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Fire Safety Engineering | Lund University

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Uppfattad realism i VR-försök för forskning om människors beteende
Perceived realism in virtual reality experiment for human behaviour research

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Abstract
Virtual reality can be a useful research tool to investigate how people behave in different fire situations. For the results from such experiments to have good validity, i.e., to represent behaviours that can occur in a real environment, the VR environment must be perceived as a good substitute for the real environment. The project focuses on how to achieve such high-quality VR environments. Two different environments, a lecture hall and a corridor, were built up in two virtual versions each and compared with a method for measuring environmental perception, the Semantic Environmental Description (SED). The two VR environments in the lecture hall were designed in a detailed version and a slightly less detailed version, a more simplified version. In the VR environments in the corridor, the main question was how distances are perceived in VR compared to in a real corridor. A total of 159 subjects participated, and all completed a SED assessment in each environment and both in VR and in the real environment. The difference between the SED description for the lecture hall was small between the three environments (real and two VR environments). Distances in a corridor are judged to be most similar between the real corridor and a VR environment that is designed with correct proportions between length, width and height.

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Preamble

The research project was initiated in 2021 and was intended to be finalised in 2023. The focus was then on investigating how VR technology could be applied to an educational situation. The education to be investigated was focused on fire safety. The purpose of the research was primarily to investigate how the people behave in a specific environment created using virtual reality, and having this being experienced as realistically as possible.

After carrying out some of the initial experiments, it turned out that there are additional aspects that may be relevant to consider in the effort to increase validity and reliability of the results. Some of these were known when the application was written. What has been added, however, is that the development of the technical equipment is proceeding rapidly, something that may not have been fully considered. It was therefore decided to have a slightly different objective, to focus more on the work of improving the virtual environment to the point that it can more closely represent the real environment. This was therefore at the expense of applying the VR technology to a practical case, fire safety training. The change was accepted by Formas.

The change was necessary in order to establish VR technology as a validated research method in the longer term. The research group appreciates Formas' decision to allow us to adjust the objective.

The research project with Dnr 2020-02034 has been carried out by Silvia Arias, Jonathan Wahlqvist, Pimkamol Mattsson, Joakim Eriksson, Thorbjörn Laike (active in 2021) and Håkan Frantzich. All are researchers at Lund University.

Sammanfattning

Tekniken med virtual reality (VR) har under de senaste åren utvecklats som en metod för att genomföra forskning i situationer är det inte är möjligt att utföra motsvarande försök i en verklig miljö. Det kan gälla scenarier där personer skulle utsättas för farliga förhållanden som exempelvis exponerade för en brandsituation eller där en undersökt teknik eller företeelse inte existerar.

Oavsett anledningen att använda VR som forskningsmetod är det nödvändigt att den artificiella miljön är utformad på ett sätt så att resultaten får en hög validitet det vill säga att resultaten skulle kunna motsvaras av de som erhålls om försöken genomförs i en verklig miljö. Validiteten i de försök som genomförs för att undersöka människors beteenden vid utrymning kan därför påverkas av hur en person uppfattar den simulerade miljön och om den uppfattas på ett liknande sätt som en motsvarande verklig miljö. Ett mål med arbetet är därför att undersöka hur en VR-genererade miljö bör utformas för att likna den verkliga miljön och hur VR-miljön kan förenklas utan att det påverkar den subjektiva uppfattningen jämfört med den verkliga miljön. För att bedöma hur miljöerna uppfattas användes en bedömningsmetod; semantisk miljöbeskrivning (SMB).

Från tidigare genomförd forskning har det framkommit att avstånd i en VR-genererad miljö kan uppfattas annorlunda jämfört med avstånd i verkligheten. Föremål långt borta upplevs vara längre bort i VR jämfört med i verkligheten. En del av försöken som genomfördes för att validera VR som forskningsmetod inkluderade bedömning av avstånd i VR och i en motsvarande verklig miljö. Vidare undersöktes även förmågan att korrekt identifiera ljudsignaler och riktningen till dessa i en VR-miljö. Resultaten jämfördes med motsvarande signaler som förekom i den motsvarande verkliga miljön.

En inledande undersökning (Background studies) genomfördes för att jämföra olika tekniker att illustrera ljus och skuggor i VR-miljöerna. Ljussättning och förekomsten av olika skuggor undersöktes och försökspersoner fick kvalitativt bedöma två olika utformningar i taget. Sammantaget undersöktes fem olika kombinationer av ljussättning och skuggor i en modifierad så kallad Cornellbox. Varje försöksperson fick sammanlagt betrakta tio parvisa jämförelser. Totalt deltog 107 personer i en online-version av undersökningen och 24 personer i en motsvarande uppställning men med en VR-genererad miljö. Undersökningen genomfördes som en förstudie inför den följande undersökningen.

För att undersöka hur en VR-skapad miljö uppfattas i förhållande till en verklig motsvarande miljö (Experimental studies) inkluderades två olika miljöer i undersökningen, en större lektionssal och en korridor. Både dessa återskapades som VR-miljöer. Lektionssalens VR-miljöer utformades med olika detaljeringsgrad, från nästan fotorealistisk återgivning till en något med förenklad men realistiskt utförd miljö. Korridoren undersöktes i VR med avseende på olika avståndsskalor för att representera en miljö i skala 1:1 och en miljö där främst avståndet i djupled skulle upplevas som kortare. Korridorens VR-miljö utfördes kvalitetsmässigt som den mer detaljerade miljön i lektionssalen. Förmågan att uppfatta ljudsignaler och riktningen till dessa undersöktes både i lektionssalen och i korridoren och både i VR och i de verkliga rummen. Miljöbedömningen (SMB) genomfördes också i samtliga fall, i VR och i de verkliga rummen.

Sammantaget deltog 159 personer i försöken och alla exponerades vardera för en av de verkliga miljöerna och den andra en av de VR-genererade miljöerna, en lektionssalsmiljö och en korridormiljö. Varje försöksperson exponerades bara för en av de två alternativa VR-miljöerna i lektionssalen och korridoren.

Resultatet från den inledande undersökningen (Background studies) är att den utformning som uppfattades som mest realistisk kännetecknas av att vara utformad med "baked, global illumination, emissive surface light source and baked shadows".

Försöken med att jämföra hur olika miljöer uppfattas i VR och i verkligt rum resulterade i att endast små skillnader kunde observeras. Det kan tolkas som att VR-miljöer kan användas som en god

representation av en verklig miljö för att undersöka scenarier där det inte går att genomföra försök i en verklig miljö. Det konstateras att den högkvalitativa och detaljerade VR-miljön uppfattades förhållandevis lika jämfört med den något förenklade miljön. Det ska dock poängteras att den mindre detaljerade miljön också ska ses som mycket lik den verkliga miljön men med exempelvis färre detaljer, belysningen utgörs av punktkällor, reflektioner ignoreras och ytor har en enklare utformad textur. Den förenklade miljön skulle fortfarande vara verklighetsnära men undvika aspekter som i VR-simuleringen kräver stor datorkapacitet eller är tidskrävande under designfasen.

Jämförelsen av avstånd i VR och i en verklig miljö konstaterades vara mer lika mellan för en utformning av VR-miljön som görs i en icke modifierad skala. Detta går emot granskad litteratur som uppger att avstånd uppfattas som kortare i VR jämfört med i den verkliga miljön.

Reaktionen på den larmsignal som förekom i försöken var vanligare i de verkliga miljöerna. Skillnaden var tydlig och även förmågan att ange riktningen till ljudsignalen var bättre för de verkliga rummen.

Rapporten ger en rad förslag till hur en VR-miljö bör utformas för att den ska kunna liknas vid en motsvarande verklig miljö. En diskussion förs om för vilka problem där VR kanske inte är en lämplig metod.

Summary

In recent years, the virtual reality (VR) technology has been developed into a research method for situations where it is not possible to perform corresponding experiments in a real environment. This may apply to scenarios where people would be exposed to dangerous conditions, such as being exposed to a fire situation or where an investigated technology or phenomenon does currently not exist.

Regardless of the reason for using VR as a research method, it is necessary that the artificial environment is designed in a way that the results have a high validity, that is, the results could correspond to those obtained if the experiments were carried out in a real environment. The validity of the experiments carried out to investigate human behaviour during evacuation can therefore be affected by how a person perceives the simulated environment and whether it is perceived in a similar way to a corresponding real environment. One objective of the work is therefore to investigate how a VR-generated environment should be designed to resemble the real environment and how the VR environment can be simplified without affecting the subjective perception compared to the real environment. To assess how the environments are perceived, an assessment method was used; the Semantic Environmental Description (SED).

From previous research, it has emerged that a distance in a VR-generated environment can be perceived differently compared to the same distance in reality. Objects far away are perceived to be further away in VR compared to reality. Some of the experiments included assessment of distance in VR and in a corresponding real environment. Furthermore, the ability to correctly identify an alarm sound and the direction to the sound in a VR environment was also investigated. The results were compared with a similar signal that occurred in the corresponding real environment.

An initial study (Background studies) was conducted to compare different techniques for illustrating light and shadows in the VR environments. Lighting and the occurrence of different shadows were examined, and subjects were allowed to qualitatively assess two different designs at a time. In total, five different combinations of lighting and shadows were examined in a modified so-called Cornell box. Each subject was given a total of ten pairwise comparisons. A total of 107 people participated in an online version of the study and 24 people in a corresponding setup but with a VR-generated environment. The study was conducted as a preliminary study for the following study.

