction or organization is to use some kind of barrier to minimize or eliminate different risks (see for instance Hollnagel, 2004). Barriers may be physical objects or more abstract symbolic messages, like safety rules. In the case of underground constructions a physical barrier is often used to enhance safety. One commonly used method is to attach a layer of concrete, often mixed with fiber reinforcement or other components (shotcrete), to the walls and ceilings and thereby prevent parts of the surrounding structure from falling down and cause injuries and problems for people and equipment located in these premises. From a safety perspective it is extremely important that the barrier of shotcrete is applied correctly and can protect people and equipment during the life cycle of the tunnel or other premises.

Rock support

Rock support usually consists of a combination of rock bolts and shotcrete, and is designed due to the statistical probabilities but often simplified to empirical methods based on experience. The layer of shotcrete should have an optimal thickness, adapted to the properties of the surrounding rock mass, ground water pressure, tunnel depth, tunnel dimension, and most important, the intended use of the tunnel or cavern. Rock support with shotcrete can be designed with different methods. Either you can strive for the tunnel profile to be as smooth and even shaped as possible. In this case the thickness of shotcrete will vary, depending on irregularities in the blasted profile. This method will for sure give the best result according to bearing capacity and durability due to arch principle, but will be very costly for the client. The method is rarely used but can be useful in situations with extreme tunnel dimensions or poor rock quality. This method might raise severe demands on the skills of the shotcrete operator as the spraying sequence will be very irregular, however the tolerances of the final tunnel form are normally not so precise in such situations. To reduce cost with adequate supporting properties there is an alternative method developed for hard rock tunnels based on plate theory and empirical data. In this case the shotcrete layer shall be applied with almost constant thickness over the rock surface, and often in combination with systematic rock bolting. This method is used globally and especially in hard rock tunneling and is, for example, described in the Q-theory (Barton, 1994). The skill of the shotcrete operator are essential, as poor skills might result in insufficient safety for tunnel users, decreased durability and increased costs due to extensive concrete waste.

To perform the job an operator can use a mobile equipment, specially designed for this purpose. The operator may use differently designed controls to steer a crane with a nozzle and spray concrete on the surrounding walls and ceiling, until an acceptable layer of concrete is established. The surrounding walls and ceiling always have an uneven shape and the learning process to be a skilled operator is long. The task is dominated by a visual input but input from other sense modalities, such as the auditory modality is also important. Visibility during the task is often far from optimal, which makes the task hard to learn. Correct feedback concerning the properties of the shotcrete layer may also be hard to get. In addition, it has been noted that operators performing this task may vary in their ability to produce the optimal result. The training of operators to perform this task is normally performed in real life and with a high cost. It is an extremely waste of resources to perform training in a training tunnel, with production equipment, supervising personnel and extensive use of concrete and additives. If training is performed in real production, which has been regular up till now, the end result of a training session is not acceptable, additional costs will be added to amend mismatches. To be skilled enough can take a long time under such conditions, and it is hard to find out when the skill level needed has been achieved. In the future there might be regulations that restrict the possibilities to train in production. Three experts within the shotcrete industry from the organizations LKAB Berg & Betong, LKAB Malmberget and BESAB were asked to answer a number of questions about the profession as a shotcrete operator. They all indicated that the profession as a shotcrete operator is both difficult as well as very time consuming to learn, estimated training times ranged from 6 to 15 months to become an average-skilled operator. According to them, beginner operators also create much higher than normal amounts of concrete waste during the long training period. Answers indicated that both over-spraying as well as rebound might be as high as 40% during the initial training phases (Svensson, Pohjanen, Krutrök, personal communication).

