Avoiding "metal astray": experience evaluation of virtual reality training for melting furnace operators.

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ABSTRACT

The work of melting furnace operators is potentially hazardous and serious accidents do occur. Training on the monitoring and safe operation of furnaces is key to the safety of the operators and their surroundings. Virtual Reality (VR) environments can simulate safety critical work environments and provide realistic, safe and engaging ways to train on situations otherwise unavailable. To address the potential of using VR in safety training, the VR environment called VR Safe was developed. This paper presents a study of the user experience of training safety critical procedures in VR. VR Safe simulates malfunction in one of the most important systems regarding safe operation of furnaces: furnace cooling system monitoring and how to respond to cooling system failure. The evaluation included professional furnace operators, and was focused on usability of the system, user engagement and the training value as it relates to the operators' work.

Keywords

Safety critical training, virtual reality, usability, melting furnace operation.

INTRODUCTION, BACKGROUND AND RELATED WORK

Training is a common strategy to reduce the risk of accidents in hazardous work environments and is centered around increasing the skills of humans to identify, analyse and assess the risks involved in a particular environment or situation (Scorgie et al., 2024). Traditionally, training is facilitated by making use of different types of learning aids such as manuals, lectures, videos and drills (Feng et al., 2018). Managing high-risk environments requires a tight coupling between understanding unwanted situations as they unfold, being able to manually carry out the necessary operations, whilst simultaneously experiencing stress. Ultimately it is about developing competences in both knowing and doing. Virtual Reality (VR) environments is an emerging and promising platform for training in contexts such as these as it offers an engaging mode of interaction by immersing the user in a representation of a real environment that offers rich interaction modes (Grassini & Laumann, 2020), feedback in the form of observing the result of actions, the development of hands-on skills and learning-by-doing, and opportunities for repetition (Deb et al., 2017). Particularly relevant to training for high-risk situations, VR can also provide first-person access to environments that are potentially dangerous, unethical, costly, temporally unavailable or unpractical to access in the real world (Freina & Ott, 2015).

VR systems are being used in education and training for their potential for creating immersive experiences, in which the users can experience a sense of presence (Jensen & Konradsen, 2018). Examples of VR-training in safety critical environments are available for firefighting (Wijkmark & Heldal, 2020; Wijkmark et al., 2021); first responders (Binsch et al., 2021; Mossel et al., 2021) and several other areas. VR in safety critical training has also been studied in industrial work settings, for example working from heights (Cyma-Wejchenig et al., 2020; Loreto et al., 2018), working in confined spaces (Lu et al., 2020), overhead load movement and operation of cranes (Zhang et al., 2023) and electrical/high-voltage safety training (Ayala García et al., 2016; Wang & Messner, 2020). While VR environments for various purposes connected to metallurgical production and melting furnace operation exist, for example visualising and simulating processes (e.g. (Freitag & Urness, 2002; Fu et al., 2009; Ratts et al., 2000)),

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little work is done on VR-based safety critical training in this domain. Li and colleagues (Li et al., 2019) describe a system developed for safety training in metallurgical production, but their approach is more oriented towards technical systems description, and not on the experience of the operator.

This paper presents a user experience evaluation of a VR environment designed for safety critical training for operators of the hazardous work environment of melting furnaces in metallurgical production. The case illustrates the potential of using VR-training for safety critical and hazardous environments. In the study we recruited professional metal furnace operators to participate in the VR-training and focus on how they experience the training. The empirical data consists of physiological sensor data, answers to standardized questionnaires on usability, user experience and VR experience, and in-depth interviews with the operators. The data is used to explore the perceived usability of the environment, the way in which it engages the operators, and what kind of training experience the environment facilitates.

The study provides a rich account of how VR-training can be used in safety critical industrial work settings with a focus on how VR environments can provide realistic training situations. Further, we discuss how VR-training experiences can be evaluated by including different kinds of empirical data to address different aspects of the VR experience including engagement, usability and user experience, and the training value.