To investigate how a VR-created environment is perceived in relation to a real corresponding environment (Experimental studies), two different environments were included in the study, a larger lecture hall and a corridor. Both were recreated as VR environments. The lecture hall VR environment was designed with different levels of detail, from almost photorealistic rendering to a somewhat simplified but realistic environment. The corridor was examined in VR with respect to different distance scales to represent an environment on a 1:1 scale and an environment where primarily the distance in depth would be experienced as shorter. The corridor VR environment was created with a quality as the more detailed environment in the lecture hall. The ability to perceive sound signals and the direction to them was examined both in the lecture hall and in the corridor and both in VR and in the real rooms. The environmental assessment (SMB) was also carried out in all cases, in VR and in the real rooms.

A total of 159 people participated in the experiments and all were each exposed to one of the real environments and the other one of the VR-generated environments, a lecture hall environment and a corridor environment. Each subject was only exposed to one of the two alternative VR environments in the lecture hall and the corridor.

The result of the initial investigation (Background studies) is that the design that was perceived as most realistic is characterized by being designed with "baked, global illumination, emissive surface light source and baked shadows".

The attempts in the Experimental studies to compare how different environments are perceived in VR and in real space resulted in only small differences being observed. This can be interpreted as VR environments being a good representation of a real environment to investigate scenarios where it is not possible to conduct experiments in a real environment. It is found that the high-fidelity and more detailed VR environment was perceived as relatively similar compared to the somewhat simplified low fidelity environment. However, it should be emphasized that the low fidelity environment should also be seen as very similar to the real environment but with, for example, fewer details, the lighting consisting of point sources, reflections are ignored and surfaces having a simpler designed texture. The simplified environment would still be realistic but avoid aspects that require large computation capacity in the VR simulation or much time consumed during the design phase.

The comparison of distances in VR and in a real environment was found to be more similar for a design of the VR environment made on an unmodified scale. This contradicts consulted literature that states that distances are perceived as closer in VR compared to real space.

The reaction to the alarm signal that occurred in the experiments was more common in the real environments. The difference was clear and also the ability to indicate the direction to the sound signal was better for the real rooms.

The report provides a number of suggestions for how a VR environment should be designed so that it can be compared to a corresponding real environment. A discussion is held about which problems VR may not be a suitable method for.

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1 Introduction

Virtual Reality (VR) is a versatile tool that has been increasingly used for both research and learning (Ahmadpour et al., 2019; Caprara & Caprara, 2022; Demetrescu et al., 2016; Gromer et al., 2019). However, the differences between virtual and real environments can still be obvious. People can perceive the virtual environment as unreal, and therefore possibly behave in a different way than in reality (Arias, Wahlqvist, et al., 2020). Bridging the gap between reality and VR could not only improve the validity of the data produced with VR methods, but also aid the development of VR training tools able to replace physical training by virtual training. Realistic virtual environments can have advantages for research and training. From research perspective, the high level of experimental control in VR experiments, combined with the representation of otherwise dangerous scenarios including fire and smoke, are very convenient. On the training side, a VR training environment has the advantages of repeatability, low risk to the trainee, and relatively low costs for each repetition once the scenario has been developed. Therefore, this project aims to identify differences in the perception of realism between real and virtual scenarios, based on studies about lighting, perception of distances, perception of sound and environmental psychology.

The present project intends to bridge the gaps observed in previous VR experiments performed at the Division of Fire Safety Engineering, at Lund University. The past experience with VR experiments showed, anecdotally, that participants react to a virtual environment in a different way than what would be expected in a real environment. For example, in a previous project about residential fires (Arias, Nilsson, et al., 2020), an existing house was used as a model for an experiment in VR. The purpose of the project was to study the behaviours displayed by participants when encountering a fire in a virtual house based on the same layout as their own house. People who lived in the same house model in the same housing development were recruited as participants. In that experiment, the data collection was based on the sequence of actions they performed once they realized there was a fire. There was no intention of collecting data about differences between the real house and the virtual one the participants were put in, as it was assumed that would not have a major impact in their sequence of actions, as long as they knew the location of the doors (which they did). Nevertheless, the participants kept bringing up differences: the virtual house felt smaller (even though it was built on a 1:1 scale), and there was clearly less clutter/objects in the VR house than in their real houses. In that experiment, a smoke detector was triggered to observe their behaviour when a fire was detected in the house. A large fraction of the participants either ignored the sound of the smoke detector completely, attributed it to something else (“a microwave”, “a truck outside the VR lab”), or only paid attention to it once they got bored. This behaviour was not expected in the design phase of the experiment, so no data was collected about it.

Later on, in a completely different VR experiment, this time about evacuation from an underground particle accelerator located in Switzerland (Arias, Ronchi, et al., 2019), a similar behaviour was observed. Participants in this experiment were employees at said particle accelerator. They were exposed to a completely different alarm (a siren), which they should have been familiar with as it was the same alarm they learned about in their mandatory safety training at work. Yet, many participants ignored the alarm again. This was completely unexpected, as it was thought that their training would have them prepared to identify the alarm and act accordingly. Some participants even expressed doubt that was “the right alarm”, or confused it with a different one. Participants in the accelerator study also brought up that the virtual accelerator tunnel they were in was “too clean” compared to the real one.

A third study, based on evacuation from a hotel room in a high rise building (Arias et al., 2022) showed a different kind of issues. A picture taken at the real hotel building, indicative if the perceived environment in person, compared to a screenshot from the virtual hotel building at the same position, were clearly different in many aspects, but mainly the lighting looked different and the end of the hallway (where the emergency staircase was) looked much smaller in the virtual building, and therefore could be perceived as further away. Similar discrepancies have also been observed in other studies aiming at replicating existing places (Elfarri et al., 2023; Feng et al., 2020; Kaarlela et al., 2020; Skarbez et al., 2022), as rendering of virtual environments are hardly photorealistic as of today. The difference in perception between a real building and its so-called "digital twin" in an immersive virtual environment can be explained by several factors:

a. The "digital twin" only captures a limited number of features of the real-world building, often focusing on representing dimensional accuracy and macro-features such as colours. This largely leaves out other aspects such as microfacet characterization of surfaces which is important in terms of making things look "realistic" when interacting with light.
b. Modern commercially available head-mounted displays simulate stereoscopic vision using two independent screens, one for each eye. While a user is in a virtual environment, it is possible to see on a computer screen the images presented in the head-mounted display. However, the computer screen only shows what one of those screens render, making the image on screen an approximation but not exactly what they are seeing. This means that the perception of an observer looking at the computer screen may be incomplete and not convey exactly the same visual input that the participants receive while looking around in VR.
c. Lighting in VR can only be as bright as the screens can be. Lighting in reality can be much brighter. Moreover, the way the light bounces in VR can be adjusted to represent reality in a better way, but technical skills are needed to understand that and be able to apply the changes needed. In addition, the human eye naturally adjusts to the intensity of the light it receives, which is a phenomenon hard to replicate in VR. When looking at the screens in VR, the light intensity is not higher when looking at a light source, as it remains generally in the same range in a lit environment. Therefore, the adaptations made by the eye may not be well represented in VR.
d. The resolution of VR: the definition on screens in modern VR equipment are simply not as high as the human sight. Therefore, some images far away in VR cannot be seen as clear as in reality, which implies that some details that would be easier to perceive in reality may be lost in VR. This is due to the size of the pixels and the size of the screens, as there are only so many pixels in each of the screens of the head-mounted display, making some details not possible to be perceived as clearly as in reality.

The anecdotal nature of these statements does not allow for a theory to be proven. Therefore, experiments need to be conducted to assess the impact of these issues, if any, and propose solutions. This project focused on having a better understanding of VR, by providing measurable data to assess the differences between VR and reality, and provide possible solutions.

1.1 Background

Virtual Reality (VR) has proven to be a versatile tool to study human behaviour in different fields. It has been used to study anxiety (Andreatta et al., 2020), fear (Gromer et al., 2019), and phobias (Miloff et al., 2019). It has also been applied for understanding learning (Shen et al., 2019), brain processes (Hertweck et al., 2019) and memory (Schöne et al., 2019). VR technology has especially useful advantages in fields like human behaviour in fire, as it allows studying scenarios without exposing participants to the intrinsic risks of real fire and smoke. Within this field, VR allows studying decision-making (Andrée et al., 2016; Arias et al., 2022; Arias, Fahy, et al., 2019), way-finding (Cosma et al., 2016; Kinateder et al., 2019; Troncoso et al., 2015) and pre-evacuation (Bode & Codling, 2018). However successful previous experiments have been, it became apparent that a portion of the participants in different samples showed little concern for behaving as they would do in a real environment. In different experiments performed (Andrée et al., 2016; Arias et al., 2022; Arias, Fahy, et al., 2019; Arias, Ronchi, et al., 2019), each of them independent in terms of objectives, scenario and sample, many participants did actions that are unlikely to be observed in a real-world experiment. Those actions could be labelled as curious (trying to break objects in VR to check if it is possible), vandal (such as throwing large objects out of a window in a virtual high-rise building), and even criminal (battery and even stabbing of virtual characters without a motive) in a real-world setup. These actions are only an example of the many ways Virtual Environments (VE) can fail to convey the same social rules that apply in the real world. In an analogous way, the technology in itself has shortcomings that need to be better understood in order to use it as a reliable research tool. Examples of these shortcomings are lack of reaction to loud and clear alarm sounds, lack of weight of virtual objects, low dexterity when interacting with objects through hand controllers (and subsequent loss of patience leading to stop any further attempts at performing that action), lacklustre feedback from the VE to the actions performed by the participant (if not appropriately programmed to do so). Therefore, there is a need to improve the way the VR method reproduces reality in order to become a fully applicable tool for studying human behaviour.

