USE OF IMMERSIVE 3D VIRTUAL REALITY ENVIRONMENTS IN CONTROL ROOM VALIDATIONS

Joakim Bergroth
Fortum Power and Heat Oy
Keilaniementie 1, Espoo, P.O.Box 100, 00048 FORTUM, Finland
Email: joakim.bergroth@fortum.com

Hanna Koskinen, Jari Laarni
VTT Technical Research Centre of Finland
Vuorimiehentie 3, Espoo, P.O.Box 1000, 02044 VTT, Finland
Email: firstname.lastname@vtt.fi

ABSTRACT

Advanced technologies (e.g., virtual and augmented reality) may provide new possibilities to facilitate control room (CR) design and evaluation activities. We studied how immersive 3D environments may augment and advance the evaluation of safety-critical CR systems. The 3D virtual reality (VR) CR was compared with a real-life development simulator environment where hardwired panels were substituted with Virtual panels. A multi-user functionality enables several operators to be and collaborate in the same VR CR environment at the same time. There is also a realistic representation of emergency operating procedures in the VR CR. Spatial audio communication through headsets makes the experience even more realistic. The results section of the paper address both technical and human factors issues associated with the use of immersive 3D VR environments in CR validation tests, e.g.: amount of technical resources required as compared to normal validation in a real-life simulator environment, creation of methodologically new testing opportunities and new opportunities to data registration and analysis.

Key Words: Control room; validation; virtual reality, immersion.

1 INTRODUCTION

There is a general trend to move towards continuous engineering and validation in order to avoid integration challenges and expensive design iterations at the late phases of the design process. That is, the evaluation efforts need to extend over the whole lifetime of the developed system and cover everything from requirement elicitation, concept design to gradual maturation of an individual concept idea/solution to final product and its implementation and appropriation in use. Availability of simulator facilities that would allow reliable analysis of the usability and user experience of proposed user interface (UI) solutions is a real bottleneck in evaluating the control room (CR) systems in early phases of design. There is a trade-off between the fidelity of simulator environments and the amount of resources (time and financials) needed for their construction. That said, there is a clear need for more flexible and agile methods and tools enabling evaluation of CR systems in early phases of design and development. Advanced technologies (e.g., virtual and augmented reality) may provide one new possibility to facilitate these early evaluation activities. We studied how immersive 3D virtual reality (VR) environments may augment and advance the evaluation of safety-critical CR systems. A feasibility study was carried out to explore and test the qualities and potential usefulness of the VR CR to support CR evaluations in an early phase of a design process. Furthermore, the evaluation conducted in the VR CR was compared with a similar evaluation that was done in a real-life development simulator environment.

All together two crews (six licensed operators) participated in the evaluation session. The evaluation test consisted of a set of smaller monitoring and operating tasks and one complete scenario run simulating an accident situation causing a serious danger of losing the main CR and causing an immediate move of the crew to the emergency control post. The evaluation session was registered by audio/video recordings and by notes. As a reference for the VR CR study, the results of the same scenario run realized in the development simulator environment with the Virtual panels (i.e., desk and wall-mounted touch screen based UIs replicating hardwired operating panels) was used.

2 CR EVALUATION OPPORTUNITIES PROVIDED BY VR TECHNOLOGIES

According to Wikipedia, virtual reality can be defined as "computer technologies that use software to generate the realistic images, sounds and other sensations that replicate a real environment and simulate a user's physical presence in this environment". VR technologies evolve rapidly, and their features and functionalities improve at a constant rate. For example, head/mounted VR devices provide a low/budget option to generate immersive and interactive virtual environments, and innovations such as hand tracking controllers and force feedback provide more realism and sense of presence to the interaction.

There are some recent studies suggesting virtual reality simulations provide new opportunities for control room evaluations [1, 2, 3]. It is common to these studies that a virtual environment has been used as a tool for ergonomic evaluation of CRs (e.g., validating the physical CR layout). However, since dynamic real-time simulation of the target process has not been possible in these studies, evaluation of lifelike interaction and functional characteristics of the UIs has not been done.

