Henrik Lucander

Data Collection in Virtual Reality

Control Room Validation

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Virtual reality brings new promising possibilities to the field of control room design. An immersive virtual reality environment can be combined with a control room 3D-model and a simulation of the processes. This makes it possible to extensively evaluate changes or different possibilities regarding user interface solutions in early stages of the control room design.

This study was commissioned by Fortum Power and Heat. The intention of this qualitative study was to determine burdensome tasks regarding data collection and analyzing in traditional control room validations and how these could be improved or supported by using a virtual reality environment. Furthermore, what virtual reality does not significantly improve and what previously impossible or utopian does virtual reality now provide the means for. The study was executed by depth interviews of experts in the field of human factors engineering and control room validation.

The principal conclusion is that using virtual reality in control room validations improves the quality of data or saves time as concerns data collected by video recording, audio recording, movement tracking and timing. Additionally, virtual reality offers possibilities for unparalleled automatic situational tracking and the collection of previously unattainable data by eye-tracking.

Keywords	Control Room, Virtual Reality, VR, Validation, Data Collection

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Tekijä Otsikko Sivumäärä Aika	Henrik Lucander Tiedonkeruu virtuaalitodellisuudessa toteutetussa valvomon validoinnissa 35 sivua 16.1.2018
Tutkinto	Insinööri (AMK)
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Virtuaalitodellisuus tuo uusia lupaavia mahdollisuuksia valvomosuunnitteluun. Immersiivinen virtuaalitodellisuus voidaan yhdistää valvomon 3D-malliin ja prosessin simulaatioon. Tämä mahdollistaa laajamittaisen muutosten ja käyttöjärjestelmävaihtoehtojen arvioimisen jo suunnittelun aikaisissa vaiheissa.

Tämän insinöörityön toimeksiantaja oli Fortum Power and Heat. Työn tarkoituksena oli selvittää perinteisen validoinnin tiedonkeruun työläitä tehtäviä ja miten niitä voidaan parantaa tai tukea hyödyntämällä virtuaalitodellisuutta. Lisäksi kartoitettiin, mitä perinteisin keinoin mahdotonta tai utopistista virtuaalitodellisuus nyt mahdollistaa. Laadullinen tutkimus toteutettiin syvähaastattelujen avulla. Haastateltavana oli inhimillisten tekijöiden (Human Factors Engineering) ja valvomon validoinnin asiantuntijoita.

Tulosten mukaan virtuaalitodellisuuden hyödyntäminen valvomon validoinnissa parantaa kerätyn tiedon laatua tai säästää aikaa mitä tulee tiedonkeruuseen videotallennuksen, äänittämisen, liikkeen kartoittamisen ja ajastamisen avulla. Lisäksi virtuaalitodellisuus mahdollistaa vertaansa vailla olevaa tilanteen seurantaa ja aikaisemmin saavuttamattoman tiedon keruuta katseenseurannan avulla.

Avainsanat	valvomo, virtuaalitodellisuus, VR, validointi, tiedonkeruu

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Contents

List of Abbreviations

HFE	Human Factors Engineering
HMD	Head Mounted Display
HMI	Human Machine Interface
ISV	Integrated System Validation
UI	User Interface
VR	Virtual Reality
V&V	Verification and Validation

1 Introduction

Virtual reality (VR) is rapidly becoming the next remarkable entertainment platform. The use of devices and technologies providing the means for VR have swiftly become more and more common and are already in everyday use in many homes and companies. Due to the versatility of the technology, it can be applied to a wide range of industry and education. The most exciting thing is that we are still trying to figure out its full potential and its influence on the future.

VR brings new promising possibilities to the field of control room design. 3D-models of control room designs can be effortlessly imported into 3D game engines which makes it possible to experience them in VR while still in early stages of development. Combining this immersive VR environment with a simulation of the process makes it possible to extensively evaluate changes or different possibilities regarding user interface (UI) solutions. Such an opportunity should not be left unexploited as it can provide unparalleled information about possible design flaws, integration problems and human factors engineering (HFE) discrepancies before the design is put into practice, thus potentially avoiding expensive modifications to design or already completed solutions.

This study was commissioned by Fortum Power and Heat. The purpose of this thesis is to map out how data collection and analyzing of control room validations could be improved or supported by using immersive VR environments. Results of this study are supposed to aid the planning of a forthcoming VR based integrated system validation (ISV) of the Loviisa nuclear power plant control room.

This study was executed by qualitative depth interviews of experts in the field of HFE and control room validation. The intention of the interviews was to determine burdensome and time-consuming tasks regarding the data collection and analyzing concerning traditional control room validations performed in physical simulators and how those could be improved by the VR environment. Furthermore, what does VR not significantly improve and what previously impossible or utopian does VR now provide the means for.

2 Fortum

Fortum is a Finnish energy company that provides electricity, cooling, heat and resource efficiency solutions for its customers. With 62% of the generated electricity being carbon-free, Fortum is a leading clean-energy company. In 2016 Fortum had a total annual revenue of 3,632 million euro and an operating profit of 644 million euro. Number of employees in 2016 was 8,108. (Fortum.com, 2017a).

This thesis concerns control room (Figure 1.) design services and the immersive VR training solutions Fortum offer. Control room design at Fortum is based on its nuclear power plant operator and license holder background. Therefore, Fortum has experience as both a control room designer and an end-user and is a precursor what comes to offering VR simulator solutions. (Fortum.com, 2017b; Fortum.com, 2017c).