Training of shotcrete operators with simulators

To amend the problems and high costs associated with training of operators the use of simulation may be a way forward. Simulation can and has been used in many different ways. One important application is simulators as tools for training. Operators in Nuclear Power Plants, Pilots, Doctors, and many other professions can train their skills with the help of advanced and realistic simulators. There are many advantages of using simulators as training tools. An advanced simulator makes it possible to have almost perfect control over the design and content of training programs, and makes it possible to repeat exactly the same training program until optimal learning is achieved, or adapt training programs individually, to a reasonable low cost. An advanced simulator also makes it possible to provide feedback of high quality by measuring the progress in training in a way that may be impossible in a similar real life situation. One important property of simulators used in training is that the training is useful when the same, or very similar task, is performed in a real life situation. This has to do with the external validity of a simulator, the extent to which performance in a simulator can be generalized to performance in other and real tasks. To achieve this goal, a simulator should be designed so that it works according to the same principles as the equipment used in a real life situation. Ideally it should have the same functions and work according to the same principles as the real equipment. As an example, an advanced car simulator should be perceived as (almost) a real car, have the same controls as a real car and respond in the same way as a real car to manipulation of its controls. To ensure that a simulator has the properties needed to be useful in training, it is necessary to establish the validity of a simulator, using established scientific methods. Validity can be defined as “the approximate truth of an inference” (Shadish, Cook and Campbell, 2002). A statement postulating that a simulator can be used for training with positive results is an inference and is normally supported by empirical findings and other sources of knowledge. Empirical findings are normally the result of different empirical tests. Other important sources of knowledge could be, for instance, evaluations made by people with relevant knowledge about the task or tasks that are simulated.

A simulator for training

In order to improve training of operators and speed up the training process and minimize the cost of training a simulator education tool has been designed by the company Edvirt AB. The simulator is equipped with a stereoscopic 3D or regular 3D visual system where a view of a tunnel can be projected. The equipment used to spray the walls and ceiling in the tunnel is also included in the 3D view. The operator controls the process with the help of a robot. Different robots from different robot brands can be used, such as Atlas Copco MEYCO and AMV that were used in the study. With the help of different controls on the robot it is possible to perform the task of spraying shotcrete on walls and ceiling. The simulator can provide real time feedback about thickness of the concrete layer and also warns if the spraying host is in the wrong direction. The aim of the simulator education tool tested in this report is, with the training program developed so far, to achieve the later rock support mentioned in the section above.

Aim of the study

In order to establish the validity of the simulator a research projects was initiated. Due to different restrictions it was not possible to perform an experimental study and an alternative solution was to use a number of experienced operators to validate the simulator. In addition a group of inexperienced operators were recruited. The experienced operators performed four different tests in the simulator and evaluated different aspects or properties of the simulator. The inexperienced operators were exposed to a training program for learning how to spray shotcrete on walls and ceiling in tunnels and performed the same four different tasks as the experienced operators. All operators also made ratings of mental workload after the performance of the different tasks. If the simulator, in the version used in the study, has an acceptable level of validity then the group of experienced operators should experience a lower level of mental workload compared to the inexperienced operators. They should also be able to perform the spraying tasks better compared to the inexperienced operators during the early phases of the training program. The experienced operators were also asked to make ratings of the simulators realism and suggestions for improvements of the simulator. Finally they were asked if they considered that the simulator could be used in the training of new operators.

METHOD

Subjects: Six inexperienced male operators and thirteen experienced operators, seven from LKAB and six from BESAB participated. The experienced operators varied in their experience of shotcrete spraying from 1 – 25 years. The inexperienced operators had no experience of performing robotic shotcreteing themselves.

Apparatus: Edvirt AB´s 3D Shotcrete Simulator was used in the study. Version 1.2 of the software was used in the simulator. The simulator has a number of subsystems. A visual system, in this study a 55 inch 3D TV, using stereoscopic 3D. The visual system is used to present a simulation of the equipment, the robot boom and nozzle, used in real life and a tunnel or a mine cavern. Several tunnels and mine caverns can be presented and used in training.

A sound system, used to present auditory feedback to the operator. The sound system presents realistic sound, based on a recording of the sound from an Atlas Copco MEYCO Potenza, working in Kiruna at the 1365 m level.

Several robots to control the spraying of concrete on the walls and ceiling(s) in a tunnel. In this study Atlas Copco MEYCO Potenza and AMV 6400 were used. The reason is that the operators that took part of the study were using those robots in reality and hence they could use the same robot as they normally are using in real life.

A shotcrete model: The adhesion model accounts angle and distance from nozzle to rock surface, accelerator level, concrete dosage, application time etc.