3 VR SIMULATION OF THE FORTUM LOVIISA NPP CONTROL ROOM

VR CR design started in Fortum Control Centres & HMI team, because there was a need to have a better tool for evaluating CR layouts. As the layout design is nowadays done in 3D design software, this part was basically just a design import task to another design environment. In Fortum we realized the power of this new immersive technology, and continued to develop the VR CR and add functionalities in order to make the VR CR usable also in validations and training, with all the relevant functionalities implemented: emergency operating procedures (EOPs), dynamic hardwired-panels, monitoring system, needed communication channels etc. (see Figure 1). During the development, the scope of usage have increased, and we are now integrating both the field operators and CR operators into the system in a way that has not been possible with regard to physical simulators. In addition, operator and technician training is planned to be implemented in virtual environments.

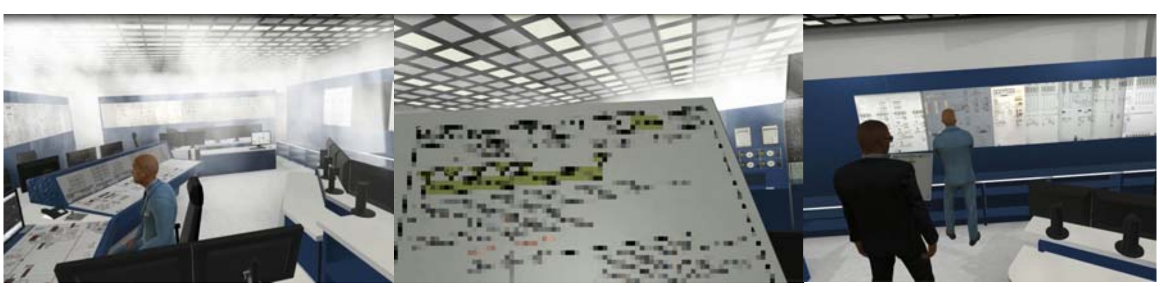


Figure 1. Fire and smoke in the MCR, EOPs (blurred) and control operations on the hardwired-panel

3.1 Technical descriptions

Apros® (www.apros.fi) is a multifunctional software for modelling and dynamic simulation of nuclear and thermal power plants as well as industrial processes. It has been developed for over 30 years by Fortum and VTT engineers, and it has been taken into use in 27 countries. Fortum uses Apros® very intensively in safety analyses, process and automation design, automation testing, and it runs the process in the current physical training simulators. Apros® is used in the VR CR as well to simulate the process.

In the VR CR the physical VR workstation includes a computer with a high-end graphic card, Oculus Rift –headset, Oculus-remote controller, keyboard and mouse. VR CR is used in seated position in front of the workstation, wearing headset and using controller, keyboard and mouse to interact with the VR CR (see middle in Figure 2).

VR CR uses Unity cross-platform engine as its main development environment. Unity supports a mass of 3D-model formats and with its engines it is possible to build realistic environments to VR CR. Unity also includes NVidia's PhysX physics engine which allows to create scenarios with realistic physical attributes of the environment and objects that can dynamically interact with each other.

VR CR uses Oculus Rift-virtual glasses and Oculus remote as its main user interface. Headset and other VR devices use Constellation- tracking system, which is constructed from separate infrared tracking sensors and infrared LEDs, which allow accurate positional and rotational tracking.

Rotation and position data affects the operators rendering angle and position inside the 3D space and is also used to create accurate 3D audio simulation. Operators use Oculus remote to move and rotate inside the VR CR, which includes four inputs for movement and two inputs for functional purposes. Functional inputs are the main mode to interact with objects and operating systems inside the VR CR. Two different ways of moving was possible to choose from; one, where it was possible look around while walking without changing walking direction (i.e. how we do it in real life), and another one, where walking direction could be changed by head movement.

Every operator in the VR CR has his/her own avatar. Avatars use animations inside of Unity, which represents operators' movements and actions in the VR CR. These animations vary from walking forward to sitting and using computers in a realistic manner. In addition, the headset movements and rotations are included to these animations so that the operators can see what other crew members are looking at and what operating system they are using at the time. Operators' movement, rotation and object interaction data is transformed through a network to other users where it is represented in real-time.

Operation of different process related control systems in the VR CR is simulated as realistically as possible in order to get the most accurate operating experience. Operators use the same HMIs as in the real CR (see Figure 2).