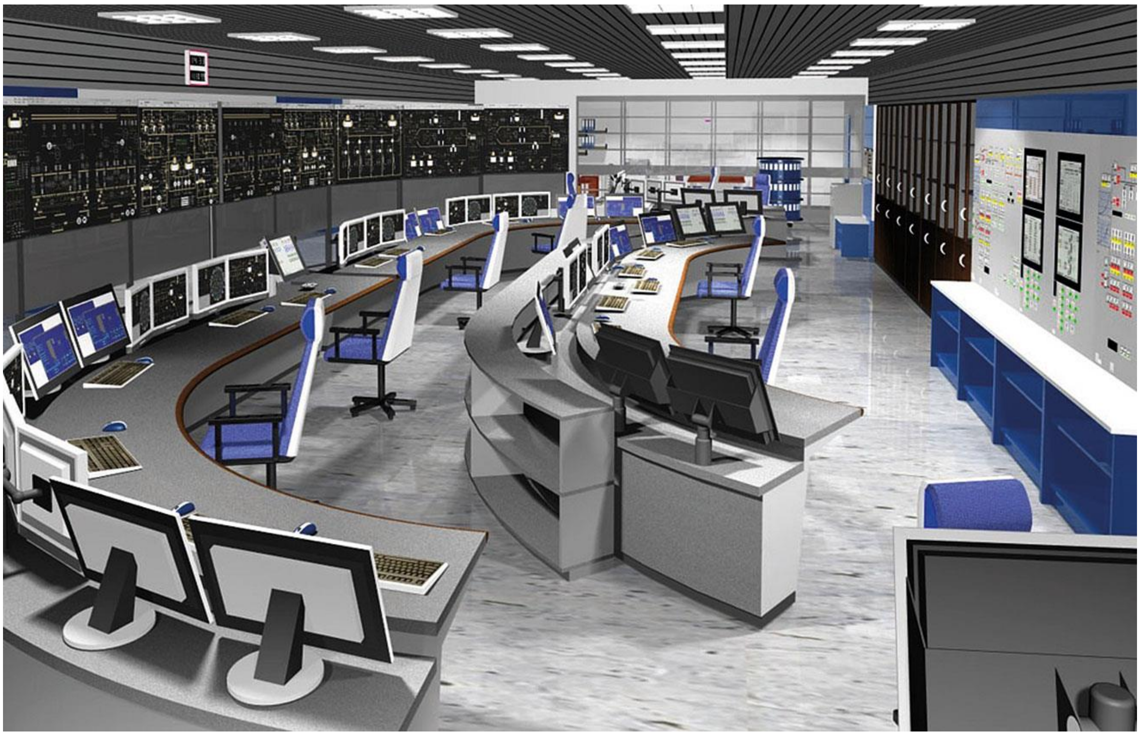

Figure 1. Control room design by Fortum (Fortum, 2017b).

3 Virtual Reality

Virtual reality (VR) is defined as a three-dimensional artificial environment created by a computer and it is experienced by the user via sensory stimuli (e.g. visual effects and sound). The term VR also refers to the technology used for creating or accessing the VR. (Merriam-webster.com, 2017). Additionally, VR can be defined as a computer generated digital surrounding which can be interacted with and experienced as if it was real life, as stated by Jason Jerald in his book *The VR Book: Human-Centered Design of Virtual Reality* (2016: 9).

3.1 History

Depending on how the term is defined, the first VR systems can be said to originate from the creation of Morton Heilig in the 1950s named The Sensorama. The Sensorama was a device that produced sensory stimuli in form of sound, touch, breeze and smell for the user while showing short films. The device was fully mechanical and did not offer any interactivity whatsoever. (Craig, Sherman and Will, 2009: 4).

The first modern, i.e. head-mounted, VR system named The Sword of Damocles was created in 1968 by Ivan Sutherland. The graphics and feel of realism of the system were obviously very primitive but many of the solutions used are still in use in today's VR systems. The Sword of Damocles introduced interactivity by tracking the users head movement which was accomplished by mechanically retracting cables. The system also included a stereoscopic display and headset. (Craig, Sherman and Will, 2009: 4-5).

VR was truly made accessible for the masses in 2014 when Google introduced their new VR platform, Google Cardboard. It is a smartphone housing that is worn on the head and as the name implies Google Cardboard is indeed made of cardboard. Google is selling it for a very reasonable 15€ price but they also provide build-it-yourself instructions on their website. Combined with a free smartphone application, anyone can get their first VR experience at an affordable price. (Statt, 2014).

VR as we know it today is experienced through a head-mounted virtual reality headset. The VR headset consists of a head mounted display (HMD) and more often than not, headphones. HMD is a device that contains small displays which are located in front of each eye of the user, thus providing stereoscopic vision. The most progressive VR headsets nowadays also include some kind of gaming controllers, which can be used for moving around or interacting with the artificial environment. The most significant benefit of using a VR headset is the increased sense of immersion provided by the possibility to look around by turning the head. This is made possible by including multi-axis head motion tracking sensors into the headset. (Virtual Reality Society, 2017).

3.2 Immersion and Presence

Immersion in videogames or VR is defined as the level of involvement with the alternative world. The game or VR becomes the user's center of attention. (Brown and Cairns, 2004). A broader, metaphorical definition by Janet Murray is the feeling of being submerged in water, thus completely being surrounded by an alternative reality which in this example would be water instead of air (Murray, 2000: 98).

According to Whitson el al., (2008) creating a truly immersive experience in videogames requires integrating and surrounding the user with a fully completed environment. Artificial environments that are highly immersive makes the user lose awareness of the real world and substitute it with the alternative environment. It is more important for it to be credible than realistic. Losing awareness of the real world can be further broken down to three phenomena:

- *Loss of self-awareness*, which can be achieved by introducing avatars to replace the real self, thus contributing to the loss of self-awareness. Interruptions or pauses in the experience provides time for self-reflection and therefore for example loading screens should be avoided by any means necessary.

- *Loss of social-awareness*, which can be achieved by not being reminded of others physical presence. In other words, one needs to be alone to fully be able to get sucked in to the alternative reality.

- *Loss of game-awareness*, which can be achieved by creating an environment as credible as possible. The objective is to replace the real world and therefore the alternate world has to appear realistic down to every detail. (Whitson el al., 2008).

Immersion is a means to evoke interest towards the VR experience. Nevertheless, it is merely a part of the experience as it takes a human being to sense and interpret the stimuli presented. How the immersion is subjectively experienced by the user is called presence. (Jerald, 2016: 45-46).

Presence is defined as a subjective sensation or psychological state where all or some of the user's senses cannot identify the contribution of technology in an experience. Even though the experience would partly or fully be made with help of technology. (International Society for Presence Research, 2000).

Whereas immersion refers to the feeling of being surrounded by the VR, presence is the feeling of being in the virtual world. Not just looking through the HMD but actually being somewhere real. (Steamworks Development, 2014). Presence is the uneasy feeling the user experiences when standing on a ledge or is about to get run over by a car in VR. It is a function including immersion and the user, as more immersive environments provide better means for feeling present. (Jerald, 2016: 46).