The representation of a room in VR can be very close to the real room in some aspects, such as dimensional representation, but that does not mean that people perceive virtual environments in the same way as they perceive reality.

Previous experience running VR experiments have highlighted key issues in the design of a virtual environment that can affect the user perception and the allocation of computational resources, such as the 3D modelling of the selected environment and its lighting. As they are unavoidable for the generation of visual virtual environments, studying different approaches can streamline the generation of environments in future projects.

This study aims at identifying differences in the perception of virtual environments and real environments in order to refine the use of VR experiences as research and training methods.

1.2 Aims

This project aims to study how to improve the perception of reality in a virtual environment. This aim will be met by identifying factors that need to be improved to create more visually realistic virtual environments. While it can be hard to determine exactly how realistic something is, as much subjectivity is involved, differences in the perception of a real environment compared to the perception of a virtual representation of it can indicate relevant factors for the viewer.

In a broader perspective, increasing the realism of virtual experiences could allow for more reliable results when using VR for research purposes in different fields. Identifying the differences and how they can impact results in VR experiments can enhance the validity of the data collected. At the same time, finding a balance between the realism of the environment and the allocation of resources to produce it can be beneficial for the efficiency of research projects.

1.3 Objectives

The main objective of this project is to investigate in what ways the perception of an environment differs between VR and reality. This will be achieved by studying three aspects of virtual environments:

a. Impact of the level of fidelity: identify differences in the perception of the real room and virtual representations of it in high and low fidelity.
b. Perception of distances: identify differences in the perception of distances to given objects in a real environment and a virtual representation of it.
c. Reaction to the sound of an alarm: identify differences in the reaction to sound in VR compared to reality, as well as the ability to determine the origin of the sound in VR.

1.4 Method

To achieve the objectives described in the previous section, a research plan was designed to gather information about the most basic aspects of developing virtual environments, and collect data about perception of them. The research plan consists of two studies, each with sub-studies, as follows:

1. Background studies
   a) Suitability of surveying methods
   b) Lighting study – pilot test
2. Experimental studies
   a) Perception of distances
   b) Impact of the level of fidelity
   c) Reaction to alarms

In the Background studies, which also use experiments as research method, the goal is to have a detailed understanding of the different methods to survey real environments to turn them into virtual ones and how apply lighting to them in VR. Therefore, the Background studies can be seen as exploratory studies prior to the main studies conducted in the second step of the project, the Experimental studies. Both surveying and lighting are fundamental to reproduce an existing room in VR. Therefore, a deep understanding of the available methods for each and their implications in needed as a bedrock for any more advanced improvements of the realism of the virtual experience.

The generation of a virtual environment requires some sort of 3D modelling of the desired environment. There are different ways to survey an existing room (e.g., photogrammetry, laser scanning, among other) to then represent it in a 3D model, each with their own advantages and disadvantages. Techniques and much experience may be needed in the case of complex environments. Moreover, there are tools that can help the modelling stage, but their suitability varies depending on the context. Understanding the differences between the surveying methods and applying them in the right context is the first step for an efficient use of time in the development of the virtual environment. In addition, a clear overview of the drawbacks of implementing one or another can also contribute to focus on the aspects that are more relevant for the perception of realism of a virtual room.

Lighting is also a complex aspect of a virtual environment. To create a realistic environment, close to the real environment requires realistic lighting and shadows, which needs to be complemented by an efficient use of computational resources to run the virtual environment. Therefore, contrasting different configurations in light and shadow rendering can lead to not only more realistic scenarios, but also a better allocation of computational resources used in the virtual environment.

The background studies were meant to compare different ways to produce a virtual environment, either by the selection of a surveying method for the design of a virtual representation of a given room, or by selection of light rendering conditions in the game engine. Both studies and their outcomes will be described in detail in sections 2.1 and 2.2 respectively.

With the background studies concluded, their outcomes were applied in virtual representations of real rooms to be included in the Experimental studies.

. Virtual environments were made to study the identified relevant aspects of the perception of realism in VR (i.e., level of fidelity, perception of distances, and reaction to alarms). The selection of the rooms, the experimental design and the results will be presented in sections 3.1, 3.3, and 4.

1.5 Ethical considerations

The design of the entire study was approved by The Swedish Ethical Review Authority, Dnr 2022-02684-01. The approval came with three conditions which all were adhered to.

There are some ethical aspects to consider when using VR equipment. The use of an HMD can cause some discomfort such as dizziness, nausea and eye fatigue. The discomfort is not common, but some individuals have reported these discomforts in previous experiments. Most of the discomfort is related to a person moving in the virtual environment. In the current case, however, the idea is that the person should stand still at one point and in principle only move their head to view the environment. The risk of discomfort is therefore considered to be lower compared to other experiments in a VR environment. The discomfort is usually mild and not permanent. When the person takes off the equipment, these disappear fairly immediately.

It is therefore important that the research subject is aware that he or she can interrupt the experiments if he or she feels any discomfort.

Other risks that are identified may be the risk of physical harm. This is also linked to the use of equipment for VR environments but is mainly caused by the person moving physically as a way of simultaneously moving in the virtual environment. The risk of a participant injuring themselves is assessed as low since the person was not supposed to be moving in the real environment nor in the virtual one. To still take into account the risk of personal injury, a special personal injury insurance was taken out with Kammarkollegiet.

It is considered that there were no ethical dilemmas linked to the integrity of the participant. No personal data was collected so there is no link between a person's identity and the results and data that was collected.

1.6 Limitations

Obviously, a study like the one presented in this report has several limitations. The purpose was to investigate if an environment created in VR could be represented in a way that people perceive in the same way. The VR environment cannot yet provide the same representation due to technical limitations in the HMD such as limited field of view, limited resolution of the two screens and the fact that most people understand they are in a virtual environment and not in the real environment. Still, using a VR representation can be a useful substitute in testing scenarios which would be harmful in reality. The experiments used the most up-to-date technology at the time for the experiment.

Practical limitations using humans in experiments are related to a natural variation within a population. This can to some degree be overcome by using a large sample. In the current study a larger number of subjects were used to handle this limitation, however, an even higher number of people participating would most likely provide an even better reliability in the results.

2 Background studies

The purpose of these background studies was to identify a suitable way to design the virtual environments to be used in the Experimental studies. These studies were relatively simple, as they were either an expert's assessment (in the case of the Suitability of surveying methods) or a pilot test (in the case of the Lighting study). Nevertheless, their output helped to make more educated choices in the design of the virtual environments to be used in the Experimental studies. It should be noted that these choices are usually made by 3D modelers who design virtual environments without much more justification than their individual preferences. Therefore, while an expert's assessment or a pilot test may not provide irrefutable evidence of the suitability of a given output, these studies were more thorough than the usual individual preferences of a modeler.

2.1 Suitability of surveying methods

In this study, the objective was first to test different ways of surveying an existing room to recreate it in VR, with the ultimate purpose of assessing the efficiency of the different methods in producing a realistic 3D model that can be used for VR experiments reducing the amount of work for the modeller. A professional 3D modeler and researcher with vast expertise in VR worked in this study. The study was made in the same environments that later were used for the Experimental studies, described in Section 3.1.2. Basically, the tests were conducted in one corridor and one university lecture room as they presented different challenges for the surveying techniques used.

Three surveying techniques were considered for this study, namely laser scanning, photogrammetry and a more traditional 3D modelling commonly used for creating VR environments.

Laser scanning was quickly deemed inappropriate for the task, upon investigation of different kinds of laser scanners. It was then clear that the results of the data collection of the laser scanning are good, but the scanning produces a highly dense point cloud, which makes the processing challenge very high. Therefore, laser scanning would not necessarily reduce the amount of work for the modeller.

The second method under study was photogrammetry. Photogrammetry has the potential to provide a very realistic 3D representation of real-life objects or environments, which can be relevant to a given experimental condition. However, photogrammetry has substantial drawbacks which became clear after having tried this technique for a sample space. One major disadvantage is that it produces a high density of polygons, which may affect the performance of some VR applications. In VR, a critical aspect is to maintain a certain framerate (typically 90 Hz or higher), in order to provide a comfortable experience. Lower framerates can lead to undesirable results like simulator sickness, or choppy visuals. Since the processing power of the graphics card used to render the virtual environment in real time is finite, an excessive number of polygons may cause the framerate to drop below an acceptable level.