Figure 2. Layout of the physical room space in which the validation test was organized, VR workstation setup and first person view of shift supervisor in the VR CR

4 METHODS AND HYPOTHESES

Participants: Two operator crews (altogether six licensed operators, two shift supervisors, two reactor and two turbine operators) were recruited for the VR CR evaluation study. Participating operators' work experience in years ranged from six to over 25 years of experience working in the field. Operators estimated their own eyesight to be in the level of good or satisfactory, and two of the participating operators reported to use spectacles or contact lenses during the evaluation tests. Furthermore, the participating operators were well familiar with the ongoing CR modernization project, to which the tested UIs and operating procedures were related. However, none of the participating operators was familiar with the VR CR development nor did they have any prior experience on using 3D environments for gaming or other purposes.

Procedure: Two separate test days (one day per operator crew) were reserved for the evaluation of VR CR environment. The test day began with a short introduction to the main motivation and goals of the evaluation. After which the operators were asked to fill in a background questionnaire. The operators also received a short training in which they were instructed the basic functionalities and ways of interacting in the VR CR environment. Two optional ways how to move and steer the avatar in the VR CR were walked through. The operators also got decent time to individually explore and practice the use of the VR CR environment and select the most suitable way of moving in the VR CR.

The actual evaluation consisted of two main parts: a set of smaller monitoring and operating tasks and one complete scenario run. The set of smaller tasks were assessed by the operators with regards five questions that were given a numerical assessment in a 5-point Likert scale (1=very bad, 5=very good). The scenario run was simulating an accident situation causing a serious danger of losing the main CR because of a sudden fire and an immediate move of the operating crew to the emergency control post. Immediately after the scenario run, multiple questionnaires (questionnaires about the spatial presence, and about the simulator sickness as well as the NASA task load index questionnaire) were handed out to the operators to fill in. As a final assignment, the operators completed the Systems usability questionnaire [4].

Data recording: The evaluation sessions were audio and video recorded. Two physical video cameras were setup in the room space were the evaluation was organized. In addition to these physical cameras that were aimed at capturing the operator activity with the VR-headset and workstations, a set of virtual cameras were placed in the VR CR environment. Two stationary virtual cameras were positioned in the VR CR environment; one capturing the overview of the VR CR and the other capturing a close-up view of the emergency control post. Also a third, movable virtual camera was tested during the scenario run. This virtual camera was controlled by one of the human factors experts. Further, also the first person views of each operator was captured. In addition to the video data, process data and control actions with time stamps was saved for further analyses.

4.1 Hypotheses of the study

The following hypotheses were proposed and tested:

- VR simulations enable an early evaluation of CR systems cost-effectively, rapidly and reliably.
  - Evaluations in VR CR can produce relevant human factors findings/observations.
- VR environments provide new tools and methods for CR evaluations.
- VR simulations provide new opportunities to CR design and operator training.