Presence is a very powerful feeling unique to VR that should definitely be strived for in every single VR application. Achieving a feeling of presence is especially important when performing validations in VR as they require the simulation to have a high-fidelity imitation of the control room. The plant model and HMIs need to be as representative of the actual ones as possible and be capable of reproducing dynamic aspects of the actual control room (ISO 11064-7, 2006).

3.3 Systems

Many significant technology companies such as Google, Samsung, HTC, Sony and Facebook have joined the VR business with their own version of the equipment. The products are either advanced computer based systems or simpler wireless systems that are attached to a smartphone. It has become more and more common to have your own VR system at home, as prices of the systems are becoming more reasonable for the average consumer. The average consumer uses VR systems mostly for watching 360-degree videos which are now widely available on e.g. YouTube or playing video games that require VR. (Virtuaalimaailma.fi, 2017).

The most realistic and immersive technologies are computer based and require a high-end computer to function smoothly. The most well-known products are Oculus Rift, Sony PlayStation VR and HTC Vive. These VR systems allow location and movement tracking and the use of hands during the VR experience. The positional tracking and high-quality graphics require high end hardware, especially the graphics card has to be one of the newer models designed for gaming. Minimum hardware and operating system requirements of the manufacturer should be pursued. Prices of the computer based VR systems are approximately 500 - 1000€. (Virtuaalimaailma.fi, 2017).

What really has brought VR headsets available to the average consumer are the wireless smartphone connected headsets such as Google DayDreamVR and Samsung Gear VR. These VR systems will set you back only 80 - 150€, but they do require a high-end smartphone which is not included. Smartphone headsets do not yet include location or movement tracking nor do they make use of any kind of gaming controllers. Therefore, they are more suitable for watching 360-degree videos than playing games. Furthermore, due to the hardware restrictions as a consequence of using a smartphone instead of a computer, the systems are graphically modest in comparison to computer based systems. (Virtuaalimaailma.fi, 2017).

The system used in Fortum VR validations consists of three Oculus Rift HMDs with Oculus Touch handheld controllers. One for each operator.

4 Simulation

4.1 Definition and Uses

Simulation means the imitation of a real-world system or a process as a function of time. If a system or a process is very complicated to analyze, it is convenient to make use of a computer for simulating the process. (Choi & Kang, 2013).

Simulation enables us to practice situations that are too dangerous to execute in the real world. Situations such as accidents, handling of dangerous goods or controlling a safety critical process are very good subjects for simulation. Simulators are also widely used for training e.g. pilots and heavy-duty vehicle operators. (Räsänen, 2004).

By simulating it is possible to investigate multiple different approaches to problems and accidents. By changing variables and parameters in the simulation that affect a process it is possible to make conclusions about its behavior in different situations. This kind of experimentation is not sensible to do in a real situation. (Räsänen, 2004).

Simulation is also widely used in control room design. Modern technology provides us with means to build integrated development simulators and use them for testing and validation of control rooms and their systems in different stages of design. When combining an UI application with virtual models of automation and the process we get a fully functional real-time simulator of the control room. In addition to testing and validation, the simulator is very useful for training purposes. (Heimbürger et al., 2010: 189).

In Fortum VR validations the Loviisa nuclear power plant process is simulated with Apros, a commercial simulation software developed by Fortum and VTT. 3D CAD drawings of the control room are imported into Unity, a game engine which can be explored with VR HMDs. Together they form a fully functional real-time simulation of the Loviisa nuclear power plant control room.

4.2 Unity

Unity is a multiplatform game engine created by Unity Technologies. It can be used to develop games and interactive VR and augmented reality applications for computers, phones, game consoles and browsers. Unity is the most popular development platform for VR and it supports several HMDs such as Oculus Rift, Gear VR and HTC Vive by default. Unity also offers the tools for easily importing 3D CAD models of control rooms into the game engine. (Unity Technologies, 2017).

4.3 Apros

Apros is a simulation software for dynamic processes developed together by Fortum and VTT. It can be used for simulations of industrial processes to support process and automation design, automation testing and operator training. Apros was originally designed for modelling power plants, but has since been applied for a variety of other industrial processes, power grids, decentralized energy production, district heating networks etc. (VTT, 2017).

Apros contains a wide library of valves, pipes, containers, pumps and a variety of automation system components. It is also possible to create new ones for specific needs. Dynamic process models can be built by combining different components. (VTT, 2017).

Apros has been sold to various projects to approximately 30 different countries (Apros, 2017a). Because of its flexibility and scalability, Apros works well for both small-scale analysis and for full-scale modelling of power plants (Apros, 2017b).

5 Verification and Validation

5.1 Definition

Verification and validation (V&V) are separate processes that are developed for evaluating a system or a product (Figure 2.). They are used in conjunction with each other to make sure specifications and requirements are fulfilled as intended. (The Global Harmonization Task Force, 2004).

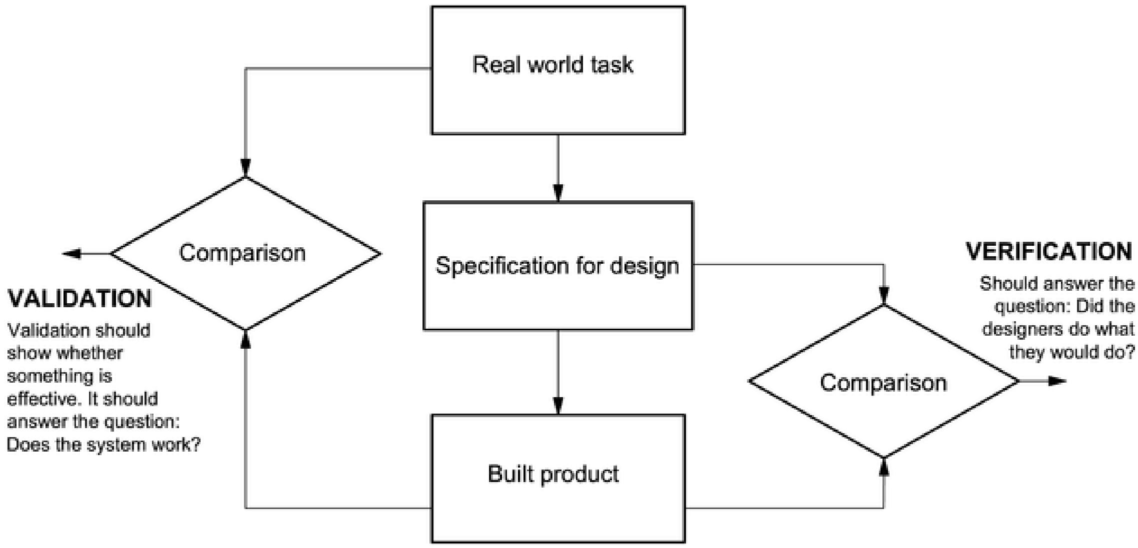

Figure 2. Verification ensures the design is done according to specifications. Validation ensures that the result matches the intended use. (ISO 11064-7, 2006).