A main disadvantage of the photogrammetry technique is the uncertainty in the quality of the results. Photogrammetry cannot always reproduce all required details. Under some conditions, e.g. when capturing reflective surfaces, or when the photographed area is insufficiently covered, the resulting 3D geometry can become greatly distorted. Moreover, photogrammetry can be time consuming. First, a high number of photos (typically a few hundred) are needed for reproducing an environment, such as a room. The photos need to be taken in a systematic way to ensure a certain amount of image overlap, as well as a total coverage of the environment, accounting for all needed angles, in order to be produce a comprehensive 3D-model. The photos are initially processed by the photogrammetry software in a camera alignment stage, by detecting common reference points between the photos. This may take a few hours to compute, and the outcome is a 3D-point cloud of these reference points. Under certain conditions, some of the photos may fail to align, and thus do not contribute to the 3D-point cloud. This can be due to many reasons: insufficient overlap between images, camera resolution, lens quality, lighting, reflections, etc. When some photos do not automatically align with each other, manual work is needed to identify common reference points, in order to complete the alignment process. This can be a highly time-consuming work when dealing with a high number of photos. The next computing step is to produce a more dense and detailed point cloud. The required computational processing time depends upon desired level of detail, and the available computing power. Based on the dense point cloud, the software can then create a 3D-geometry (i.e. a 3D-mesh built up by an arbitrary number of polygons). The software can also produce and apply textures onto the 3D-mesh, using the aligned photos as a basis.

Due to these drawbacks, the photogrammetry models generated were not straight-forwardly used for the Experimental studies. Instead, those models were imported into the 3D modelling tool Blender (Blender Foundation, n.d.). Here, a new 3D geometry was created following the architectural plans and using the photogrammetry model as a "scaffold". In addition, the captured photos formed the basis for the creation of materials and textures to be applied. This means that the photogrammetry output was used to complement a classic 3D modelling, in which the designer models the environment in 3D from scratch. This mixing of both methods gave an optimum middle-point of manual work, number of polygons and capturing of all relevant features needed for the desired virtual environment.

The interior space of the corridor and of the lecture hall, respectively, were documented using a digital camera (GoPro Hero 10, image resolution 5568x4176 pixels), a laser rangefinder, and a measuring tape. The digital photos were imported into the photogrammetry software Agisoft MetaShape (*Agisoft Metashape: Agisoft Metashape*, n.d.). With this technique, the photos were processed to form a 3D-point cloud, and later converted into a 3D geometry. The photos were also used for creating textures onto the 3D geometry. A few points of reference were measured with a laser rangefinder, and a measuring tape, and the dimensions of the 3D geometry were calibrated according to these references.

After Blender export, the 3D models were imported into the game engine Unity (Unity, n.d.), where the VR scenarios were built for the Experimental studies.

2.2 Lighting study

The lighting study was meant as a pilot test to choose the best configuration for the representation of light and shadows in VR, aiming for a realistic representation of the environments created for the second step, the Experimental studies. The study aimed at comparing combinations of factors that may affect the perception of realism in participants when it comes to the rendering of light and casting of shadows in VR. The factors under study were the lighting mode, the type of light source, and the type of shadows.

2.2.1 The room

A simple room, inspired by the Cornell box (Goral et al., 1984; *History of the Cornell Box*, 1998) was generated. The dimensions of the room were kept proportional to those of the Cornell box, and the prisms in the original Cornell box were replaced by chairs to make the room look inhabitable. The colours of the chairs were red and green, to resemble the original Cornell box. The modelled room is shown on Figure 1.

2.2.2 The factors

The three factors that were studied are described as follows:

Lighting mode: there are two ways to render light in the Unity game engine. The light can be "baked" or rendered in "real time". The baking of the light is a computationally expensive method, as the light bouncing from an object to its surroundings is affected by the colour of the object, This phenomenon is usually referred to as "global illumination" (Pharr et al., 2017). This means many calculations are to be performed by the computer to generate the environment correctly. Baked illumination is also called "offline" rendering, because it is rendered before the actual VR experience. When baked illumination is used, the user cannot make any changes to the lighting conditions during the VR experience, making the shadows static, as they would not move if the objects casting them move. A more interactive alternative is the “real-time” light rendering mode, in which the computer processes the lighting in real time, allowing the shadows of objects to move with the objects as in reality. Real-time rendering is also very expensive in computational terms, which means that simplifications need to be made in order to make the VR experience smooth and keep the lighting relatively realistic. Moreover, real-time lighting also has a limit of typically 8 light sources that can be used on real-time. Therefore, real-time lighting may impose limitations on how much computational power can be used for the rest of the VR experience for the user. For these reasons, the selection of lighting mode is important for the design of the virtual environment, as both baked and real-time modes are computationally expensive, and each presents advantages and disadvantages that may make one more desirable than another in a given experimental setup.

Type of shadows: one of the simplifications made by real-time lighting is implemented through the selection of the type of shadows. Unity offers two types of shadows, namely “hard” and “soft” shadows, plus the alternative of “no shadows”. When hard shadows are used, there are two distinct light regions: shadow and no shadow, or *umbra* and *fully lighted* (Assarsson, 2003) respectively. There is no light gradient or other form of transition between them. When soft shadows are used, an intermediate region named the penumbra emerges, which is a gradient from the umbra to fully lighted (Assarsson, 2003). Soft shadows are therefore more realistic than hard shadows, but also computationally more expensive than hard shadows (*Unity - Manual: Shadows*, n.d.). The alternative of “no shadows” means that objects are configured not to cast any shadows, sparing computational power for other features of the virtual experience. Using the “no shadows” configuration is not realistic, but it can be a way to reduce the computational costs for objects for which the lack of shadows may not be very noticeable.

Light source: this feature refers to the way the light is emitted from the source. Two light sources were included in this study, namely “emissive surface” and “point light”. The point light casts the light from a single (ideal) point in the environment, while the emissive surface is more realistic as real-world light-emitting objects have surfaces. Point lights have the advantage of the light origin point being invisible to the user during the VR experience, allowing for the designer to add as many point lights as needed to simulate real-world lighting conditions in the room sin a simplified way. However, the overall illumination they produce is not very realistic, as the pattern of light and shadows they cast are based on the location of said points. Alternatively, emissive surfaces represent real-world light fixtures better than point lights, as the light and corresponding shadows correspond to the emissive area of the represented light source instead of an idealized single point in the 3D space.

Five combinations of these three factors were used in this study, resulting in five versions of the same room. Table 1 presents the different settings used to generate the rooms.

Table 1 – Settings or combination of factors used to generate each experimental scenario

Setting	Lighting mode	Light source	Shadows
0	Baked (global illumination)	Emissive surface	Baked
1	Baked (global illumination)	Point light	Baked
2	Real-time (direct lighting)	Point light	Soft shadows
3	Real-time (direct lighting)	Point light	Hard shadows
4	Real-time (direct lighting)	Point light	No shadows

2.2.3 Immersive and non-immersive VR

The lighting study was divided into two parts: a non-immersive VR experiment (hereon referred to as the *online experiment*) and an immersive VR experiment (hereon referred to as the *onsite experiment*). In the first part, an online survey was created, in which participants assessed 2D pictures in pairs displayed on their computer screens, to judge which one looked more realistic. The pictures presented renderings of the same room geometry, using the settings presented on Table 1. The pictures are presented here on Figure 1.

a) Image 0

b) Image 1

c) Image 2

d) Image 3

e) Image 4

Figure 1 a, b, c, d, e– The images used in the online experiment. The full 3D versions of them were used in the onsite experiment. See Table 1 for details on the combinations of settings used to generate each image.

The pairs of images were chosen at random. In the second part, the onsite experiment, the same room rendered with the same combinations of lighting and shadows settings were presented in 3D in a virtual environment using an HMD (HTC Vive Pro Eye, 2448 x 2448 pixels per eye, 5K resolution, 120° field of view, 120 Hz refresh rate). Analogously to the online experiment, participants judged which of the two rooms presented to them at a time looked the most realistic according to themselves, based on a subjective assessment of the term "realistic".

Conducting the online experiment had the purpose of taking advantage of the simplicity of recruiting participants by sharing a link on social media intending to reach a high number of participants. However, it was considered that non-immersive VR may not provide the same experience to the participants, hence the onsite experiment was also performed. The comparison between the results of the two experiments was meant to assess differences due to the medium where the judgements were made (non-immersive and immersive VR). It was then possible to evaluate any differences in the results of the online experiment compared to the results from the onsite VR experiment aimed at studying perception of realism.

2.3 Participants

Participants in the *online* experiment were recruited through a post on a subreddit dedicated to surveys and polls (r/SampleSize). In addition, a link to the experiment was posted in one of the authors' Linkedin profile, in order to increase the number of participants. In total, 107 participants joined the online experiment, producing up to 10 datapoints each. Each datapoint consisted of a judgement made between two images. The experiment lasted only a couple of minutes, as there were only 10 pairs of images to compare, and participants were asked to make a quick assessment. No compensation was offered for their participation.

No information about gender, age, experience using computer games or similar background data were collected as it was not deemed necessary for the study.

Participants in the *onsite* experiment were employees at the university, recruited in person. The participants were aware of VR being used as a tool by the researchers involved. However, given the context of the experiment (visual perception of a simple room configuration), it was considered that the familiarity with the researcher would not play a role. The onsite experiment was considered a small pilot test to assess methodologically whether the results of the online experiment are comparable to onsite results. In total, 24 participants joined the onsite experiment, producing up to 10 data points each, analogously to the participants in the online experiment. Due to the necessary mounting and dismounting of the VR equipment, and the instructions on how to use the hand-controllers, the onsite experiment took around 10 min.