TECHNOLOGY AND CONTEXT: MELTING FURNACE OPERATION AND TRAINING

Melting Furnace Operation and Training

The educational requirement for the staff who operate the melting furnaces is a certificate of apprenticeship as industry process operator or chemical process operator. There are several safety risks connected to operating the furnaces, and the most commonly referred to hazard is called "metal astray". "Metal astray" means metal in liquid form anywhere else than where it is designed to be handled. "Metal astray" covers both minor or major spilling from containers, but also ejections from the furnace as a result from explosions. To avoid metal astray, the furnaces need to operate at the correct temperature. To ensure correct temperature, the furnaces rely on a cooling system consisting of a set of pipes streaming pressurised water surrounding the furnace exterior. Cooling water leakage occurs infrequently and episodically, but causes a situation that can be very dangerous because of the high energy matters and volumes involved. These situations require intervention by the operators, and how to intervene depends on the nature of the leakage, and the understanding of which depends on the perception, experience and discretion of the operator. The water pressure in the cooling pipes is monitored in a control room. Falling pressure, readable on manometer displays, is an indicator of leakage in a pipe, which reduces cooling. The leakage is not visible to the naked eye because of the temperature of the water and visual hindrances caused by the furnace (fire, smoke), but a mild reduction of the furnace temperature can make the leakage visible. These situations occur very rarely, but when they do the operator is usually alone. The risks are both economical and physical. Shutting down the furnace if not necessary is very expensive, whilst not shutting down if required is potentially catastrophic.

The current practice for safety training at the plant involved in this study consists of lectures and bi-annual certification tests presented as imaginary scenarios with challenges responded to in writing. They also use a digital reference manual, where all the relevant procedures are described. Additionally there is on-the-job training and knowledge exchange between novice and experienced operators. The opportunities for practical and physical experimentation are limited, due to the costs of taking the furnace out of production. Needless to say, there are also limits on the experimentation with the furnace because of the dangers involved with mixing high temperatures (ca 1600 degrees Celsius) and large quantities of melted metal, electricity and pressurised water. With VR it is possible to overcome some of these limitations. With VR, the physical environment can be realistically recreated, including the visual, three-dimensional appearance of the plant, the sound, and how the environment is manipulated in a dynamic way. VR can also provide opportunities to train on safety procedures without stopping the furnace.

VR Safe

VR Safe is a prototype of a training environment for melting furnace operators, currently containing one training scenario. It is developed by a consortium of VR software companies, in collaboration a Norwegian metallurgical production company. VR Safe allows operators to handle loss of cooling of a furnace. The cooling system consists of several water pipes, and currently VR Safe can simulate malfunction in one of those pipes. Additional common safety hazards for operating furnaces have been been placed in the environment, for example misplaced objects and hindrances that can cause safety issues. VR Safe is being created using the Unity engine to recreate the environment of an existing furnace, with adhering cooling system, building and control room. VR Safe is interacted with using a Head Mounted Display (HMD). Figure 1 illustrates clockwise from top left: a. The furnace, b. The control room, c. Break area and d. Water pipe panel with valves.

Figure 1. VR Safe environment

When opening VR Safe, the operator is placed in the melting plant control room. When the operator looks around, he/she can see the computer displays with readings of the pressure in the water pipes (b.), the inspection window to the furnace opening (a.). When turning around, the operators can see the rest of the control room with the kitchen area and electrical boxes (c.). There is a lever for reducing the energy in the furnace. The operator can also navigate to the valve panel area and close the correct valve (d.). Additionally, the operator can navigate to the furnace itself. The currently available scenarios are 1. falling pressure in one of the pipes, and 2. cluttered work spaces around the furnace area.

EVALUATION APPROACH AND METHODS

Evaluation Approach

This study examines the experience of interacting with VR Safe. Three aspects of the interaction is in focus, all considered central to the overall goal of facilitating critical safety training for furnace operators: 1. engagement, 2. usability and 3. training value. Each of the aspects were examined in its own way. The overall approach is illustrated in Figure 2

How users engage with training exercises can have an impact on the outcome (Xin, 2022). While different ways to measure and understand engagement have been suggested (Doherty & Doherty, 2019; Flobak, 2023), we focus on how we can use physiological data as an indicator of engagement. As Electrodermal activity (EDA) has been used as an indicator of mental effort (Agarwal et al., 2021; Pijeira-Díaz et al., 2018), we explore how such data, obtained with the biosensor Empatica E4, can be used to inform our study of the experience of VR-safety training for furnace operators. We assume a correlation between EDA values and an affective response - here understood as levels of