5 RESULTS

5.1 Monitoring and operating tasks

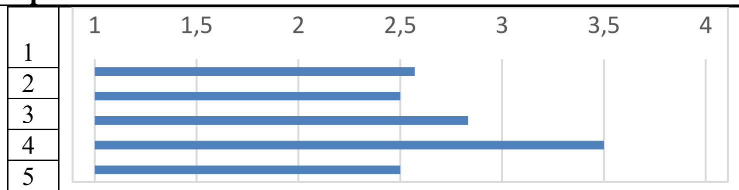
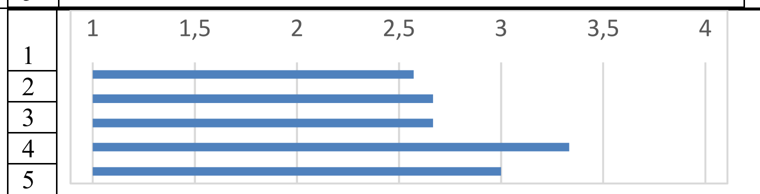
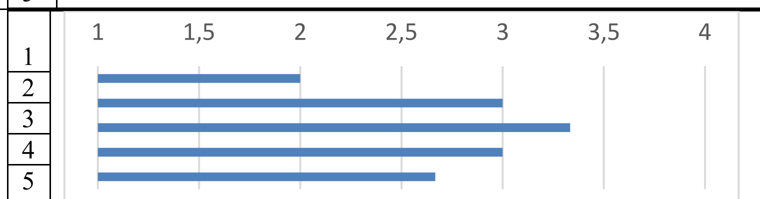
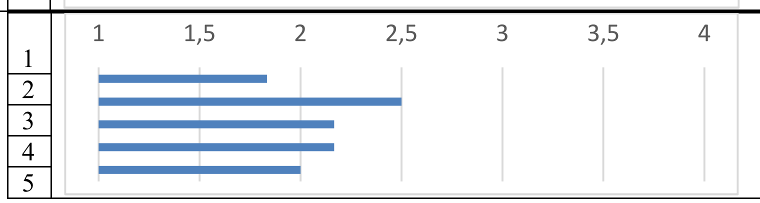
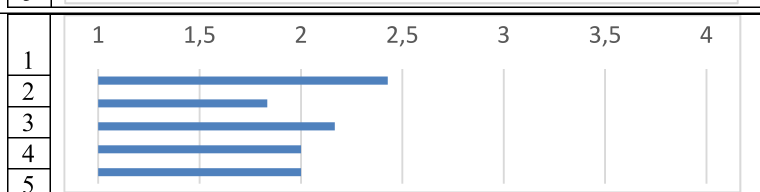
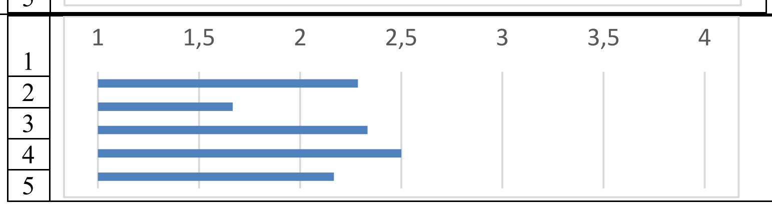
The first part of the evaluation session consisted of a set of individual monitoring and operating tasks. Three specified tasks concerned the monitoring qualities, two tasks were simple operating tasks and one task concentrated on the procedure usage (Table 1). After each individual task execution, the operators were asked to assess the monitoring and operating qualities of the VR CR with regards five questions that were given a numerical assessment in a 5-point Likert scale (1=very bad, 5=very good). The five specified questions were: 1. How *accurate* you experienced the monitoring/operating? 2. How *natural* you experienced the monitoring/operating? 3. How *fast* you experienced the monitoring/operating? 4. How *reliable* you experienced the monitoring/operating? 5. What is your *overall estimation* of the monitoring/operating qualities of the VR CR?

Three tasks focused on the monitoring qualities of the VR CR, and they concerned monitoring the process state, state and alarm light indicators, and meter and dial displays (see Table 1). The monitoring and observation of the process state in VR CR, were experienced relatively natural and thus regarding the question 2 assessed “fairly” good by the participating operators. The other four questions on perceiving the process state were assessed to be at an average level. The overall assessment (i.e., question 5) and the naturalness (i.e., question 2) of the monitoring of the state and alarm light indicators were experienced “fairly” good. Regarding the other three questions about the light indicators, the evaluations were at an average level. When assessing the monitoring of meters and dials the accuracy (i.e., question 1) was evaluated to be weaker than average. The resolution of the meter and dial displays were reported to be the main reason for this estimate. However, the estimates regarding the other four qualities were positive.

Control operations were the main topic in two tasks (see Table 1). Operation of valve and pump elements received a negative evaluation. Only the naturalness of the control operations were estimated to be average that is, “nor good or bad”. The overall grade may have been brought down by the fact that the shift supervisor was assigned to monitor the execution of the control operations but because of the technical limitations in the VR CR, he could only see the operators standing in front of the control panel not the actual physical hand movement manipulating the control element. The operating task concerning the emergency shutdown operation was defined as follows: first, the shift supervisor gives a command to execute the emergency shutdown operation after which the operators execute it and then monitor the shutdown’s immediate effects on the process. All the estimations concerning the emergency shutdown operation were below the average. Especially, the naturalness (i.e., question 2) of the operation was assessed to be “fairly” bad. According to the operators, the reason for this was that the UI (i.e., shutdown button) did not provide tactile feedback. Moreover, after the emergency shutdown operation, the VR CR did not “come to live” in the same way as the physical CR does (as during the test session most of the control panels were just mock-ups and not connected to the actual process simulator, while resources on the shared server needed to be kept free for other processes).

A procedure related tasks (i.e., taking the procedure into use, reading it and changing pages) received an overall assessment of “fairly” bad. Naturalness (i.e., question 2) of the procedure usage was rated as the poorest quality. The operators complained that the procedures in VR CR did not support their normal procedure usage patterns. For example, usually when applying a procedure the operators first take an overall look at the procedure and then quickly glance at the control panels to locate the right control elements, after which they get back to reading the procedure more carefully. The alternate reading of the procedure and monitoring the process/ surroundings should be much more effortless in order to receive higher scores from the operators.