Control units: Same as supplied by machine manufacturer.

Modes: Practice mode (Free mode), Assignment Mode (Training scenarios).

Assignments: 18 levels. Operator training on control, robot booms, thickness optimization, waste management, rebound optimization, accelerator levels, spraying areas, corner spraying, avoiding drop-outs etc.

The simulator also includes safety increasing features such that it warns the operator if he/she walks under newly sprayed concrete, has too high/low accelerator level, starts with the nozzle pointing upwards etc.

Tools: The simulator has tools to help the operator when training. Some of them are, e.g. real-time thickness visualization, target precision indicator, spray pattern visualization for systematic spraying.

The equipment used in the training and testing of BESAB's operators has differences from the one used in testing LKAB's operators. The difference is in robots and control units. The operator stands next to the robot, often by the robot wheels, when maneuvering the Atlas Copco MEYCO Potenza robot. The operator sits inside a cabin on the AMV 6400 robot when maneuvering the boom and shotcrete hose.

The Hetronic control, supplied with the Atlas Copco MEYCO Potenza robot has four joysticks to maneuver the robot booms (see image 1). The AMV 6400 robot only has two (see image 2).

Image 1. Atlas Copco MEYCO Potenza

Image 2. AMV 6400

The different characteristics and designs of the robots and controls of course affect the spraying result of the operator. It's likely that the robots and designs have different advantages when possessed to different scenarios in tunnels and mines.

Procedure: All operators were informed about the aim of the project and were given an introduction about geology, safety in underground tunnels and buildings, how to improve the stability of the surrounding environment, factors affecting the quality of work done, etc. They were informed that participation in the study was mandatory and that they could decide to stop at any time if they so wished, without any demand on explaining why.

The training conducted on the inexperienced operators was performed in Betongsprutnings Aktiebolaget BESAB's facilities in Stockholm and Gothenburg. BESAB has a 3D Shotcrete Simulator unit, equipped with the robot Atlas Copco MEYCO Potenza (see image 1 and 2) and the remote hand control from Hetronic (see image X). The simulation of the is displayed on a 55 inch 3D TV, using stereoscopic 3D. Version 1.2 of the 3D Shotcrete Simulator was used during training and testing.

The testing of the experienced operators from BESAB was conducted in Stockholm and Gothenburg, using the same equipment. The testing on the experienced operators from LKAB was conducted in Malmberget, using LKAB's equipment. LKAB has a 3D Shotcrete Simulator unit, equipped with the robot AMV 6400 (see image 1 and 2) and the hand control from AMV. The simulation of the robot boom and nozzle is displayed on a 55 inch 3D TV, using stereoscopic 3D. Version 1.2 of the 3D Shotcrete Simulator was used during the tests.

The experienced operators were first given instructions on how to use the simulator before testing them. They also got to familiarize themselves with the simulator by practicing in "Practice mode" for 10 minutes, practicing "Assignment 7" for 10 minutes and "Assignment 11" for 10 minutes. In total the experienced operators got to familiarize themselves with the simulator for 30 minutes before doing the tests.

The specification below shows the design of the tests. The operators got a short description on what to do on each test. This is shown under "Description" and "Criteria" below. The tests were not time limited, so the operators had to decide for themselves when they considered the tests to be finished, meaning when they thought they had performed according to specification.

Tests

Four tests for the operators were created for this study, numbered from 1 to 4. All inexperienced operators went through all the four tests. Test 1 was performed after one day of practice, i.e., while still very inexperienced with the shotcreting process. Test 2, 3, and 4 were performed at the end of the two week training period.

The experienced operators performed Test 1, 2, 3 and 4 after a 30 minutes warm up period. Test 1 will be used to evaluate the performance of spraying between inexperienced and experienced operators. Test 2, 3, and 4 will be used to evaluate how much the performance of the inexperienced operators has improved after two weeks of training.

Test 1

Description: Spray an area according to a specification.

Environment: A normal working environment in a mine. Uneven blasted surfaces.

Area: A 4m by 3m area was placed on the left side of the tunnel wall. (12 square meters).

Criteria: The operator was given the instruction to spray 75 mm inside the marked area in the tunnel.