ISO 9000 defines validation as "confirmation, through the provision of objective evidence, that the requirements for a specific intended use or application have been fulfilled". Verification is defined as "confirmation, through the provision of objective evidence, that specified requirements have been fulfilled". (ISO 9000, 2015).

Verification tries to answer the question "are you building the thing right?". In other words, is the thing being built as specifications and requirements of the design demands. Validation tries to answer the question "are you building the right thing?". In other words, does the thing satisfy the needs of the user and does it perform as expected in its predetermined surrounding. (STF, 2017).

5.2 Control Room V&V

Control rooms and HMIs have a significant impact on the plants efficiency, safety and environmental factors and comfort of the employees. Therefore, a proper evaluation process to ensure sufficient quality must be implemented. This is particularly important for control rooms with demanding safety or quality requirements. In this context, quality describes how well the control rooms features match up to the client's needs and expectations. These needs and expectations can be separately defined, universally required or obligatory. (Heimbürger et al., 2010: 192).

In control room V&Vs, verification reviews results made during design. The reviews mainly consist of going through documents produced in the previous stage of design and evaluating how well the control room plan fulfills it predetermined requirements and specifications. Validation reviews how well the design results suit the intended use, i.e. meet user needs. (Heimbürger et al., 2010: 193).

V&V is an essential part of design quality management, thus it should be performed and play an essential part during the whole life cycle of the project. Evaluations should be performed as early as possible to avoid expensive modifications in late stages of design. (ISO 11064-7, 2006).

As stated before, control room evaluation is an integral part of the design process. It consists of the following three phases:

- Preparation. A V&V plan is developed, which should contain an accurate description of required tests, measures and tools needed. The plan should also include descriptions of all areas at which tests are supposed to be targeted at and the scope of those tests and their acceptance criteria. Furthermore, members, resources and responsibilities of the V&V team are defined.

- Execution of actual V&V measures. The measures are carried out during stages of design as described in the V&V plan.

- Processing of results. Outcome should consist of all found deviations systematically documented and solutions for their correction. Risks of possible side effects due to design alterations should also be evaluated. (ISO 11064-7, 2017; Heimbürger et al., 2010: 194-197).

V&Vs evaluates both control room layouts and HMIs. Evaluations include determining the functionality of all room facilities and the control systems and other workstations placed in them and all HMIs. A special emphasis is on the realization of required communication when completing tasks in the control room and the fulfillment of ergonomic requirements. Evaluation can be done by using different sorts of checklists and applying relevant standards. The validation is carried out by methods evaluating the facilities through a number of different scenarios or chains of events. The scenarios should be as realistic as possible and be based on actual situations. (Heimbürger et al., 2010: 185-188).

Usual evaluation targets and acceptance criteria are:

- Compatibility. Presentation of information and the performance expected from the operator are in tune with human capabilities.

- Information presented is in an easily understood form and operations are given a clear feedback.

- Situational awareness is on an accepted level at all times.

- Mental workloads of operators.

- Situational manageability. The situation should be under control at all times.

- Teamwork should work effortlessly.

- Understandability of HMIs.

- How design results support the performance of the operator, e.g. by decreasing the probability of human error.

- Ability of the automation system to keep process variables in allowed range.

- Structure of the workstations. (Heimbürger et al., 2010: 198).

5.2.1 Ergonomics

In addition to conventional technical design, control room design includes ergonomic tasks. Whereas the evaluation of technical design is rather straight forward as it is mainly based on stating that technical requirements are implemented, defining ergonomic requirements and evaluating their fulfillment calls for special knowledge in HFE. (Heimbürger et al., 2010: 195).

Ergonomics, or human factors, is a discipline which strives for human well-being and optimizing overall system functionality by making use of essential theories and methods during design. Ergonomics is usually divided in the following three specialized sub-sections:

- Physical ergonomics, which considers a human beings reaction to physiological loads. The field pays attention to the physical features of the workplace, e.g. layout, lighting, safety and load factors such as repetition and unpleasant or static working postures.

- Cognitive ergonomics, which considers intellectual processes such as perception, memory, learning and decision making. It strives to make the interaction between humans and systems compatible with human cognitive abilities and restrictions. Therefore, improve the performance, working conditions, health and safety of employees and avoid unnecessary stress, mental workload and human errors.

- Organizational ergonomics, which considers the teamwork, job satisfaction, co-operation, motivation, shift scheduling, management and ethics in an organization. (IEA, 2017).

5.2.2 V&V Team

The evaluation of design solutions must be done by a V&V team which is independent of the particular design process that is under evaluation. However, interaction between the team and the design project should be stimulated and supported. Access to crucial documents relevant to the process must be granted and the V&V team should be supplied with adequate resources. Members of the V&V team needs to represent sufficient professionalism in HFE and control room systems. (ISO 11064-7, 2006).

5.3 Data Collection

According to an interview with Koskinen & Laarni from VTT, data collection in traditional control room validations in physical simulators is carried out by video recording and sound recording during the validation and questionnaires and discussions afterwards (2017, pers.comm.).

Data acquired by video and sound recording provides information about the performance and communication of operators. In this case performance comprehend the amount of errors, fluency and amount hesitation. (Koskinen & Laarni, 2017, pers.comm.).

Questionnaires are used for mapping out situational awareness and workload of operators in addition to their opinions on HMI usability and fluency of team work by using relevant rating tools (Koskinen & Laarni, 2017, pers.comm.).