Table 1. A summary of the results concerning the smaller monitoring and operating tasks.

Task		Operators' assessment	Improvement needs
Monitoring	Process state		- all relevant information needs to be made available in VR CR - resolution of the VR CR needs to be improved
	State and alarm light indicators		- in physical CR environment the state light indicators can be seen from further off
	Meters and dials		- resolution of the meter and dial displays needs to be improved
Operating	Valve and pump control elements		- the shift supervisor can only see the operator being in front of the control panel but not the actual control operation as physical hand movement
	Emergency shut down		- no tactile feedback from the control operation - VR CR did not "come to live" the same way than the physical CR
Procedures	Procedure and reading, page change		- does not support normal procedure usage patterns (e.g., glancing at environment while applying procedure) - procedure blocks the whole view

5.2 Scenario run

The second part of the VR CR evaluation session included one complete scenario run in which an accident situation causing a serious danger of losing the main CR because of a sudden fire and an immediate move of the operating crew to the emergency control post was simulated. The shift supervisor first picked up the right EOP for the situation, and gave the operator-specific procedures to each operator. The operators then performed actions according to their procedures. After a while, the shift supervisor made the (right) decision to start following the "loss of main control room" -EOP, and again handed the right procedures to the operators. When the crew had executed the necessary operations, and the CR started to be filled with thick smoke, they left the main CR and walked to the emergency control post, which is located in the main CR of unit 2, to perform and finalize safe shutdown.

5.2.1 Observations

During the scenario run the human factors experts were observing the operators' task execution and taking notes. The operator work in VR CR was followed through several camera views (see Figure 3).

The main observations are grouped under four themes that are, 1) human factors, 2) VR UI, 3) VR technical and 4) process simulator issues. Observations regarding human factors were related to the operator performance in the scenario run. Both crews were able carry out the required actions instructed in the operating procedures related to the loss of main CR situation and move to the emergency control post. Moving to the emergency control post locating at the unit 2 main CR took approximately four minutes from both crews. When acting in the emergency control post the operators commented about the lack of space when "three operators trying to work on this small panel section". Similar notice was made also in the evaluation in the development simulator environment use as a reference evaluation. Regarding the VR UI, (theme 2) issues that were clearly related to activities in the VR CR were included. Many observations were made about the difficulties faced when moving and trying to pass the other operators in the VR CR. The operators more clearly needed to speak out loud, when they wanted to pass another operator "I am behind you, could you move a bit so I can pass you?" With regard to process monitoring, the operators could not see the meter and dial values from few steps' distance, instead they needed to walk nearer and stand right in the front of the control panel in order to be able to read a measurement value. Furthermore, since only one operator at a time could walk close enough and stand nearby the panel the other two operators had to ask the operator who was standing in front of the panel to read the values also for them, or the crew had to attempt to coordinate the reading turns in the panels. Some operators had some difficulties to remember how to conduct particular control operations and interact in the VR CR. However, after the operation had been executed once, the same problem did not seem to occur again, suggesting the operators were able to learn new ways to interact with the interfaces. Most observations in theme 2 are however, related to the procedure usage. For example, the operators were not always able to take and read the procedure they wanted, they were not able to put away the procedure or they lost a procedure meanwhile trying to glance at some other relevant procedure. During the scenario run, the operators were also requesting if they could have more than one procedure at a time in use and many times, they had troubles and confusion in using procedures in VR CR. In VR technical (theme 3), most observations were related to communication and using the radiophones in the VR CR. Either it was bad connections or there was no connection at all. In addition, the sound volume was too low, and the operators could not hear each other or the technician on the phone well. Once or twice during the scenario runs, the operators also reported the screen view to go black, freeze or upload something. In the process simulation (theme 4), Apros model related issues were included. It was observed that during the scenario run some pumps did not work as expected and this was due to the changes done in the Apros model that still had not been updated to the CR VR model.