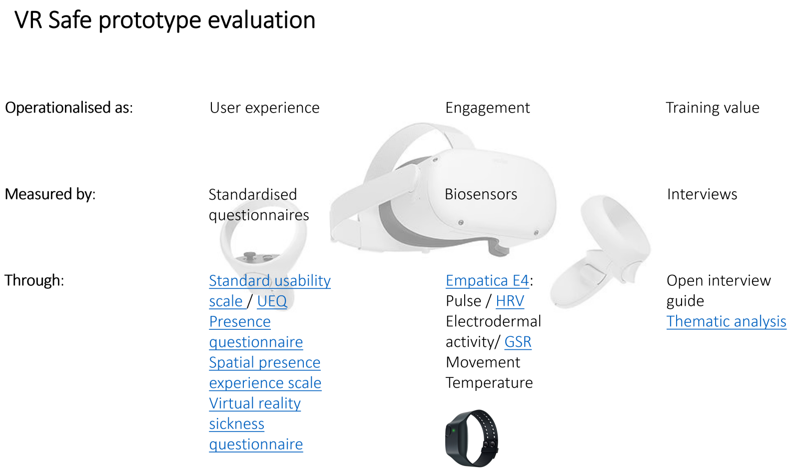

Figure 2. Overview of the evaluation

arousal, which again can be used as an indicator of the level of engagement with the environment and the training content.

The evaluation also focused on the user experience of the VR-training. In Human-Computer Interaction user experience is a term that can encompass both the usability of a system and the experience that the user has when using the system (Turner, 2023). We have approached the evaluation of the total VR-training experience as including both usability, user experience in general, but also including more specific elements that pertains to interaction in virtual environments.

The training value is seen in relation to the existing work and training practice for melting furnace operators. The training is studied in terms of how it relates to the operators established, professional understanding of work, with emphasis on critical safety procedures. These procedures consist of monitoring output from the furnace and the cooling system, and investigating and solving potential problems.

Methods

We collected physiological data for each participant to compare three different conditions: baseline, VR Safe use and VR gaming. Baseline was defined as taking part in a lecture for 15-20 minutes. Baseline should represent the "normal" training situation for the operators, but training takes place across a range of modalities as described above. We are interested in seeing how using VR Safe compares with taking part in lectures. Additionally, we included a VR game (Richies Plank Experience), to see how VR Safe compares with games that are designed for fun. Our expectation is that EDA will increase with VR Safe, as it involves the user in carrying out safety critical professional tasks, and expect it to increase even more when playing VR games. Physiological processes are individual, thus we are not interested in comparing persons, but rather how the different activities affect the physiological processes for an individual.

For this pilot study we decided to provide standardised questionnaires to expert/professional users. We chose to use questionnaires as we see it as an efficient way of getting user experience data with few participants accessible for a short time. The questionnaires are therefore analysed descriptively, and the results are seen as valuable when combined with the other data. We used two questionnaires for general usability assessment; System Usability Scale (SUS) (Brooke, 1996; Lewis, 2018), and User Experience Questionnaire (UEQ) (Schrepp et al., 2014). Two questionnaires were more specific to user experience with VR systems: Presence Questionnaire (PQ) (Witmer & Singer, 1998) and Spatial Presence Experience Scale (SPES) (Hartmann et al., 2015). Finally, two questionnaires for assessing any discomfort or unwanted bodily effects with use of VR Safe were used: Virtual Reality Sickness Questionnaire (VRSQ) (Kim et al., 2018) and Cyber Sickness Questionnaire – VR (CSQ-VR) (Kourtesis et al., 2023).

The part of the evaluation considering training value is about how the operators work in a wider context of colleagues, information systems, tasks, goals, tools and work culture. To access this information, an open qualitative interview guide was constructed. The themes included are how the operators understand learning goals for VR Safe,

Figure 3. Evaluation timeline

engagement, their perception of interacting with VR Safe, realism and fidelity, the relevance of the content and tasks, immersion, comfort and ergonomics in addition to how they would like to see VR Safe further developed.

The timeline for the evaluation activities is illustrated in Figure 3.

EVALUATION WITH MELTING FURNACE OPERATORS

The evaluation with melting furnace operators was carried out over two days at a smelting plant. The first day involved observation and getting an overview of the basics of melting furnace operation. The second day was used for evaluation with operators. Five melting furnace operators took part. Two worked at the furnace that VR Safe is a replica of, whilst three worked on a different furnace. Four were young, yet experienced operators (age < 30), and one was more senior (age > 50). One participant had used VR Safe previously. The evaluation was carried out in groups, following the structure 2+2+1. Two were first introduced to VR Safe through listening to a presentation of VR Safe for 15-20 minutes. This was used as baseline for the physiological data capture, with one of the participants. Then they tried out VR Safe using one HMD each for around 20 minutes, whilst the physiological response was recorded for the same participant. Afterwards, they played RPE, for up to five minutes. Finally, they completed the questionnaires and took part in an interview. We recorded the physiological response for three of the participants, as we only had one Empatica available.