There was no exclusion criterion other than being underage. No data was collected about the participants' demographic descriptors such as age, gender, nationality, etc.

2.4 Results

Figure 2 presents the results of the Bradley-Terry model for paired comparisons. As the figure shows, in the onsite experiment, the probability of setting 0 being selected as more realistic over the rest was 59%, ahead from the second-best performer, setting 1, with 26% chance. The likelihood of settings 2 to 4 to be chosen ranged between 6% and 3%.

In the online experiment, the results showed settings 0, 1 and 2 ranging between 25% and 28% likelihood of being chosen. Setting 3 had a 16% chance of being chosen, while setting 4 was clearly far behind, with less than 2% chance of being chosen.

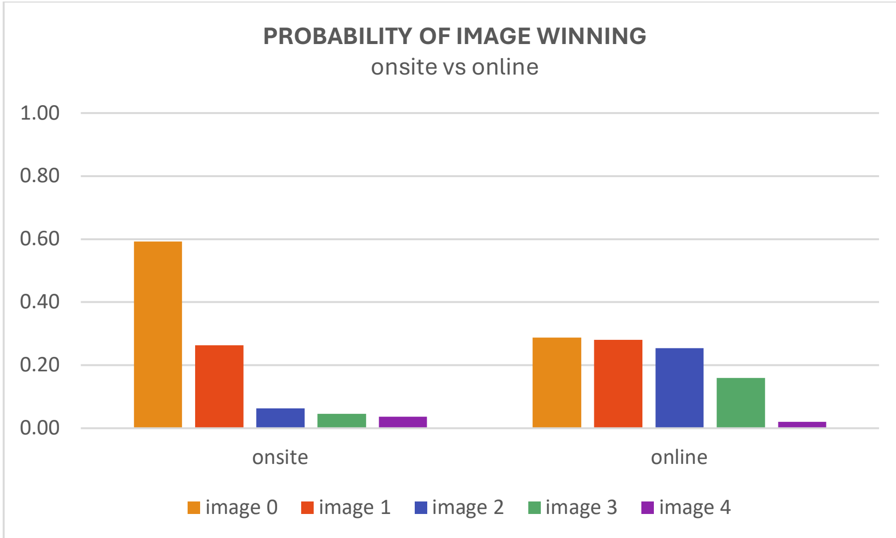

Figure 2 – Probability of each image winning in each experiment

Figure 3 presents the same results, contrasting each setting's chance in the onsite experiment and the online experiment. As can be seen, the differences between the experiments are large in most cases. It is not possible to tell from the data obtained if setting 1 and setting 4 are perceived as the same in both cases or it is a mere coincidence.

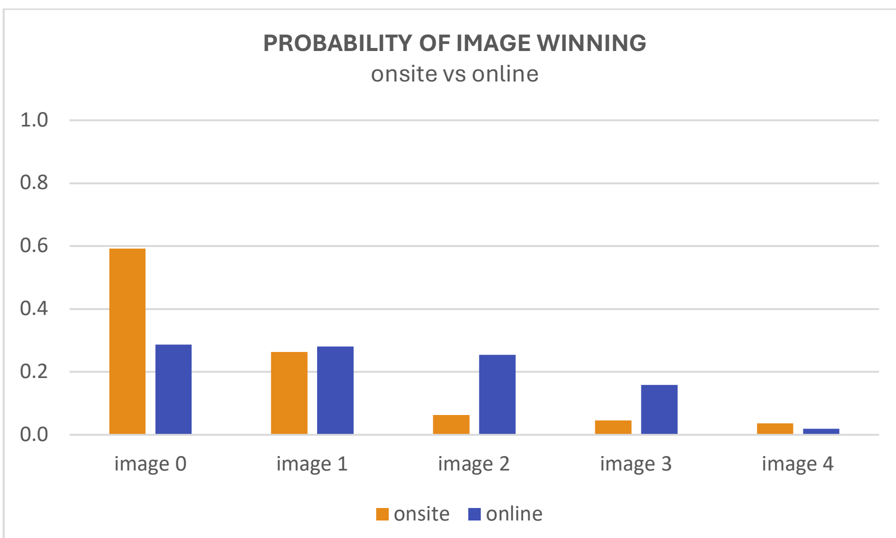

Figure 3 – Probability of image winning in the online and the onsite experiments

Participants were not asked to give a reason for their judgement, but many of them did so casually, both in the online experiment (through messages to the researcher on LinkedIn) and in the onsite experiment (verbally). The recurrent themes were their aversion for the lack of shadows (setting 4), and something being off with the hard shadows. Since the experiments were not designed to collect this data, the information is presented here anecdotally.

2.5 Discussion

In the onsite experiments, Setting 0 (baked, global illumination with emissive surface lighting) was clearly the most preferred. In the case of the online experiment, Setting 0 performed best but only slightly better than Setting 1 and Setting 2. In essence, Setting 0 showed a much higher probability of success in the onsite experiment than in the online one. Even though the study was not designed to investigate why there might be a difference between both experiments, one can speculate as to why this is. A potential issue is the lack of control in the online experiment. A user might sit in a well-lit or a completely dark room, use a cellphone screen or a large screen to view the images, have external distraction present, all of which can affect the assessment. In comparison, the onsite experiment was conducted in a much more controlled environment with the exact same set of equipment for all participants.

Setting 1 (baked, global illumination with point light) came second with a generous margin over any of the remaining three settings in the onsite experiment. It presented a similar probability of winning in both experiments.

Setting 2 (real-time illumination, point light, soft shadows) and Setting 3 (real-time illumination, point light, hard shadows) showed a major drop in probability of success in the onsite experiment compared to the online one. However, it is likely that the difference between a soft shadow and a hard shadow was harder to notice in the onsite experiment due to the distance between the participant and the rooms being observed.

Setting 4 (real-time illumination, point light, no shadows) was consistently rated as the least realistic in both experiments. As mentioned before, some participants alluded to the lack of shadows as a problem for the image/room to be considered realistic.

2.6 Conclusion to the lighting study

Participants in the onsite experiment considered Image 0 (baked, global illumination, emissive surface light source and baked shadows) as the most realistic by a wide margin. It is then suggested that this combination of settings is used when generating virtual environments for immersive VR setups for the Experimental studies. In addition, a hybrid solution can be implemented by adding real-time lighting once the scene is baked, for movable objects to cast the right shadows in real time.

The results of the onsite experiment and the online experiment were not consistent, which means that a 2D, non-immersive VR medium was not an adequate alternative to the immersive VR setup in this case. However, this difference might be due to the lack of control in the online experiment, and future studies could have the participants conducting the onsite assessment in the controlled environment of a laboratory, to make a more solid comparison between the online and the onsite methods.

The Background studies are further described on a paper submitted for publication by Wahlqvist, Arias and Frantzich (2025).

3 Experimental studies

The second stage in the project focuses on finding aspects in the VR environment that makes it realistic in terms of how similar the environment is compared to the same but real environment. In the experiments the virtual environments were created to represent rooms that exist in reality and apply the results from the first step in creating the new VR environments.

The Experimental studies consisted of three different experiments, conducted in sequence. The experiments are

- Perception of distances,
- Impact of the level of fidelity and
- Reaction to alarms

and they all had different objectives, but the shared purpose of improving our understanding of how VR can be perceived compared to reality.

3.1 Selection of the real rooms

Given the purpose of the project, two rooms were to be recreated in VR for the Experimental studies. A set of requirements guided the selection process, as follows.

3.1.1 Requirements for the real rooms

3.1.1.1 Types of rooms

In principle, any room could be selected but as one of the purposes was to compare the perception of distances a room with at least one dimension being considered long should be preferred. Another purpose was to determine how the levels of details in the VR room was perceived in comparison with appearance in the real room. For this purpose, a room having many smaller and larger objects would be preferred. In addition, rooms in which the lighting conditions could easily be controlled (i.e., no windows or covered windows) were preferrable, as sunlight and overcast conditions could affect the perception.

3.1.1.2 Availability of the rooms

The rooms needed to be easily available for the surveying as the experiments were conducted at times convenient for the participants. In addition, costs and convenience were considered.

3.1.1.3 Technicalities

The rooms needed to be easily reachable by participants. Also, a secure space for the mounting of the VR equipment was needed, since the experimental phase would span several months.

3.1.2 Selected rooms

The two rooms selected are located at the V-building, in the Faculty of Engineering at Lund University. Located on the campus, the building is easily reachable by potential participants among the student body and people in Lund and surroundings. In addition, the VR lab from the Division of Fire Safety Engineering could be used for the conduction of the virtual part of the experiments in the Experimental study, meeting the secure space required.

3.1.2.1 Corridor

A corridor located in the basement of the V-building was chosen as one of the two rooms. The corridor was easily available as it is normally used for circulation of the cleaning staff and as access to storage facilities from different research groups. This meant that experiments could easily be conducted there without blocking the main circulation paths of most building occupants. This fulfilled the requirements for availability of the rooms.