Tools: No tools were provided. The concrete output volume was fixed at 12 m^3/h. The accelerator dosage volume was fixed at 5,5 %.

Test 2

Description: Spray an area according to a specification.

Environment: A tunnel emulating a TBM drilled tunnel. The tunnel was circular and had a very smooth and even surface.

Area: A 3m by 3m area was placed on the left side of the tunnel wall. (9 square meters)

Criteria: The operator was given the instruction to spray 100 mm inside the marked area in the tunnel.

Tools: No tools were provided. The concrete output volume was fixed at 12 m^3/h. The accelerator dosage volume was fixed at 5,5 %.

Test 3

Description: Spray an area according to a specification.

Environment: A normal working environment in a mine. Uneven blasted surfaces.

Area: A 4m by 3m area was placed on the left side of the tunnel wall. (12 square meters).

Criteria: The operator was given the instruction to spray 75 mm inside the marked area in the tunnel.

Tools: No tools were provided. The concrete output volume was fixed at 12 m^3/h. The accelerator dosage volume was fixed at 5,5 %.

Test 4

Description: Spray an area according to a specification.

Environment: A normal working environment in a mine. Uneven blasted surfaces.

Area: A 50 square meter area was placed on the left, top and right side of the tunnel wall. The area was placed in the very end of the tunnel.

Criteria: The operator was given the instruction to spray 75 mm inside the marked area in the tunnel.

Tools: No tools were provided. The concrete output volume was fixed at 12 m^3/h. The accelerator dosage volume was fixed at 5,5 %.

Performance measures: The total volume (m3), rebound (m3), excess volume (m3), mean thickness of the concrete layer (cm) were used as dependent performance measures.

Subjective measures: After completing all test tasks, the operators were asked to make ratings of mental workload, using the NASA - RTLX questionnaire. After answering that, the experienced operators were asked to make ratings concerning the realism and usefulness of the simulator. This was made using a questionnaire with rating scales and open answers. Ratings were made concerning the overall realism of the simulator on a rating scale, ranging from 1 = not realistic at all, through 7 = very realistic. Ratings were also made concerning the realism of the simulator when different subtasks were performed, using the same rating scale. The subtasks were: to keep a correct distance and angle to the area to be sprayed, to apply a layer of a certain thickness, to perform the task quickly, to follow a pattern when spraying the surface. For each rating made, the subjects also were asked to state what they considered to be the largest differences between performing the job with a simulator and performing the same task in real life, with real equipment. Finally they were asked to suggest how the simulator should be improved to be more realistic and if, in their opinion, believed that the simulator could be used as a tool for learning the task. A complete version of the questionnaire used can be found in the Appendix, annex 1.

RESULTS

The results from tests 1 through 4 will be presented here and a comparison will be made between the performance of the experienced and the inexperienced operators. The concrete output volume in all tests was fixed at 12 m^3/h. The accelerator dosage volume was fixed at 5,5 %. The speed of the robots booms was also fixed according to factory defaults.

Test 1- spray a marked area 4 by 3 meters on the left side of an uneven blasted surface with a layer of 75 mm concrete. The results are shown in Table 1 below.

Table 1. Performance in test 1 as a function of experience of spraying

	Group	
	Experienced	Inexperienced
Total volume (m3)	1,188	1,820
Rebound (m3)	0,295	0,363
Excess volume (m3)	0,362	0,732
Mean thickness (cm)	10,650	13,317

As can be seen from Table 1 the group of experienced operators used a considerably lower volume of shotcrete and produced a lower volume of rebound compared to the inexperienced operators. The mean thickness of the concrete layer was also closer to the requested level. Tests for significant differences were performed using two tailed t-tests with a significance level of p = 0.05. This showed a significant differences for volume, t_{17} = 2,350, p = .031 and a significant difference for excess, t_{17}=

2,284, p = .036. No other differences were significant. From Table 1 it can also be seen that the average thickness of the shotcrete layer was higher than the requested layer of 75 mm for both groups.

Test 2 – spray a marked area 3 by 3 meters on the wall of a circular tunnel with a smooth and even surface with a layer of 100 mm concrete. The result from this test is shown in Table 2 below.