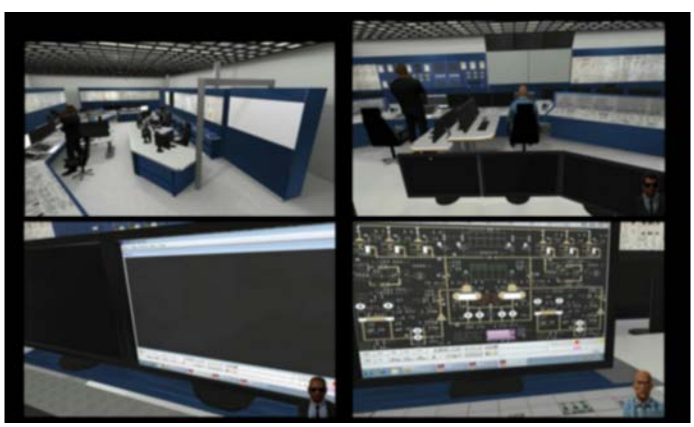


Figure 3. Synchronized camera views to VR CR. In top left is the overview camera view and the rest three shows the first person views of the operators.

5.2.2 Operator evaluations

A novel rating scale tool, the Spatial Presence Experience Scale (SPES), was used to measure spatial presence. The SPES has been developed by [5], and it is based on a process model of presence according to which participants first generate a mental representation of the presented physical space, and then they activate and test perceptual hypotheses concerning the acceptance of the mediated environment as their primary frame of reference [6]. The SPES measures people's self-location (SL) and perceived possible actions (PA) in the mediated environment. It was expected that sense of presence would be quite high in an immersive 3D environment. In fact, it seemed to be that the operators experienced a quite high sense of presence, and there seemed to be no difference between the SL and PA scores (Figure 4).

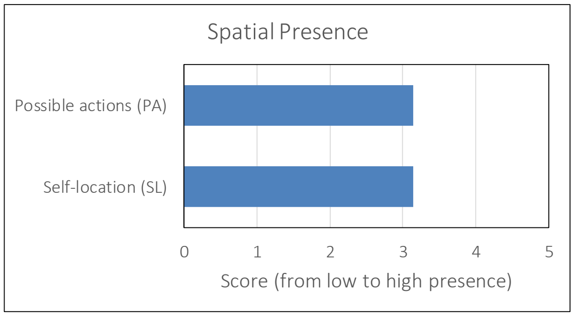


Figure 4. Spatial presence scores for two operator crews (i.e. six operators). The higher the score the higher the sense of spatial presence.

Simulator sickness was measured by means of the Simulator Sickness Questionnaire (SSQ; [7]) after the simulator run. Overall, scores are quite low, indicating that symptoms of simulator sickness were moderate. As can be seen in Figure 5, scores of General discomfort and Fatigue are somewhat higher than the other scores, whereas the scores of Eye dizziness and Salivation increasing were somewhat lower. Because of the fact that the operators were not familiar with the head-mounted VR system and that they had to wear it a quite long period of time, it is not surprising that some degree of fatigue was experienced. It is possible that scores would have been higher if simulator sickness had been measured also during the monitoring and operating tasks, because somewhat higher levels of symptoms of simulator sickness were perceived during them.

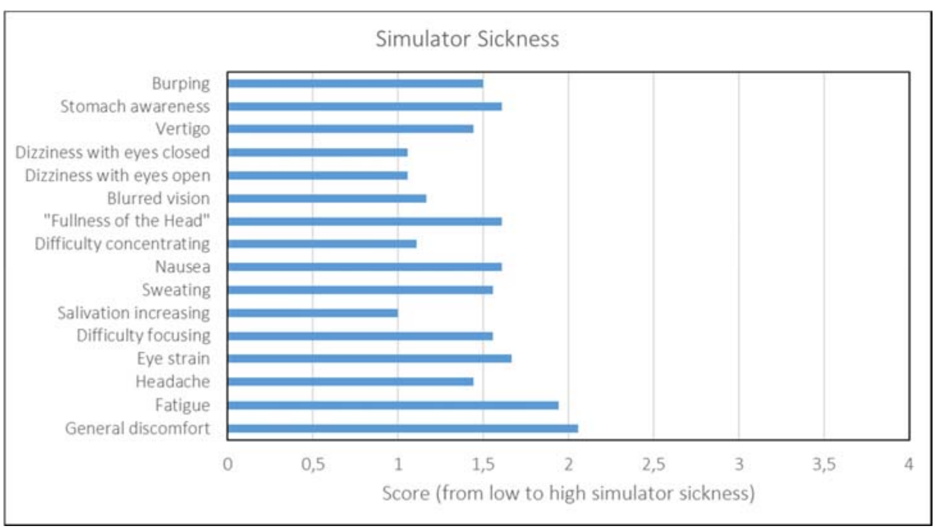


Figure 5. Simulator sickness scores for two operator crews (i.e. six operators). The higher the score the higher the symptoms of simulator sickness.