Moreover, the corridor is part of an evacuation route within the building, which means that it could be used in the future for evacuation studies focusing on the movement phase. Examples of those possible studies are route choice, design of signage or exits, and even pedestrian dynamics (e.g., movement speeds or biomechanical processes). Being a corridor, it obviously had one dimension being longer than the others making distance assessment convenient. Therefore, the requirement for types of rooms was also fulfilled.

3.1.2.2 Lecture hall

The lecture hall "V:C" located by the main entrance of the V-building was the second room chosen. The lecture hall can accommodate up to 160 sitting occupants, distributed in tiers. Naturally, the lecture hall is easily accessible by people on campus. Moreover, it could be used for the conduction of experiments when not being used for lectures.

The lecture hall could also be a useful configuration for future studies. Similar to a theatre or a cinema theatre, different scenarios could be studied, considering variations in type of occupancy (based on age, familiarity with the building, and mobility), location of the fire, and design of alarms and signage. The lecture hall was also equipped with many typical objects to be found in similar lecture rooms such as a set of chalk boards, a lecture stand, a sink, audio equipment, fire extinguishers and evacuation signage. Therefore, the requirement for types of rooms was fulfilled.

3.2 Participants

Participants were recruited from the student body, employees at the Department of Building and Environmental Technology at Lund University, and the general public. The public was reached out through a specialized website hosting calls for participants from several Swedish universities (www.accindi.se).

A total of 159 participants joined the experiment, between mid-May and early December 2024. Their ages ranged from 19 to 75, with an average age of 31, with 47% of them identifying as females, and the rest as males. They were mostly students (72%) at the university. Their fields of study were fire safety engineering (63%), civil engineering (24%), surveying (5%), and various other (8%), which means most of them were studying courses taught at the V-building, in which the experiments were conducted.

The high frequency of fire engineering students was due to the recruitment campaigns aimed at students in the courses taught by the researchers. It was considered that their background in fire safety engineering would not play a role in the data they produced, as what was measured was unrelated to their field of study.

The inclusion criteria were being 18 years of age or older and being a Swedish or English speaker. Exclusion criteria were being legally blind or deaf, or having epilepsy or any sort of stress disorders.

3.3 Experimental design

The experimental design was a considerable challenge, as the three experiments were to be run in an efficient manner in terms of time for completion, number of participants needed, and technical aspects of the execution. The experimental design of each experiment is described in the following sections.

3.3.1 Impact of the level of fidelity

To produce a functional virtual environment a participant can interact with and feel present in, many skills are needed. 3D modelling alone requires technical skills and abilities to work in an efficient manner. Then, the 3D model needs to be imported into a suitable game engine, where much programming (scripting) and game development skills are needed (e.g., lighting, sound effects, materials). It is in the game engine where the interactions are defined, and where the lighting, sound effects and animations are introduced. All of these, illustrated in Figure 4, require a high skillset that is fully independent of the field of research the virtual environment is designed for. This means that many researchers running VR experiments in their research field may lack the expertise needed to produce a high-end virtual environment for their experiments. Subcontracting game developers implies additional costs to a given project. Independently of the costs, game developers may not have a full grasp on what is important for the ecological validity of the data collected.

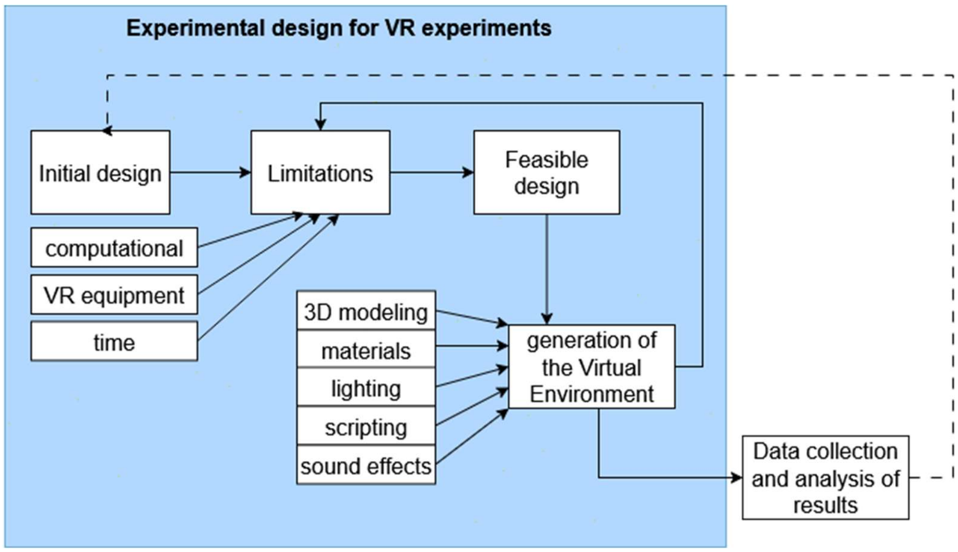

Figure 4 – Overview of the process of experimental design for VR experiments

This experiment was intended to assess whether the investment of time and effort in creating a high-fidelity VR environment was noticeable by the participants. The objective was, therefore, to assess whether participants would rate the high-fidelity version higher than the low-fidelity one, and how each version compared to the assessment of the real room.

Given this, two alternative VR scenarios of a lecture hall were created: a high-fidelity and a low fidelity one. Figure 5, Figure 6, and Figure 7 present a view of the real lecture hall, the high-fidelity virtual representation of it and the low fidelity version, correspondingly.

Both scenarios were made by an expert VR designer and researcher with vast expertise in 3D modelling. The Hi-Fi scenario included a high degree of details, as well as textured materials and more realistic light mode and shadows. The goal in the design of the Hi-Fi scenario was to make it look highly realistic, i.e., visually as close to the real room as possible. It is of course difficult to objectively assess what "highly realistic" is, particularly if time or budget restrictions can vary widely. The idea was to generate the scenario with a high level of details (like textures, reflections, technical installations, etc.) without which the room would still unequivocally still be identified as a lecture hall. Those details were arbitrarily defined due to a lack of an objective metric.

A low fidelity (Lo-Fi) scenario was created and based on the Hi-Fi one, but it represented a more pragmatic approach to 3D modelling and game development. A researcher with ample VR experience scaled down the level of fidelity in the Hi-Fi scenario. This simplified, Lo-Fi scenario omitted details, such as small objects, and textures. The materials used were plain coloured. The textures in all materials were removed, turning everything flat and homogeneous in finishing. For example, all wooden surfaces were the exact same light brown colour, without wood grain. In the Hi-Fi version, the different textures used resembled the finishing of each wooden object. The lighting in the Hi-Fi version was based on area lights, directional lights, and point lights, matching the location of the light fixtures in the real room. In the Lo-Fi version, simple point lights were used, placed where convenient, and the light temperature was set to default values. Table 2 lists the changes made.

Table 2 – Initial features in the Hi-Fi level scenario that were removed or modified in the Lo-Fi scenario

Feature	Reason for modifications in the Lo-Fi version	Example objects
Number of materials	It takes time and effort to create the many different materials that exist in the real room. All similar materials will be boiled down to a plain colour that on average represents all materials.	Seats, risers on steps, tables, podium
Textures on materials	To recreate the patterns in objects, pictures need to be taken. Instead, an approximated plain colour was selected.	Upholstery, linoleum floor, wood grain, cement plaster
Small objects	Everything less than 20x20x20 cm^3 may be too small for participants to realize it is not there.	Thermostat, microphones, sensors, cable ducts, switches
Complex objects	Recreating objects in detail in 3D models takes time. Everything that can easily be a box, is a box.	Radiator, speakers, podium, paper towel dispenser, projectors
Lighting	Replicating the illumination of a real room takes time and knowledge on how lighting works in a game engine. Point lights are easy to add and modify. Point lights replaced all the lighting. Default light temperature was used.	Lighting at the blackboard, area lights above the sitting area, general directional light
Granularity	Patterns in fabrics, wood, plaster, are very clear on close proximity to the observer. Adding the right patterns to the virtual environment takes time. All patterns were removed.	Upholstery, linoleum floor, wood grain, cement plaster
Reflections	Adding reflections takes additional time. All reflection probes were removed.	Metallic surfaces, smooth surfaces like the floors or polished wood