Table 2. Performance in test 2 as a function of experience of spraying

	Group	
	Experienced	Inexperienced
Total volume (m3)	1,508	1,309
Rebound (m3)	0,466	0,100
Excess volume (m3)	0,534	0,688
Mean thickness (cm)	15,641	15,251

As can be seen from Table 2 the group of experienced operators used a slightly higher volume of shotcrete and produced a higher level of rebound compared to the inexperienced operators. On the other hand the excess volume was lower for the group of experienced operators. Tests for significant differences were performed using two tailed t-tests with a significance level of p = 0.05. This showed a significant differences for rebound, t_{17} = 2,720, p = .015. No other differences were significant. From Table 2 it can also be seen that the average thickness of the shotcrete layer was higher than the requested layer of 100 mm for both groups.

Test 3 – spray a marked area of 4 by 3 meters on an uneven blasted surface with a 75 mm thick layer.

Table 3. Performance in test 3 as a function of experience of spraying

	Group	
	Experienced	Inexperienced
Total volume (m3)	1,188	1,243
Rebound (m3)	0,295	0,155
Excess volume (m3)	0,362	0,380
Mean thickness (cm)	10,65	10,50

As can be seen from Table 3 there are only minor differences between the groups of operators with the exception of rebound. A two-tailed t test revealed a significant difference between the groups, $t_{17} = 2{,}452$, $p = .025$. It is also possible to see that the average layer of concrete is higher for both groups compared to the requested value of 75 mm.

Test 4 – spray a 50 square meter area placed on the left, top and right side inside a marked area with a layer of 75 mm.

Table 4. Performance in test 4 as a function of experience of spraying

	Group	
	Experienced	Inexperienced
Total volume (m3)	5,619	5,675
Rebound (m3)	1,611	0,730
Excess volume (m3)	1,265	1,692
Mean thickness (cm)	8,447	9,815

From Table 4 we can only see small differences between the groups with the exception of rebound. . A two-tailed t test revealed a significant difference between the groups, $t_{17} = 3,681$, $p = .002$. It can also be seen that both groups produced a thicker average layer than the requested layer of 75 mm.

Measures of mental workload

After the performance of the four tests each subject was asked to make ratings of mental workload, as measured by NASA – RTLX. It was expected that the inexperienced operators would make higher ratings of mental workload compared to the experienced operators. Table 5 shows the mean rating and standard deviation for each component in NASA-RTLX for the experienced and inexperienced operators.

Table 5. Ratings of mental workload as a function of operator experience

	Number of subjects	Mean rating	Standard deviation
Mental demand			
Experienced	13	4,26	2,48
Unexperienced	6	6,09	2,08
Physical demand			
Experienced	*13*	*1,16*	*1,69*
Unexperienced	*6*	*2,17*	*1,67*
Time pressure			
Experienced	13	1,75	1,46
Inexperienced	6	3,62	1,72
Achievement			
Experienced	13	5,09	1,46
Inexperienced	6	5,66	1,72

Effort			
Experienced	13	4,83	2,67
Inexperienced	6	6,97	1,25
Frustration			
Experienced	13	3,08	2,60
Inexperienced	6	6,10	2,01

As can be seen from Table 5 the average ratings of the different components in NASA RTLX were higher for the group of inexperienced operators for the components mental and physical demand, time pressure, effort and frustration. The differences between the two groups of operators were tested with independent t-tests. Significant differences were found for "time pressure" (t_{17} = 2,167, p = .044), "frustration" (t_{17} = 2,700, p = .015) and effort (t_{17} = 2,438, p = .025).

Ratings of simulator properties and open comments

How realistic was it to perform the task in the simulator? How well did the tasks in the simulator correspond to similar tasks in a real environment with real equipment?

The average rating on the seven step scale (1= not at all realistic, 7 = very realistic) was 4,7. Ratings varied between two through six.