Scores of mental workload, measured by NASA-TLX, are at an exceptionally low level, suggesting that the operators did not experienced mental workload during the simulator run. Since the scores are lower than in the same scenario run conducted in the development simulator with Virtual panels, the operators apparently did not adopt a very serious attitude to the VR CR test (Figure 6).

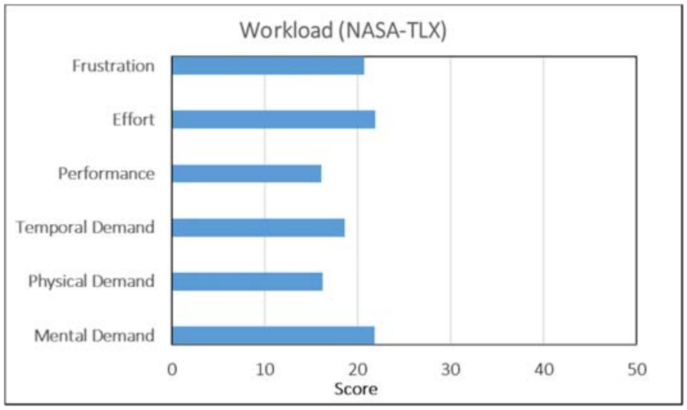


Figure 6. Mental workload scores for two operator crews (i.e. six operators). Higher scores implicate higher experiences of mental workload.

5.2.3 System usability questionnaire

According to the system usability questionnaire results, the operators thought that communication was smooth, operation errors were infrequent, and the respondents were quite satisfied with the display resolution (Figure 7). On the negative side, they sometimes got lost in the virtual reality, and mouse control could have been simpler, since it was quite difficult to move around and make operations with the mouse. Overall, most of the scores were somewhat below the mean level, so there is still plenty of room of improvement in terms of, e.g., appearance of depth, presentation of sounds and applicability to CR design. However, the most promising thing is the operators thought that the VR system suits well to the CR V&V.

According to operator comments, screen resolution was sufficient for procedure reading activity but not for reading measurement values from the panels/desks from a distance. It was easy to read procedures, but it was cumbersome to alternately read the procedure and look at information displayed on panels/desks or computer screens because the procedure page covered the whole screen. Communication between operators through the virtual environment went smoothly, but sound volume was too low. Some of the operators also thought that it would also be necessary to present environmental sounds, because they provide important information about the status of the nuclear process. Overall, the operators thought that they were able to do everything that was required in the VR CR, and the amount of operation errors was small.

The operators commented that they were able to learn to use the system without too much difficulty, but more practice would be needed to make performance more fluent. Overall, the operators thought that with some improvements and added functionalities the system could be used for CR design and V&V testing. It could also be used in operator training, even though the system can never replace training in a physical CR environment.