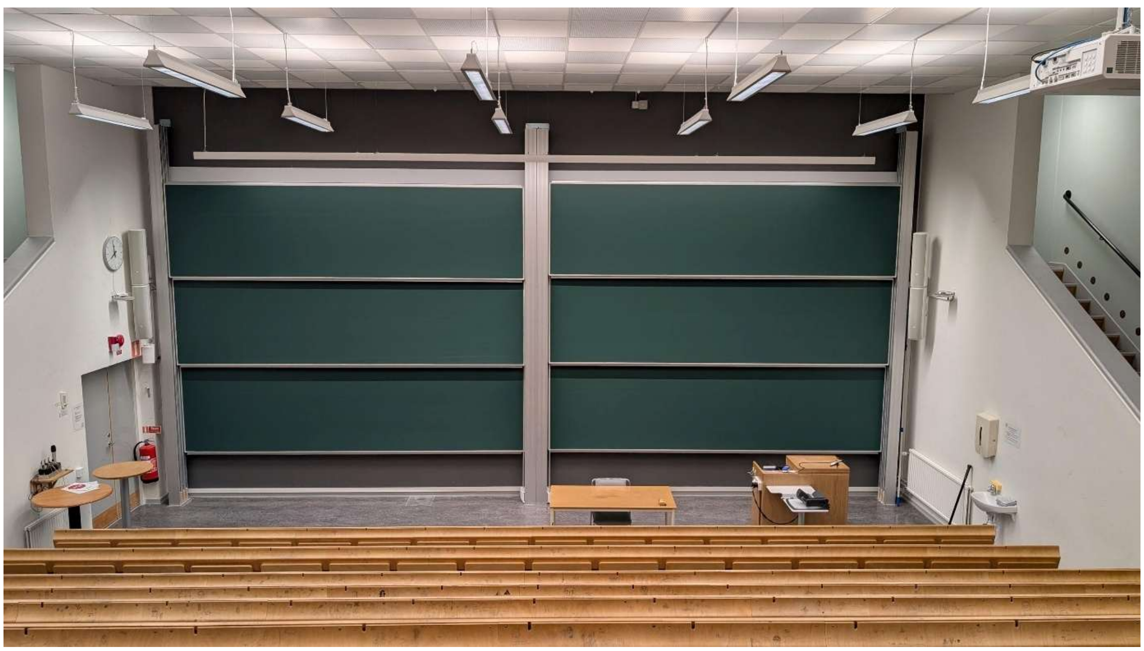

Figure 5 – View of the real lecture hall, from the standpoint of the participant in reality.

Figure 6 – View of the virtual lecture hall from the standing point of the participant in the Hi-Fi scenario.

Figure 7 – View of the lecture hall from the standpoint of the participant in the Lo-Fi scenario.

It should be noted that the objective for the Lo-Fi scenario was to resemble a design situation with limited amount of time to create the environment, not to necessarily make it look different. The scenarios produced may not look radically different, but the Lo-Fi scenario used an approach that required less technical expertise and less time to make. Therefore, if participants gave a lower rating to the Lo-Fi scenario than they gave to the Hi-Fi scenario, it would be clear that the time investment is worth it. Moreover, using the real room as a threshold, the realism of the Hi-Fi scenario could also be assessed.

3.3.1.1 Assessing the perception of environments

Having the three versions of the lecture hall, a method to assess perceived differences between rooms was needed. The chosen method was the Semantic Environmental Description, SED (in Swedish: Semantisk Miljö Beskrivning – SMB) which is a semantic tool measuring human perception of a physical environment as a room, a building, indoor and outdoor spaces, as well as landscapes. The tool was developed in both Swedish and English by Rikard Küller (1972) to evaluate and therefore, provide a better understanding of overall perception of an environment. The tool has been applied to evaluate car interiors (Karlsson et al., 2003), room interiors (Eklund et al., 2024), and outdoor environments at nursing homes (Bengtsson et al., 2015).

The tool contains 36 adjectives. A factor analysis has divided the 36 adjectives into eight factors (see Table 3). The participant will usually be asked to answer how well each adjective suits the environment through 7-point rating scales where '1' is *'slightly''* and '7' is *'very''*.

Table 3 - The Semantic Environment Description – adjectives and factors. Adapted from Küller (1991)

Factor	Description	Adjectives included in the factor	
		Positively correlated	Negatively correlated
1. Pleasantness	The quality of being pleasant, beautiful and secure experienced in the environment	GOOD, IDYLLIC, STIMULATING, PLEASANT, SECURE	BRUTAL, UGLY, BORING
2. Complexity	The degree of variation or specially intensity, contrast as well as abundance of the environment	MOTLEY, LIVELY, COMPOSITE,	SUBDUED
3. Unity	How well the various parts in the environment fit and function together	FUNCTIONAL, WHOLE, CONSISTENT, PURE STYLE	
4. Enclosedness	A sense of spatial enclosure and demarcation of the environment	DEMARCATED, CLOSED,	AIRY, OPEN
5. Potency	The degree of power and/or force in the environment and its various parts	POTENT, MASCULINE,	FEMININE, FRAGILE
6. Social status	The socio-economic value of the environment including maintenance	EXPENSIVE, LAVISH,	WELL-KEPT, SIMPLE
7. Affection	A sense of similarity related to the age of the environment and also, a feeling for the old and genuine	MODERN, NEW	TIMELESS, AGED
8. Originality	The unusual and surprising in the environment	CURIOUS, SPECIAL, SURPRISING	ORDINARY

According to Küller (1991), the SED tool is reliable for capturing a comprehensive description of the environment at the individual level. This tool was originally tested with a group of technology students by asking them to evaluate a lecture hall on two occasions (the second occasion took place one week after the first one). The stability was determined over the eight factors at satisfactory level, and the weak correlations among the factors (Küller, 1972). Thus, the tool is considered to capture the individual's overall impression of the environment in different aspects that may be independent from each other. Further, the tool was tested in a cross-cultural study conducted in England and Singapore (Kwok, 1979 cited in Küller, 1991).

In a previous study, Laike (1999) applied the SED tool to measure the perception of a car interior. Though it was noted that the result of SED evaluation of a virtual test-object could differ slightly from that of a real one, the SED tool showed to be able to discriminate different car interiors in the forms of virtual objects. Based on this study, the SED tool is considered as having potential to capture a comprehensive description of the environment both in real-world and virtual settings and to identify whether and to what extent the evaluations of these two types of settings differ from each other for the same environment. More importantly to the study on Impact of the level of fidelity, even if the SED method has a sort of bias, the same bias will be present in the assessment of each room, making the differences between the rooms still comparable.

Initially, the SED tool was applied as is, as indicated by Küller (1972). The experiment was designed to be conducted in either Swedish or English, depending on the participants' choice, as it was deemed that a good understanding of the words was important. However, during pilot testing before the lecture hall and corridor experiments were initiated, two native English speakers indicated they were not very familiar with the definition of the word "motley" (it was considered old-fashioned), and they were unsure of what the term "of pure style" meant. If native English speakers had issues with some definitions, it was expected that non-natives will struggle more. In addition, native Swedish speakers pointed out that they did not agree with the English translation of the original Swedish words. They claimed other English words would describe better the Swedish term. This can be due to changes in the usage of words in Swedish or English since the development of the SED tool in 1972. Therefore, a new list of English translation of the original Swedish words was used in this experiment. The English translation was made by a native English speaker with a C2 Mastery level in Swedish based on the Common European Framework of Reference for Languages (*Common European Framework of Reference for Languages*, n.d.), translating the original Swedish words. The improved list of words used in the experiments is presented on Table 4

Participants were asked to fill in an SED questionnaire assessing whichever lecture hall they were seeing either in VR or in reality. The participants gave their answers by marking one of seven alternative gradings on a canvas in the virtual room, or in a tablet in the real room. The output of that questionnaire would then be compared to each other to assess perceived differences. They were also asked to fill in an SED questionnaire for the corridor, to assess perceived differences there too, which may provide more context for the differences in the perception of distances.

Table 4 – Original words of the SED questionnaire and the adopted English terms for the present experiment. The words modified from the original English version are marked in bold.

Original Swedish	Original English	Modified English
modern	modern	modern
brokig	motley	cluttered
ful	ugly	ugly
egendomlig	curious	strange
dyrbar	expensive	expensive
maskulin	masculine	masculine
stimulerande	stimulating	stimulating
sluten	closed	enclosed
funktionell	functional	functional
välvårdad	well-kept	well-maintained
vanlig	ordinary	common
trygg	secure	safe
stilren	of pure style	elegant
tråkig	boring	boring
ömtålig	fragile	fragile
dämpad	subdued	toned-down
tidlös	timeless	timeless
öppen	open	open
idyllisk	idyllic	idyllic
överraskande	surprising	surprising
enkel	simple	simple
ålderdomlig	aged	historic
konsekvent	consistent	consistent
livlig	lively	lively
bra	good	good
avgränsad	demarcated	demarcated
kraftfull	potent	strong
ny	new	new
påkostad	lavish	lavish
sammansatt	composite	cohesive
trivsam	pleasant	pleasant
feminine	feminine	feminine
helhetsbetonad	whole	complete
brutal	brutal	brutal
speciell	special	unusual
luftig	airy	airy

The experiments were conducted in successive order, and participants were assigned to different experimental settings as detailed in Figure 12. The settings were designed in such way that the following conditions were met:

1. Alternating realms: each part of the experiment took place in a different realm. If a participant started in the real realm, the second part would take place in the virtual realm, and vice versa.
2. Alternating rooms: the experiment took place in the two rooms. If a participant started in the corridor (either in VR or in reality), the second part would be conducted in the lecture hall (either in reality or in VR).
3. Perception of distances in each realm: this task was performed exclusively in the corridor by all participants. This means some assessed the distances in one of the two virtual corridors, and some in the real one. Participants only assessed the distance once.
4. Impact of level of fidelity: this task was performed by all participants twice, by the use of the SED questionnaire (used to describe the perceived environment, section 3.3.1). All participants filled in the SED questionnaire twice: once in the virtual scenario they were exposed to, and once in the real room they were exposed to. This means that all participants filled in an SED questionnaire for the corridor (whether in VR or in reality), and for the lecture hall (whether in reality or in VR).
5. Reaction to alarms: the bogus task on perception of an audio signal was completed by each participant exclusively in the first part of the experiment. This means that the alarm was placed in the first room they assessed, whether real or virtual, and whether it was the corridor or the lecture hall. This means that no participant was exposed to the alarm sound more than once.