The most important differences between the simulator and a real task

- In the simulator it is harder to perceive the distance between the nozzle and the area to be sprayed compared to a real life situation. (N=10)
- The robot's booms in the simulator reacted slower compared to a real life situation. (N=7)
- The visual field in the simulator is more restricted compared to a real life situation where you can change your own position in order to inspect the layer sprayed. (N=9)
- In the simulator it is harder to see how the concrete spreads out when the job is performed. (N=2)
- Lack of auditory feedback in the simulator. In a real life situation you can use auditory feedback to perform the job better. (N=4)

- In a real situation you can see and hear waste, concrete that bounces back and falls down. (N=7)
- In a real life situation it is easier to see the thickness of a layer sprayed on a surface. (N=2)

How realistic was it to keep a correct distance to the surface that should be sprayed?

The average rating for this subtask was 3,9 and ratings varied between two through six.

The most important differences between the simulator and a real task

- It is harder to perceive the distance between the nozzle and the surface in the simulator
- Limitations of the visual field in the simulator
- No possibility to change your own position in the simulator
- It is harder to perceive rebound in the simulator

How realistic was it to keep the correct angle to the surface?

The average rating for this subtask was 4,3 and ratings varied between three through six.

The most important differences between the simulator and a real task

- The movement of the nozzle is to slow
- It is harder to see the angle in the simulator
- It is not possible to change your own position in the simulator
- It is harder to perceive waste in the simulator

How realistic was it to apply a layer of requested thickness in the simulator?

The average rating was 3,8 and ratings varied between two point five through six.

The most important differences between the simulator and a real task

- In a real life situation you can easier see the edge between a sprayed and a not sprayed surface
- It is possible to move around in real life and inspect from different positions
- It is easier to use other references in a real life situation
- The simulator is different to a real situation where you can count the number of pump strokes and use that as a reference

How realistic was it to perform the task quickly?

The average rating was 4,6 and ratings varied between two through six.

The most important differences between the simulator and a real task

- The effect of the pump in the simulator was to low
- No information of waste in the simulator

How realistic was it to follow a certain pattern when spraying the tunnel?

The average rating was 5,8 and ratings varied between two through seven.

The most important differences between the simulator and a real task

- The robot’s booms in the simulator are to slow
- No information of return goods
- No possibility to move around and inspect the job

How should the simulator be improved to be more realistic?

- Increase the speed of the robot in the simulator and make it faster
- Provide information concerning waste
- Improve the visual system so that it is easier to make judgments of distances
- Make it possible to move or change your own position

According to your opinion can the simulator in its present design be used to train operators?

- All operators were positive to the use of the simulator as a training and learning tool.

DISCUSSION

The results from this study showed that the experienced operators performed significantly better initially, on Test 1, when the inexperienced operators still were inexperienced. The group of experienced operators also worked quicker during task 1, compared to the inexperienced group. The difference in time spraying was significant ($t_{17=}$ 2,632, p = .017). A reasonable interpretation is that the skills experienced operators already had acquired caused the difference in time needed to perform the task. It is also an indication of the validity of the simulator, since knowledge from performing similar tasks in a real life situation could be used to perform the task in the simulator.

The difference in time spraying and other measures of performance disappeared when the group of inexperienced operators had been exposed to a two week long training program. Furthermore, the group of inexperienced operators produced significantly lower volumes of rebound in the following three tests.

The finding that the difference in performance, and time needed to finish the different tasks, disappeared after the training of the inexperienced operators can be interpreted as an effect of the training in the simulator. The manual task of controlling the equipment, steering the robot and changing directions of the nozzle, can be trained in the simulator until an acceptable level of skill is achieved. To follow a certain pattern when spraying can also be trained in the same way. To produce a layer of a certain thickness is probably a task that either is supported by visual input or input by estimating time, or a combination of both sources. The visual input in a simulator will probably be of lower quality compared to the visual input in a real life situation, but can be compensated in the simulator by adding appropriate information on a display. Time or timing can be used, but the effect or concrete output volume in the simulator should match the output in a real life situation to be maximally useful for learning the relation between time used for spraying and thickness of a layer. Feedback on rebound also plays a role in the creation of a layer with a certain thickness. An interesting finding was that the group of inexperienced operators produced lower levels of rebound compared to the experienced operators after training for two weeks in the simulator.