Discussions are used for mapping out the operators' understanding about how the system works, differences to the old solutions and their situational awareness regarding the state of the process. Furthermore, the discussions include self-evaluations of overall performance and workload. Operators are also asked about suggestions for improvement regarding the new HMIs and ways of working. (Koskinen & Laarni, 2017, pers.comm.).

6 Methods

This study was carried out by qualitative interviews of experts in the field of V&V and HFE. The interviews were executed in person with the experts as a depth interview.

An interview as a method offers first and foremost flexibility. The interviewer has the opportunity to repeat questions, clarify phrases of expression, correct misunderstandings and further discuss essential topics. Questions and topics can be discussed in a flexible order depending on how the interviewer considers it appropriate. (Tuomi and Sarajärvi, 2009: 73-74).

According to Vilkka, qualitative interviews are frequently used in studies which are not concerned with finding the truth about the subject but rather are interested in the experiences and feelings of the interviewee (2015: 120). Therefore, the interviewee is given more freedom to broaden their answers outside the original scope. Qualitative interviews allow gathering of in-depth information that is not possible to acquire through questionnaires. (UK Data Service, 2017).

The interviews were executed in a depth interview manner. A depth interview is a fully or partially unstructured, conversation like interview. Only the discussed topic is defined and open questions are used to support the conversation. It is important for the interviewer to guide the conversation by building on information provided by the interviewee, thus further deepening the answers. It is the interviewer's responsibility to keep the discussion on track, but also let the interviewee speak freely. A depth interview is based on going through the topic as thoroughly as possible. Therefore, it is not uncommon to interview only a few people. (Vilkka, 2015: 122-127; Tuomi and Sarajärvi, 2009: 72-77).

The theme of the interviews was *data collection in control room VR validation*. The interviews purpose was to map out laborious and time consuming traditional data collection and analyzing tasks and methods regarding control room validations in physical simulators. Furthermore, how these tasks and methods could be implemented and possibly improved in VR. In addition to determining time-saving solutions for burdensome tasks, the intention was to figure out what new, previously impossible or utopian in traditional ways, VR could provide the means for. Primary topics discussed were:

- data collection traditionally
- timing
- speech recognition
- video recording
- eye-tracking
- new possibilities
- VR data reliability

Discussion around the topics was followed up with more specific secondary questions as the interviewer saw necessary. The interviewees were informed beforehand about the theme and topics of the interview, thus allowing them to prepare and think about them in advance.

The interviews were recorded, which allows the interviewer to more freely participate in the discussion. Recording the interview eliminates the need for doing comprehensive notes during discussion and therefore increases involvement, perception and concentration of the interviewer. It also mitigates the possibility of accidently overlooking important information which does not at that time seem relevant. Having a recording of the interview also prevents possible misunderstandings and the interviewer can ask for clarification of unclear statements afterwards. The recordings were only used by the interviewer and no one else. Furthermore, they were properly dealt with after the study was completed.

Recordings were afterwards fully transcribed. Transcription means converting audio to a written format. Transcribing is necessary as the material needs to be in a format which can be examined as qualitative studies are based on either images or written material. Although transcription is a burdensome process it further increases the researcher's interaction with the material. (Vilkka, 2015: 137).

Content analysis was done by categorizing contents of the transcripts under the following five categories:

- what VR does improve
- what VR does not improve
- new possibilities
- challenges with VR
- VR data reliability.

Contents of the categories were analyzed by making use of a cluster analysis. In a cluster analysis, contents of the material are thoroughly examined for similarities. Similarities are then further combined into groups that are given content describing names. (Tuomi and Sarajärvi, 2011: 110). The content analysis did not directly influence reporting of the results but rather acted as a guideline. An example of a cluster analysis of factors decreasing the reliability of data collected in VR can be seen in figure 3.

What decreases the reliability of data collected in VR?			
Original expression	**Simplified expression**	**Lower group**	**Group**
"Biggest challenge in VR is still the resolution, it does not match up to the real world"	Resolution is not good enough	Hardware limitations	Technical limitations
"Last time we had clear user problems with VR. However, there are individual differences. Validations should focus on user interfaces and their functionality and not other, technical problems."	Some users had problems with using VR	User VR using skills	User related problems
Refering to user performance in former tests: "How did this work? I'm not able to do this function"	Some users had problems remembering how to do things in VR		
Refering to user performance in former tests: "We had one who started feeling sick"	Someone started feeling indisposition	Simulator sickness	
"In VR the load is lower. One could think it is not taken so seriously."	Mental workload is lower	Lower workload	
"The physical movement is missing."	Physical workload is lower		

Figure 3. Cluster analysis example. What decreases the reliability of data collected in VR?

7 Results

7.1 Overview

Two of the interviewees of this study are experts in the field of HFE and control room V&Vs and one of them is a control room simulator training expert. All interviewees have significant experience in their own fields of work. Two of the interviewees have previously participated in the first Fortum control room VR V&V suitability test in 2016. Therefore, they have a comprehensive understanding of what can be expected and they recognize the vast potential of using VR when performing control room V&Vs.

Every interviewee had very positive expectations regarding time-saving possibilities, data quality improvements and the possibility of collecting previously unprecedented data by taking advantage of VR in V&Vs.

The interviewees all agreed that in control room V&Vs the amount of all data collected by video and audio recording is so vast that there is no possibility to go through it all:

> *It would take terrible amounts of time if everything would be analyzed. If every second would be looked through and analyzed it would take an eternity. Having said that, everything that speeds up manual work would be good.*

Analyzing every bit of data would take a tremendous amount of time and more often than not the deadlines are very tight. Only a fraction of available data can be thoroughly analyzed. Therefore, everything that can speed up the manual processes of data analyzing and collection is very useful.

The results were divided under three chapters (7.2 - 7.4) according to the research questions of this study: what VR improves, what VR does not significantly improve and new possibilities. Some topics discussed such as timing were reviewed under more than one chapter, as VR is both able to improve and not able to significantly improve some parts of the data collection measures and challenges regarding the topic.

7.2 What VR Improves

This chapter presents the data collection subjects VR improves. In this case improvement is anything that either saves time regarding data collection or improves the quality of the data. This chapter will not cover new previously unimaginable data collection subjects that VR now provides the means for. These new possibilities will be presented in chapter 7.4.