Results

EDA: The physiological responses are presented in Table 1, for participant 1, 3 and 5, clockwise from top left. The EDA levels for VR Safe are higher than for baseline for the three participants. Although EDA levels are individual (Baker et al., 2010), the tendencies between activities are similar, and seem to support our expectation that EDA levels would increase with engaging with VR Safe compared to baseline. For the two participants who played RPE, they show a (relatively) flat line before peaking rapidly.

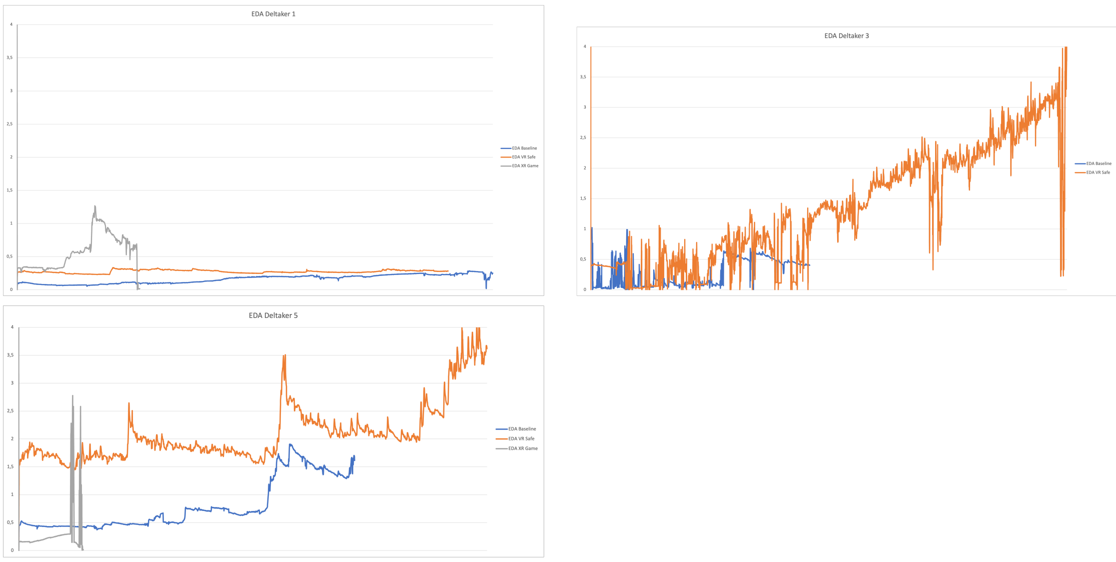

Table 1. EDA results, evaluation with operators

Participant 1 has marginally higher EDA levels with VR Safe compared to baseline, whilst both levels are low. RPE is higher, which increases trust in the data. The EDA levels for Participant 3 is higher than for baseline, and also increases noticeably throughout the activity. Participant 3 declined the RPE activity. The EDA levels for Participant 5 are higher with VR Safe than for baseline. The EDA levels for RPE seem to follow the same structure as for Participant 1. Overall, the EDA results can be an indication that the mental effort exerted with VR Safe is higher than listening to a presentation and taking part in a discussion, and that training with VR Safe is a more active way of training.

Questionnaires: The results from the questionnaires have been visualised and analysed descriptively. In the visualisations, the positive/negative phrasing of questions have been rearranged to show the most positive responses to the right, to increase readability. For the two questionnaires measuring unwanted effects or discomfort following use of VR (the last two), the most positive responses are to the left.

The SUS questionnaire contains 10 statements about the perceived usability of a system. In the visualisation in Table 2, the SUS results appear mostly positive, with the most or second most affirmative responses being most frequent. The average SUS score is 77,5. For SUS scores, results over 70 are considered good. UEQ measures the qualities attractiveness, perspicuity, efficiency, dependability, stimulation and novelty. The major tendency in the replies are positive.