The fact that the difference in performance disappeared after the training period for the inexperienced operators may also depend upon the level of difficulty of the test tasks and the measures used to assess performance. An interesting future task is to develop more measures to assess performance in the simulator, measures with a strong implication for safety.

It is not possible to know with certainty why the inexperienced operators produced lower volumes of rebound compared to the experienced operators, after the learning period. A reasonable explanation is that the feedback provided by the simulator caused this effect. In the simulator it is possible to receive real time feedback concerning the thickness of the shotcrete layer, something that is not possible in a real life situation.

On the other hand, the experienced operators indicated that the feedback they received in the simulator deviated slightly from the feedback they received in a real life situation. This could be a possible explanation of the fact that the experienced operators produced higher levels of rebound in Tests 2 – 4. From some verbal reports it was stated that in a real life situation an operator may use auditory feedback to control the process. Changes in sound may, according to some operators, provide valuable information about the process. Still another possible explanation may be that in a real life situation there is a conflict between the speed of the process and the cost caused by rebound, and that speed is the dominating factor for experienced operators.

Another factor that probably had an impact on the results was that the experienced operators from LKAB sometimes work outside the robot cabin and that they are able to shift position in order to inspect the progress of spraying. This was not possible in this study and may have had a negative impact on the performance of the operators from LKAB.

The expectation that the mental workload of the experienced operators would be lower compared to the inexperienced operators was supported. This may be interpreted as an indicator of the simulators validity. A reasonable interpretation is that the similarities between a real task and the task performed in the simulator made the experienced subjects experience a lower level of mental workload. They already had a mental model of the task to be performed in the simulator, which had a positive impact on their level of workload. A reasonable interpretation of this is that the simulator can simulate real tasks with some precision.

The subjective ratings of the realism to perform the tasks in the simulator, compared to performing the same tasks in real life, showed a reasonable correspondence between the simulator tasks and the real life tasks. It should be noted that performing a task in a simulator never can be identical with performing the same task in real life. A rating of maximal correspondence between a task performed in a simulator and real life should not be trusted.

The most important differences between the tasks performed in the simulator and in real life were, according to the skilled operators, of perceptual nature. It is harder to perceive the distance between the nozzle and the area to be sprayed in the simulator. The same problem was reported for the possibility to perceive the angle of the nozzle, towards the area to be sprayed. This is not at all surprising, since a common problem for all simulators presenting a visual image on a screen is to simulate a three dimensional world on a two dimensional, flat or curved, screen. In this version of the simulator 3D glasses were used to create a three dimensional world.

From the interviews it was also pointed out a difference between auditory feedback in real life and in the simulator. To spray an area correctly the operators rely on visual as well on auditory information. Auditory information can be used to get feedback concerning the quality of the shotcrete used (if the accelerator is lacking, or the doseagee is to littlel, the sound when the shotcrete hits the surface will change). It can also provide information concerning the angle and distance to the area to be sprayed and the amount of rebound.

Another important difference between the simulator and a real life situation were caused by differences in the pace or speed of the AMV robot in the simulator. Operators from LKAB also considered the concrete output volume of the simulator to be much lower compared to a real life situation.

A final important difference was that the operators from LKAB who normally could stand outside the truck and inspect their job from different perspectives could not do so in the simulator study.

Conclusions about validity

Judging from the results in this study a reasonable conclusion is that the simulator, in the version used in the study, has validity enough to be used as a training tool. The predictions about performance and mental workload were both validated. In addition, the judgments of the experienced operators are important. All experienced operators considered that the simulator, in the version used in the study, could be a good or valid tool for training of operators. Some of the most common differences between the robot in the simulator and a real robot, the concrete output volume and the speed of the booms, can easily be changed and adapted to a more normal working situation. The advices for improving the simulator, such as better feedback concerning rebound, can be used to improve the validity of the simulator.

The comparisons between inexperienced and experienced operators showed that inexperienced operators could perform their tasks as well as the experienced operators, after two weeks oftraining. In the simulator the operators can learn to control the system by using their control devices and learn the manual parts of the task. This can be done repeatedly, until the learning of the manual skills are good enough, and at a lower cost compared to training in a real situation with real equipment.