Based on the interviews it can be stated that VR does offer possibilities to save time regarding the data collection and improves the quality of the data provided by movement, video recording and speech. Furthermore, it saves time concerning collection of data provided by timing but does not significantly improve the quality of the data. (Figure 4.).

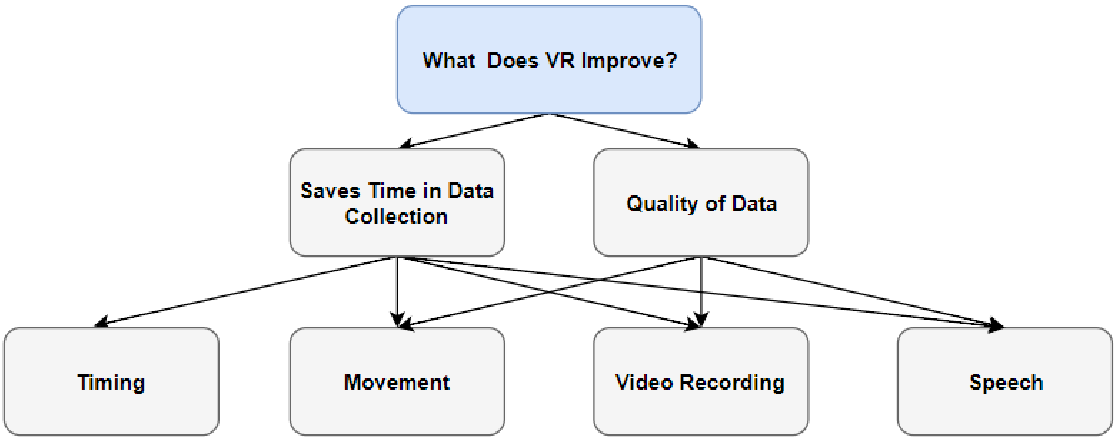

Figure 4. Data collection subjects that VR improves.

Movement

When asked about data provided by movement of operators in the control room, one of the interviewees said that it is becoming more important than before because of the digitalization of HMIs and the reduced need for moving around the control room as a consequence:

> *When new digital work station displays and such started being used, it reduced the need of walking around. One thing we have been thinking is that movement might drastically change due to digitalization. Therefore, we have been observing how much they move.*

On the other hand, another interviewee stated that movement can indeed tell us something about HMI modifications but it should be noted that movement does not on its own provide any significant information. It needs to be studied in proportion to the state of the process. Amount of movement is more of a personality question than anything else:

> *Some operators want to move around more to for example go check something or do different things than others. It is not a measure good performance on its own.*

Two of the interviewees pointed out that tracking movement of operators is burdensome and very hard in traditional validations as it is almost impossible to draw a map or graphs with movement as a function of time manually. They felt like this is something VR would be useful in, as heat maps and graphs can be automatically generated:

> *VR could automatically draw maps of movement. This could be a good opportunity.*

It was further added that this would eliminate the need to manually go through the video material and count the amount of times operators moved to certain places or the duration they spend at certain areas.

Video Recording

According to the interviewees it has been traditionally very important to plan what camera angles will be used to make sure everything crucial will be recorded accordingly. There have been cases where cameras had to be moved mid-validation when operators moved to another HMI. Everything that the V&V team wants to evaluate based on video material needs to be defined in advance:

> *It is important to carefully choose video camera locations. There needs to be a good overview recording angle and when specific displays or panels are being tested the cameras have to be in front of that particular HMI. It is extremely essential that the camera is precisely at the HMI being tested and very close.*

One interviewee mentioned that some dynamic camera angles for recording an overview of the situation could be useful. When using traditional methods, the overview video material has not been very valuable. Often, nothing of value can be gained out of the material as no details can be seen and there are lots of blind spots in for example corners. Dynamic cameras that would follow some sensible criteria or logic would offer more useful overview video material:

> *If there could be a camera that would record a third-person view of the operators and would follow her/his gaze direction. That would be a possibility to gain sensible overview material without blind spots. Such material is very hard to get in a physical control room.*

When asked opinions of the possibility to implement flying, i.e. freelook cameras that can be freely flown through space, not only during the validation but also afterwards, the interviewees thought this could be potentially a great idea. This implementation would remove the need for careful camera placement planning and prevent potential unwanted blind spots in the video material:

> *If the resolution is good enough for details, that would make it possible to for example check things afterwards if there is something that was missed or not remembered.*

According to the interviewees the most useful video material is the one that is shot very close to the target. Therefore, flying freelook cameras would be a major improvement to the quality of the material. It was mentioned that in traditional validations the most valuable material, in addition to close shots of the HMIs, is shot through head mounted cameras. Head mounted cameras provides point of view material which is useful when going through the validation together with the operators. However, this kind of video tends to be very shaky and thus not very sharp or easy to watch:

> *Material shot with head mounted cameras is often tedious to watch as it is very shaky. We have often used this kind of point of view video in the walkthrough of the validation but it is shaky and moving the head around makes it tough to look at details.*

It was further added that point of view video material provided by the VR HMD is of a much higher quality regarding the stability of the material as shakiness due to gaze wandering is non-existent:

> *When you look at point of view material in the VR world, there is no shakiness. In the real world, the camera might even get non-horizontal and sometimes you can even start to feel indisposition when looking at bad quality video. In VR, it is quite nice to look at.*

Speech

When asked about data provided by speech of operators, one of the interviewees pointed out that many tasks in the control room require operators to say certain preset things at certain times. The control room’s action manuals may demand the operator to say or inform her/his colleagues about process values or a completed task. These communication requirements are known in advance and therefore would be easy to automatically recognize:

> *If something could be done, there are certain communication points in the manuals. These might be something that could be automatically picked up as we know what should be said, when it should be said and to whom it should be said.*

One interviewee mentioned that the best-case scenario would of course be total automatic transcription of all communication with time stamps as manual transcription is too burdensome. Some concerns about the current technological state of speech recognition came up, especially as the professional language of Loviisa nuclear power is Finnish:

> *If one could hope, then all talk would be automatically transcribed. Dialects and slang could of course be a problem and there is a lot of background noise in the control room.*

It was further added that background noise and possible alarm sounds does not affect the voice input in VR as a headset is used which prevents all audio from disturbing the microphone input. Therefore, the voice quality is notably better.