The results from the questionnaires that measure the VR experience are visualised in Table 3. The results are mainly positive, with the most or second most affirmative answer option being used for most of the items. The PQ contains how control and realism factors contribute to the experience of presence in a VR system (Witmer & Singer, 1998). The SPES questionnaire contains 20 items that measure the subjective feeling of being present in a virtual environment (Hartmann et al., 2015), and is based on the theory that to experience spatial presence, users first develop a mental model of the VR environment, and secondly accepts it as their egocentric viewpoint (ibid.). The users ability to visually create a mental model of the VR space affects the experience of spatial presence positively. This experience is relevant for the participants in our study, as the virtual environment is based on an environment that the participants know well.

The results from the two questionnaires measuring discomfort resulting from using VR are available in Table 4, where the lowest symptom reports are presented to the left in both tables. We consider these to indicate no serious discomfort from using VR Safe.

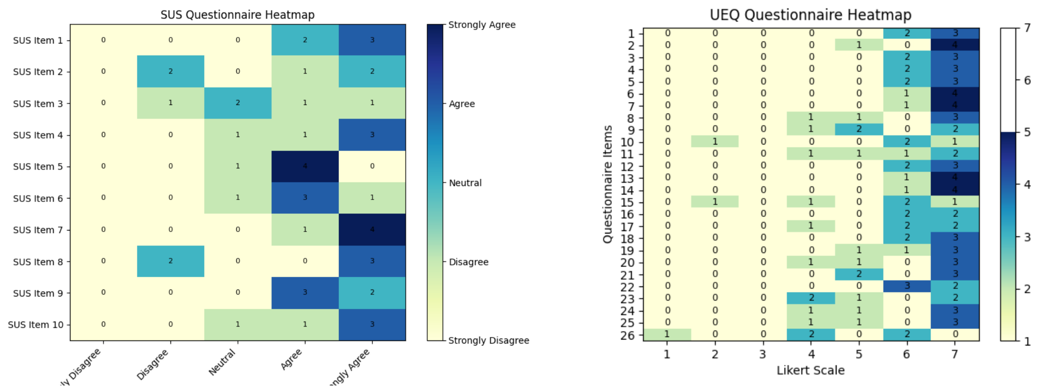

Table 2. Usability questionnaires

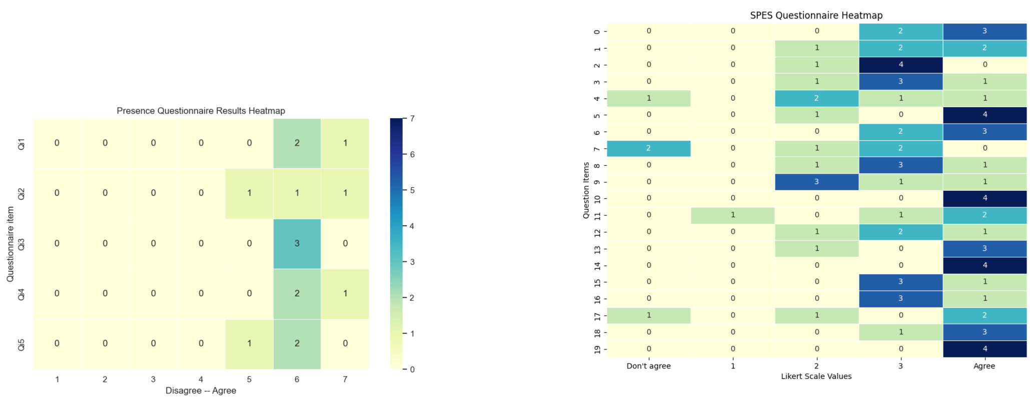

Table 3. VR experience questionnaires

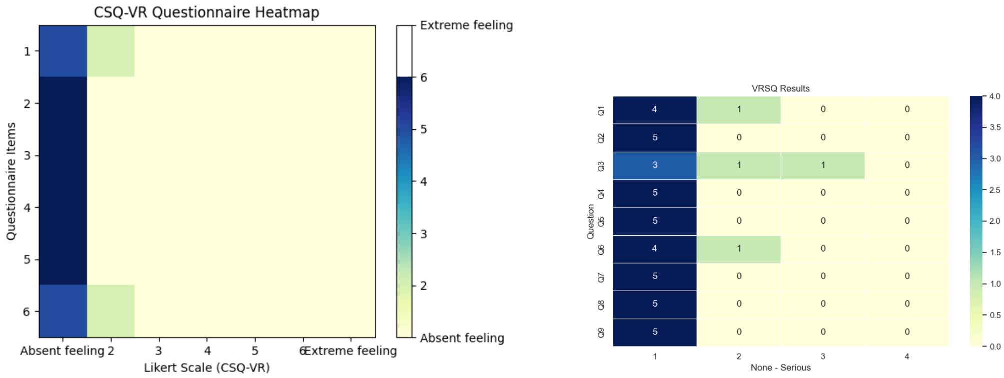

Table 4. Unwanted effects of VR use

Interviews: The interviews were recorded and transcribed in full before being analysed using Thematic analysis (Braun & Clarke, 2006). One theme is how the VR training is relevant to the existing training practices and needs at the smelting plant. This means in how it fits in with current practices, and whether and in which way it creates new training opportunities. The following two quotes illustrates how the operators considered the training relevant; it makes available situations that are unpractical, uneconomical or unsafe with their training practices today. There is also a need to train on practical intervention and solving problems in a manual way.

Participant 5: “I have trained a lot of new people (*operators*). And what is difficult with training new employees is, what do you do with a water leak? We can´t just go up and close a valve... ”

Participant 5: “There is a lot of theory. But if you are unlucky and actually get a water leak, then you have to go up and close a valve. But here (*in VR Safe*) you actually get to do it. We are actually trying to do those things.”

The operator is speaking about the notion of opening and closing furnace cooling valves on a furnace in production. The environment in which the operators work can be considered "low risk / high consequences". The low risk is contingent on following the designed procedures for handling high energy matter, and also being competent to perceive and intervene in randomly occurring unwanted situations. Tied to the theme of relevance is also managing the potential magnitude of the consequences, whilst experiencing stress. The following dialogue captures how they consider the consequences if things should go wrong:

Participant 1: “Yes, the potential that it can go wrong is very large, in case there should be an accident. I think that would be the very worst that could happen.”
Participant 2: “Yes. That would be a crisis.”