Recommendations for development

The evaluation of the simulator made by the experienced operators resulted in also pointed in a number of suggestions for improvement.

Based on the interviews and ratings some suggestions for development of the simulator can be given. The task to spray concrete on an uneven surface and produce a layer of a specified thickness is a task dominated by visual input. The operator must be able to see the result of his or her job. One recommendation is to improve the quality of the visual system in the simulator, and, if possible make the 3D impression stronger.

It was also indicated that auditory feedback plays an important role when performing the job. Auditory feedback can be used to hear if the amount of accelerator in the shotcrete is optimal and if material bounces back from the surface and falls down. One operator also mentioned that the strokes of the pump can be counted to get an impression of the thickness of the layer produced. A recommendation is to improve the auditory feedback in the simulator and especially the type of feedback that can give information about rebound.

It was also pointed out that, especially from the operators at LKAB, that the robot in the simulator was slower and that the effect of the pump was lower compared to a normal work situation.

References

Barton, N. (2003). Rock mass classification and support design. NGI, Norway

Shadish, W.R., Cook, T.D.,Campbell, D.T. (2002). Experimental and Quasi-Experimental Designs. Houghton Mifflin Company, U.S.A

Hart, S.G., Staveland, L.E., (1988). Development of NASA TLX (Task Load Index): Results of Empirical and Theoretical Research, ref in P.A. Hancock and N. Meshkati (Editors), HUMAN MENTAL WORKLOAD, Elsevier Science Publishers B.V. North-Holland.

Hollnagel, E. (2004). Barriers and Accident Prevention. Ashgate, ISBN 0754643018

Appendix, annex 1

Frågor efter simulator uppgifterna

- Hur realistiskt upplevde du att det var att arbeta med betongsprutning i simulatorn? Hur bra liknade arbetet i simulatorn ett motsvarande arbete i verklig miljö med verklig utrustning?

1 ------- 2 ------- 3 ------- 4 ------- 5 ------- 6 ------- 7

Inte alls realistiskt Mycket realistiskt

- Vilka tycker du var de största skillnaderna mellan att genomföra jobbet i simulatorn jämfört med att göra samma uppgift i verklig miljö? Ange så många skillnader du kan!

Om vi tittar på olika delmoment som du genomför under simulatorstudien, hur realistiskt eller likt verkligheten upplevde du att de var?

- Hålla rätt avstånd till ytan som ska beläggas med betong

1 ------- 2 ------- 3 ------- 4 ------- 5 ------- 6 ------- 7

Inte alls realistiskt Mycket realistiskt

På vilket eller vilka sätt var det en skillnad mellan simulatorn och arbete i verklig miljö med verklig utrustning?

- Hålla rätt vinkel mot bergytan

1 ------- 2 ------- 3 ------- 4 ------- 5 ------- 6 ------- 7

Inte alls realistiskt Mycket realistiskt

På vilket eller vilka sätt var det en skillnad mellan simulatorn och arbete i verklig miljö med verklig utrustning?

- Lägga lagom tjockt lager betong

1 ------- 2 ------- 3 ------- 4 ------- 5 ------- 6 ------- 7

Inte alls realistiskt Mycket realistiskt

På vilket eller vilka sätt var det en skillnad mellan simulatorn och arbete i verklig miljö med verklig utrustning?

- Genomföra arbetet snabbt

1 ------- 2 ------- 3 ------- 4 ------- 5 ------- 6 ------- 7

Inte alls realistiskt Mycket realistiskt

På vilket eller vilka sätt var det en skillnad mellan simulatorn och arbete i verklig miljö med verklig utrustning?

Genomföra arbetet genom att följa ett visst mönster för att spruta betong?

1 ------- 2 ------- 3 ------- 4 ------- 5 ------- 6 ------- 7

Inte alls realistiskt Mycket realistiskt

På vilket eller vilka sätt var det en skillnad mellan simulatorn och arbete i verklig miljö med verklig utrustning?

Hur tycker du att simulatorn bör förbättras för att bli så lik en verklig uppgift i en verklig miljö? Ange så många förbättringsförslag som du kan!

Tack för din medverkan!