Timing

According to the interviewees timing actions and operations is not a particularly good way to measure performance or usability. However, stopwatches are being used to some extent and VR could automatically time certain actions or operations based on preset criteria and thus have a time saving influence on timing. Why VR does not significantly improve the quality of data provided by timing will be further reviewed under chapter 7.3.

7.3 What VR Does Not Significantly Improve

This chapter presents the data collection subjects VR does not according to the interviews significantly improve. In this case improvement is anything that either saves time regarding data collection or improves the quality of the data.

Based on the interviews it can be stated that VR does not bring any significant improvements concerning saving time in data collection nor does it improve the quality of data regarding thoughts and situational awareness of operators. Furthermore, VR does not significantly improve the quality of data provided by timing. (Figure 5.).

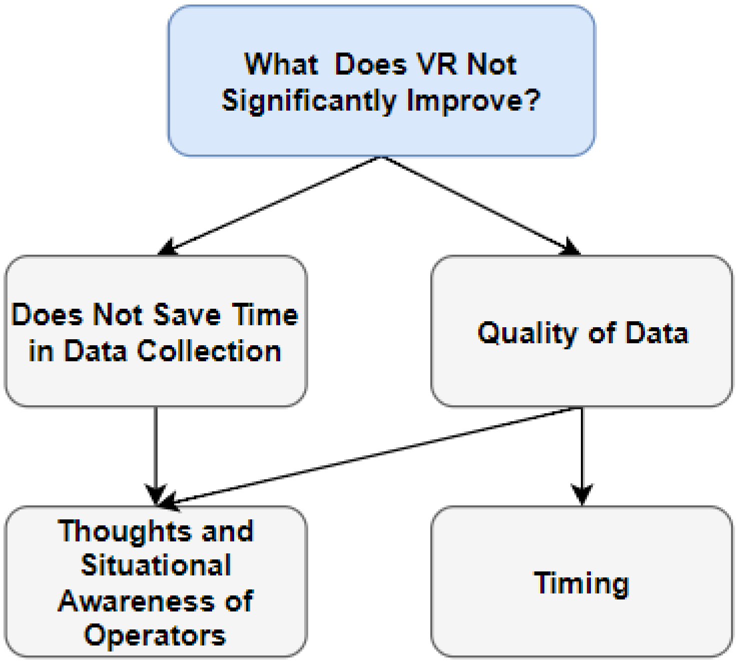

Figure 5. Data collection subjects that VR does not significantly improve.

Thoughts and Situational Awareness of Operators

According to the interviewees something that is not traditionally possible is to know what the operators are thinking and what they understand about the task or state of the process. Thoughts and situational awareness is reviewed by going through the video material afterwards and asking relevant questions. The interviewees did not feel like VR could offer any significant improvement in this case, neither by saving time nor improving quality of the data.

One interviewee briefly pointed out that it could be argued that eye-tracking could provide some useful data what comes to situational awareness and thought of operators. Eye-tracking will be review under chapter 7.4.

Timing

Although VR does save time when it comes to data collection by timing tasks and operations as stated in chapter 7.2, it does not significantly improve the quality of the data gained. One interviewee compared timing with data provided by movement tracking, as neither do grant any valuable information on its own. Timing, like movement needs to be studied in proportion to the state of the process. It does not directly act as a measure of performance. Another interviewee said that you can't define a good time for a certain task in advance:

> *We have never defined what a good time is for completing a task. You will notice if it is going too slowly. It depends on the behavior of the process.*

Based on the interviews it was clear that timing on itself does not offer particularly valuable data and all the interviewees agreed on that VR does not at least yet bring any significant new opportunities or data quality improvements what comes to data gathered by timing.

7.4 New Possibilities

This chapter presents new previously impossible data collection possibilities that VR now provides the means for.

During the interviews two new subjects that would support V&Vs surfaced: eye-tracking and situational tracking (Figure 6.).

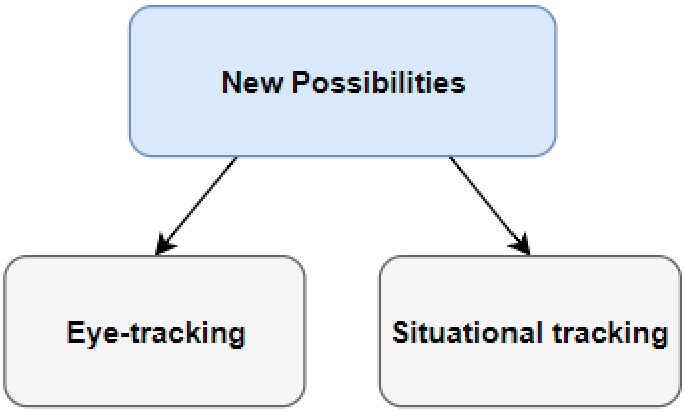

Figure 6. New data collection subjects now made possible by VR.

Eye-tracking

Eye-tracking is based on the interviews the most anticipated and potentially most valuable new data collection opportunity that VR provides the means for:

> *Something that is not available in traditional validations that VR can provide the means for is eye-tracking. It will be very useful in certain situations.*

All interviewees did express their concern about the operators decreasing need to move around and the problems it may bring. Noteworthy possible problems are the operator's situational awareness of other operator's actions and likewise the situational awareness of the V&V team during a validation. It was described by one of the interviewees as follows:

> *When somebody is clearly browsing through displays on a HMI but you have no idea of what she/he is looking for or doing. That is when we need eye-tracking. If you can't see movement with feet or hands, then we have to look at the eyes.*

It was even pointed out by one interviewee that digitalization of HMIs and consequently the lack of movement is such a hurdle when evaluating operator performance that fortunately most of the controls are still done via HW. Digital HMIs are still mostly used for monitoring. Eye-tracking would indeed remove this problem.

One interviewee explained that from the video material provided by head mounted cameras you can often guess what the operator is looking at but a good guess is often not sufficient:

> *Head cameras show the way they gaze, but there remains an uncertainty about what they really look at. Some specific numerical value or just generally that way? Is she/he still looking for something or did she/he already find what she/he was looking for?*

It was stated that eye-tracking provides a lot of valuable and formerly unimaginable information about the ways operators use manuals or directives while they work. It would be beneficial to see how operators use these manuals in conjunction with the tasks they execute.