Participant 1: “Yes, you don´t want that to happen on your watch, to put it like that.”

When considered as to how VR Safe is relevant to the safety training of the operators, the dialogue further highlights how being able to train repeatedly on detecting unfolding, unwanted situations and practical intervention becomes available in VR. VR also supports the formation of automated actions through repetition, as automated actions are much easier and probable to be undertaken when a person is experiencing a high state of stress.

Regarding the design of VR Safe, and whether it is developed in a way that the operators can recognise and find meaningful, the operator reported that they found it to be a useful way to carry out training. In the first quote, Participant 1 explains this by making a reference to the real world functioning of the furnace, and that VR Safe matches this. His conception of VR Safe is similar to that of the real life furnace. This is an indication of the importance of creating simulations that align well with real-world processes, when creating VR-based safety critical training environments. The operators who did not work at "Furnace 5" responded similarly to the operators that did, indicating that the formation of mental models corresponds to more than visual similarity of real and virtual environments, and also include dynamic relations in processes. This relates to the underlying theoretical foundations of spatial presence. Participant 3 highlights how VR-based training is more interesting than some other alternatives, such as the digital reference manual where every relevant procedure is described in detail in text.

Interviewer: “Was it an adequate way to learn to handle leakages in the cooling system?”
Participant 2: “Yes it is.”
Participant 1: “It is sort of made the way that it actually works. It is quite easy to discover what you should do.”

Participant 3: “Yes, it is, absolutely. I would rather use this than "Rosa". "Rosa" is where we keep all in-depth content. It is a system where we read and sign that we have understood (the procedures). It describes how to do everything in detail.”

Regarding the visual representation of the furnace in VR Safe, it is considered to be adequate by the operators. One operator described the audiovisual appearance as meeting his expectations. “Participant 2: It appeared the way I imagined it would. The representation of objects...”

Participant 1: “The recognition effect. It is the way it looks.”

Four of the participants had never used VR Safe previously. When asked about how it was to learn to interact with VR Safe, all participants reported that it was easy to use, although it took a little while to learn how to move for some (VR Safe uses the "teleport" mode for moving in the environment, where the user points the controller to a spot on the floor and click the joystick to move, or press the joystick forward to move in steps.). Once they had learned it, all participants found it easy to interact with VR Safe. One exception was operating the valves. The design for user input on objects is done by highlighting the objects when moving the hand/controller near the object. When highlighted, the valves can be opened/closed by making a twisting motion with the hand. This operation was experienced as difficult to perform by most operators. It is a central operation in connection with the safety procedures.