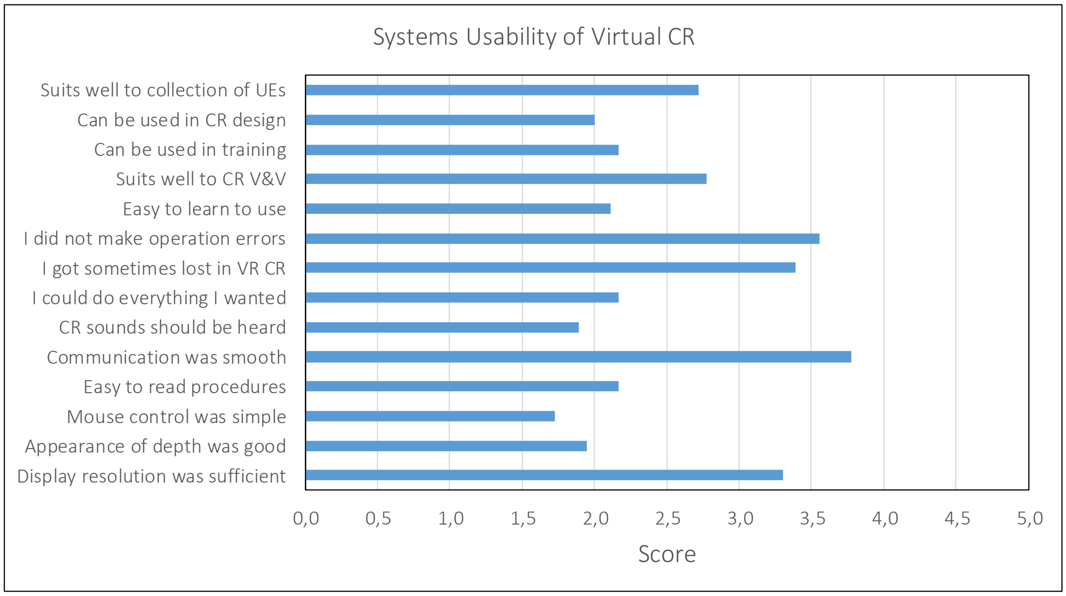


Figure 7. Systems usability of a virtual CR. The higher the score the more the respondent agreed with the statement.

6 DISCUSSION

6.1 Summary of main findings

Overall, the operators were able to execute individual monitoring and control tasks successfully, and their comments were quite positive. Both participating crews also performed the loss of the main CR simulator run without much difficulty.

Operators experienced a moderate level of spatial presence in the virtual environment. Ratings are somewhat lower than in our previous studies carried out in a CAVE environment. This may reflect the fact that a virtual environment created with a head-mounted display is less engaging and immersive due to user immobility and deficient control capabilities. The good news was that the symptoms of simulator sickness were low, even though the operators used the system for a quite long period of time, and most of them were novice users of head-mounted VR systems. Taking into account the fact that typical simulator runs last for 30-45 minutes, it seems to be that simulator sickness is not the factor limiting the use of head-mounted VR systems in CR V&V tests. Moreover, during a long test there are peaceful moments during which it is possible to take off the system for a while and relax.

According to the system usability questionnaire, the respondents thought the VR system promising and suitable for CR V&V tests. Especially, they thought that communication through the virtual environment was smooth, and operator errors were infrequent. Some of the scores are, however, quite low, because the system is not yet completed and there is still much work to be done.

6.2 Lessons learned

The following lessons learned can be derived from the results of the simulator study:

- The system provides support for early-stage evaluation of design solutions (a realistic impression of the CR can be obtained in the very early stage of the design process).

- New testing opportunities are created (e.g., more serious beyond the design based accidents can be simulated with special effects).
- The system enables realistic simulation of events such as fire, smoke and earthquake, which cannot be performed in physical simulator environments.
- New opportunities to data registration and analysis (e.g., automatic registration of operator-related behavioral data such as walking paths during the scenario run, registration of gaze direction) are created.
- Cost savings can be achieved for many reasons: e.g., validations can be performed several times in the VR CR before any modifications are done in the physical simulator or even before a physical simulator exists, and operators/human factors experts can participate remotely.
- Prospects and challenges from the perspective of simulator fidelity (e.g., psychological fidelity, immersion, engagement) have to be carefully considered.
- Because changes in the VR CR can be done quickly, comparison of alternative CR concepts and their early evaluation have been made possible.
- Participants for the evaluation studies have to be selected in a more careful manner than for validation activities conducted in a physical simulator because of possible symptoms of simulator sickness and deficiencies in stereo vision.
- Amount of technical and other resources required are much smaller than in normal validation in a real-life simulator environment, e.g., because operators/human factors experts can participate remotely.
- Screen resolution plays a role as a limiting condition and a key determinant for simulator fidelity.
- Touch controllers that imitate the operator's movable virtual hands is a necessary requirement for a 3D virtual CR.
- Environmental and alarm sounds increase the realism of a virtual environment and provide important information of the process, and therefore they should be implemented as well.
- Procedures should be displayed in such a way that operators can look alternately at both the procedure and information displayed on panels and computer screens; operators should also be able to use two or more procedures simultaneously.

In the future work of VR technologies in the context of CR design and validations, we aim to further develop the technical setup (e.g., to allow a more realistic lifelike interaction), test the possibilities of VR CR environment to support and augment different type of scenarios runs and develop new methods and techniques for human factors data registration and analysis.

7 CONCLUSIONS

We studied how immersive 3D environments may augment and advance the evaluation of safety-critical CR systems. The VR CR was compared with a real-life development simulator environment where hardwired panels were substituted with Virtual panels. Several operators were able to work in the same VR-environment simultaneously and performed their tasks successfully. The operators thought that the tested VR CR facility is promising and suitable for CR validation and evaluation activities. New functionalities such as introduction of touch controllers and environmental sounds make the system even more promising and suitable for CR V&V in near future.

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