According to the interviewees eye-tracking would offer human factors research lots of new possibilities. What comes to validations, eye-tracking would offer unparalleled information about why errors occur:

> *With eye-tracking we could review errors affecting the process. We could closely see what they have been looking at, thus gain very specific information about what the operator was doing while she/he was supposed to do something else. What information she/he has been looking at.*

It was further added that eye-tracking would in a way provide information about the thoughts and situational awareness of operators. This kind of data has been formerly unimaginable:

> *Eye-tracking could be a way to in a sense get inside an operator’s head. A way to understand the situational awareness and to build understanding what she/he is thinking.*

One interviewee pointed out that it would also make it easier to go through the video material with the operators as it is very hard to try to remember afterwards what you did at a certain time or what you were looking at. You could ask much more specific questions about what they were thinking about when they were looking a certain way.

Situational Tracking

Based on the interviews a significant problem in traditional validations is the situational awareness of the V&V team. V&V teams consists of experts that are independent of the design process and although they know the process and design the validation tests, it can be very demanding to be fully aware all the time of what is happening in the control room:

> *Even though we study the manuals, it is very hard to follow what the operators are really doing. They do not talk a lot.*

One interviewee said that even though every operator is observed by an expert who focus only on their dedicated operator, it is still hard to be fully aware what the operator is doing a certain time:

> *Even though you can focus only on one operator, it is good if you manage to recognize the important steps that you know in advance. But everything in between is kind of hard to follow very precisely.*

Situational awareness of the V&V team is also further decreased by the digitalization of HMIs and consequently the decreased need to move around. When an operator walks to a certain HMI it is easy know what step of the manual she/he is on at that moment but when the operator is sitting down and looking at digital HMIs it gets a lot harder:

> *It is hard to know what they are doing when they sit down for prolonged times as the situation quite down. We don't know if they are just sitting there and if they are doing something or nothing at all. Only afterwards can we ask them.*

Two of the interviewees suggested that if the manuals used by the operators and the V&V team for monitoring the situation could somehow be linked certain controls. In other words, the steps in an action manual would be matched to the specific controls and automatically track progress like a block diagram:

> *It would not be impossible to do a manual that would automatically follow what steps are done. You could see where we are and also see if some steps are missed or done in the wrong order.*

This would considerably improve the situational awareness of the V&V team and thus save time and free them to focus on more important things during the validation.

8 Discussion and Further Research

Multi-user VR simulators built with game engines have already been found to be promising regarding evaluation of control rooms. Gatto et al. (2013) states in a study about using VR as a tool for evaluating safety-critical control rooms, that game engines may be valid tools for estimating operator action times. Likewise, Bergroth et al. (in press) found VR to have huge potential in their study about use of VR in control room evaluation. These claims are further strengthened by the results of this study.

Even though VR still has some minor problems with usability and resolution it seems to be quite clear that it will be a significant part of control rooms design and evaluation in the short-term future. The possibility for cost-efficient evaluations in early stages of design can provide valuable information about design flaws, integration problems and HFE discrepancies and thus potentially save significant amounts of resources.

As stated in the results of this thesis, VR control room validations can potentially provide us with a lot of what seems like high quality data and even data that has been unattainable before. How reliable or usable this data is compared to data collected by traditional methods is still slightly questionable.

According to Koskinen from VTT, VR does have some advantages compared to traditional physical simulators as concerns fidelity of the test environment. The VR environment can be made to match the real control room to every tiniest detail, whereas physical simulators often does not exactly imitate the real world. Furthermore, VR provides the means for simulating effects like fires, smoke and earthquakes which further increases the fidelity of the validation situation. (Koskinen, 2017, pers.comm.).

Factors decreasing the reliability of data collected in VR was also discussed during the interviews of this study. After a cluster analysis of the discussion it was noticed that data reliability is mainly decreased by two factors: technical limitations and user related problems.

The only major technical limitation now is resolution. Because of resolution limitations it is not possible to see minor details from far away, but rather it requires you to be very close to small objects to see them clearly. This forces operators to get unnaturally close to HMIs which consequently decreases realism. Fortunately, it looks like this problem is getting a solution very soon as new hardware is released all the time. The most promising solver of the problem now seems to be Varjo. Varjo is talking about human eye level resolutions higher than 70 megapixels per eye in their own upcoming HMD, which would be a major improvement to the 1.2 megapixels per eye provided by the Oculus Rift (Engadget, 2017).

The user related problems consist of three problems. These problems which decrease data reliability are: VR using skills, simulator sickness and lower workload.

Some users that are not familiar with videogames or VR equipment from before, tend to require a lot of time for getting used to the equipment. Not being able to use the equipment with ease or constantly forgetting how to perform certain actions significantly reduces reality of the situation and thus reliability of acquired data.

According to a study based on Fortum tests, concerning how immersive 3D environments can augment and advance safety-critical control room evaluations, the workload of operators in VR validations is exceptionally low (Bergroth et al., in press). Lower workload might imply that operators do not yet take VR validations as seriously as traditional ones.

Based on the interviewees experience, simulator sickness might negatively influence performance of the operators. However, simulator sickness is a sum of various factors associated with hardware and software and as they improve will simulator sickness consequently be less of a problem (Oculus VR, 2017).

An interesting further research subject is analyzing the consistency, reliability and usability of data collected in VR validations. Furthermore, how it compares to data acquired from traditional control room validations in physical simulators. Possible subjects could include how the validation medium affects operator performance and execution times. Additionally, does the lower physical and mental workload in VR affect results in any way.

9 Conclusions

This study concerns how utilizing VR could improve or support data collection of traditional control room validations performed in physical simulators. The principal conclusion was that immersive VR environments combined with 3D-models of control rooms and process simulations do provide the means for gathering higher quality data more efficiently than possible with traditional methods.

The results indicate that VR improves the quality of data and saves time as regards data collected by video recording, audio recording and movement tracking. Utilizing VR also saves time in data collection by timing but does not significantly improve its quality. Furthermore, VR does not significantly improve the quality or save time as concerns data providing information about thoughts and situational awareness of operators.

VR now also provides the means for unparalleled automatic situational tracking which greatly facilitates the work of the V&V team. Additionally, VR makes it possible to collect valuable previously unattainable data by eye-tracking.

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