Participant 3: “(VR Safe) was easy to learn. That went smoothly. The only thing that did not work properly, was opening the valves.”
Participant 4: “It worked okay to close them, but not opening them again.”

DISCUSSION

In this study, we have engaged professional experts in testing a virtual environment for critical safety training. VR Safe simulates certain safety operations in the handling of a real furnace, and is, as such, a representation of key aspects of a real system for metallurgical production. To be useful for the operators in training, the virtual environment needs to simulate the real environment in a realistic way. To further understand the realism and perceived authenticity of the VR system, the study highlights how the fidelity of the representation affects the user experience. We describe these as **audiovisual, task** and **operational** fidelity. The audiovisual fidelity of representation concerns how the virtual environment matches the environment known to the operators. The task fidelity describes how the tasks in the virtual environment matches the tasks carried out by the operators while they work. The operational fidelity describes how the manual operations that the operators carry out in their work matches those in real life. In our study, the operators described the virtual environment as familiar to them in a visual sense, and that there was a recognition effect. The interviews also highlight that task representation is likely to affect their overall experience, including the audiovisual experience. The audiovisual representation in VR Safe contains a limited selection of the smelting plant, and even includes some minor mismatches with the real environment, such as it being possible to walk near the furnace (something that they would not to in the real environment, but instead use a forklift for protection). The fact that they understand the task (possible cooling malfunction), prompts them to carry out operations that they can understand based on their professional experience. The task fidelity, which speaks to the relevance of a task in the virtual environment, is likely to support the operators in forming a mental model of the virtual environment, and experience spatial presence. The interviews also revealed that there was an interactional problem with carrying out an operation important to the task, which was opening/closing the valves. This is a critical safety operation, needed for the safe operation of the furnace, and was not represented very well in VR Safe as it is a simple operation to complete on an actual furnace. Further refinement of VR Safe should look into different solutions for this operation. This identified shortcoming, points another kind of fidelity, namely haptic or tangible fidelity. To train on the physical and motor skills required for operating the system, can be hard to replicate in a virtual environment. Still, advances in haptic interaction in VR systems can possibly help to increase also the haptic fidelity and increase the realism of performing such tasks virtually.

The measurement of physiological responses of the participants revealed an increase in EDA levels whilst using VR Safe, indicating an increase in mental effort or activeness whilst using the VR environment. Activeness, and cognitive and emotional arousal has previously been found to be conducive to learning (see e.g. (Baker et al., 2010; Bjork et al., 2013; Pijeira-Díaz et al., 2018). Whilst the interview and questionnaire data are based on self reporting, the affective sensing represent more direct measurement of the process of engaging with VR Safe as it unfolds. Yet, we don't know exactly what in the VR experience that caused changes EDA levels. A further refinement of the method would be to connect physiological responses with what the participant is doing in VR at each moment, for example by streaming the view of the user. This approach could provide useful design information, for example by identifying particular tasks or other design elements that correlate with particular responses. The EDA data, and particularly the VR Gaming data indicate that these kind of responses exist. Noori and colleagues (Noori et al., 2019), have demonstrated that continuous capture of physiological responses can be used to create VR systems that adapt to the users physiological responses for VR-based exposure therapy. In the context of safety critical training the responses could be used to increase or decrease difficulty or complexity of the task.

Considering VR Safe as a Proof-of-concept, the questionnaire data from expert participants seem to indicate that there are no major usability issues with VR Safe, and that the usability does not provide major hindrances to engaging in training based on VR.

Limitations: A major limitation in our study is that the data are based on a limited number of participants for the findings to be generalised to a larger population. Still we have recruited expert professional operators and there is a limited number of such professionals available. This limitation could be met by doing a less episodic study over time with several iterations of design and evaluation with professionals.

CONCLUSION AND NEXT STEPS

The paper has reported on a user experience study of professional operators engaged in VR-based safety critical training on handling malfunction of a melting furnace. A method for evaluating the experience focused on engagement, usability and training value was designed, and carried out in practice. We found the prototype VR Safe to be a method for safety critical training that has a promising potential as a way to overcome the limitations associated with other ways of training, such as the need for tying theoretical knowledge with operational practice and engaging the user.

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