3.3.2 Perception of distances

Perception of distances is an important object of study in VR. Many studies indicate that the perception of distances is different in VR than in reality (Feldstein et al., 2020; Maruhn et al., 2019; Masnadi et al., 2022; Rousset et al., 2018). A review concludes that there is a clear underestimation of distances in VR compared to the space modelled (Renner et al., 2013). Therefore, the objective of this study on Perception of distances was to improve the perception of distances in VR by producing two scenarios in VR (a control and a treatment scenario) and compare the distances assessed by participants in them to those assessed by participants in the real corridor.

The scenario consisted of a 3D model of the existing corridor, modelled as described on section 2.1 and using the lighting conditions selected by the lighting study described in section 2.2. The scenario was based on the architectural plans of the building, which was reproduced in a 3D model on a scale of 1:1. Without any modification, this scenario would therefore represent the usual way in which virtual versions of an existing building are made. The treatment scenario consisted of the same 3D model used in the control scenario, but a “modified projection” was applied. The purpose of the modified projection was to compensate for the underestimation of distances that is expected in VR according to the literature (Renner et al., 2013). In principle this was done by enlarging any geometry with increasing distance from the camera, creating the illusion of them being closer. A detailed explanation of the modified projection is presented in Appendix A. In the context of this project, the control scenario was therefore named “default projection”, as no changes were made to the usual way a 3D environment is projected into 2D displays.

To assess the right modification factor to be applied, the VR equipment was mounted in the real corridor, to match the standing location for the participants in both VR and reality. From that location, it was possible to wear the HMD and evaluate the aspect of the end of the corridor both in VR and in reality, by lifting the HMD up to see the real corridor, and pushing it down to see its VR version. The initial condition was the default projection in VR. Three of the researchers conducted this highly subjective, visual assessment of differences between VR and reality. A discrepancy was found in the alignment of the intersection lines between the floor and the walls. It was also apparent that the end of the corridor looked larger in reality than it did in the default projection in VR. Through a trial and error method, the modification factor chosen was 1.12, compared to 1 in the default projection. This modification factor made the VR version match closely what the researchers observed in reality: the intersection lines were aligned, and the end of the corridor seemed to be the same size.

The study on perception of distances was designed to be run in the corridor. Pictures of the experimental corridor both in VR and in reality are presented in Figure 8, Figure 9, and Figure 10.

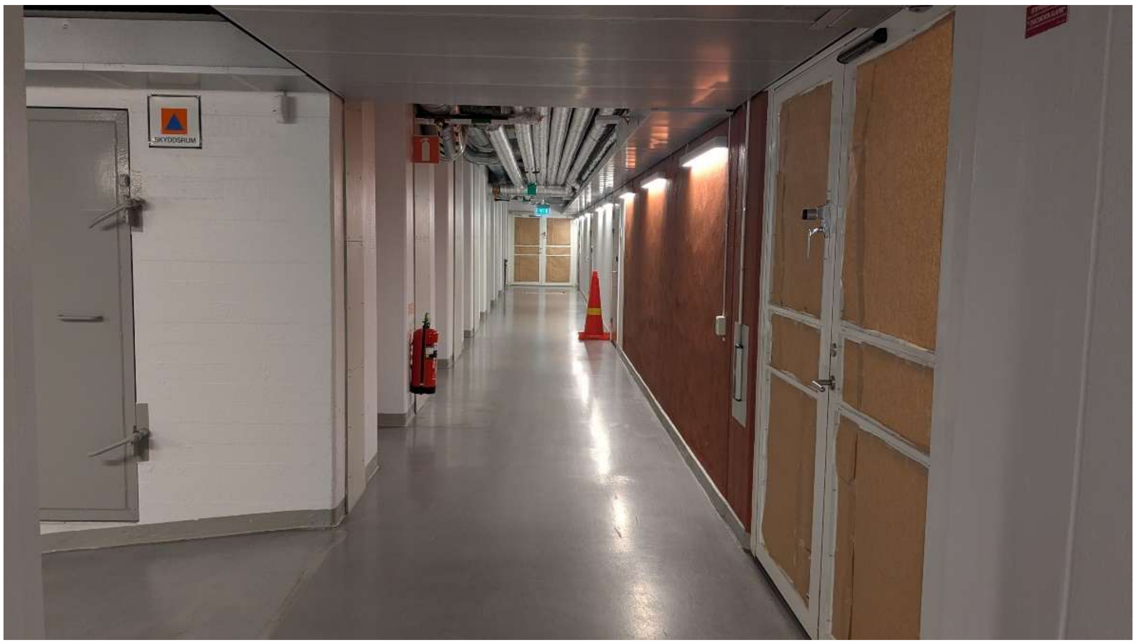

Figure 8 – View of the real corridor, from the point of view of the participant.

Figure 9 – View of the virtual corridor, from the point of view of the participant in the default projection scenario.

Figure 10 – View of the virtual corridor, from the standpoint of the participant in the modified projection scenario.

In this experiment, the participant was standing in the location shown in Figure 11, and was asked to assess the egocentric distance (the distance between themselves and a target object) to three different objects from their standing position: a fire extinguisher, a traffic cone, and the end of the corridor, which consisted mostly of a double-leaf door.

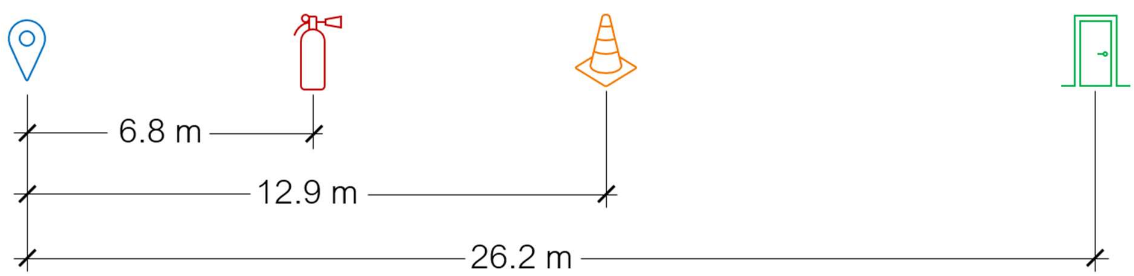

Figure 11 – Schematic representation of the location of the different target objects (fire extinguisher, traffic cone, and the end of the corridor) with respect to the standpoint of the participant in the corridor.

It is well-known that humans are not particularly good at assessing egocentric distances from a standing-only position (Andre & Rogers, 2006; Philbeck & Loomis, 1997). Research has shown that people are better at estimating distances by walking (Andre & Rogers, 2006; Maruhn et al., 2019; Schneider et al., 2018).

Nevertheless, the study on Perception of distances was meant to recreate an evacuation scenario. When building occupants understand the need to evacuate, they have to make decisions about the routes they will use. There are several factors affecting the route choice: familiarity with the route, social influence, walking distance, queueing, presence of smoke or any sort of blockages, etc. Distance is only one of those factors, but it can be difficult to extrapolate route choice in a VR experiment when it is known that distances are underestimated in a virtual environment. Therefore, studying how distances are assessed in VR is needed, so that additional factors can be explored in future experiments without the systematic underestimation expected in VR.

When a building occupant assesses said distance to the exit, they do not walk down to each available exit first and then choose the closest exit. Most likely, they take a look at the available routes, and when it comes to distance, a visual assessment of the egocentric distance is what they can do. Due to this reason, it was considered that the standing-only visual assessment of the distance was suitable for this study. Moreover, the error in the assessment of the distance on itself was deemed irrelevant to the project. What was relevant was the relative difference between the assessments made by participants in each VR scenario compared to the assessments made by participants in the real room. In other words, as long as participants were equally wrong in their assessment of distances in a VR scenario as in reality, it could be argued that scenario provided a reasonably good representation of distances in VR.

The assessment of distances was made by asking the participant to estimate the distance to three specific objects placed along the corridor, from their standing position: a fire extinguisher, a traffic cone, and the end of the corridor (which consisted mostly of a double leaf door with an emergency exit sign). The questions were presented in successive order, without the participants knowing ahead of time which objects they were asked to assess the distance to. The order in which the three questions were presented was randomized. The participant gave their answers using a numerical pad in a tablet in the real corridor, or using a similar numerical pad on a canvas in the virtual corridor. The numerical pad included all cyphers from 0 to 9, and it also included a decimal point, a delete button and an OK button. No instructions were given about levels of precision. The study on perception of distances was performed in the corridor, both in VR and in reality.

3.3.3 Reaction to alarms

The experiment on reaction to alarms was based on the lack of response to alarms observed in previous experiments (Arias, Nilsson, et al., 2020; Arias, Ronchi, et al., 2019). It was observed that a large proportion of participants in VR experiments would fully ignore the alarm as such, misidentify it, claim it was not in VR but in the real environment, even claim they did not hear it. These are anecdotes, as they emerged unexpectedly in experiments that were not meant to capture this behaviour.

Much thought was put into the experimental design, as a reaction can be difficult to define. For example, if someone hears the alarm, recognizes it as such, and proceeds to fully ignore it, is it a reaction? Moreover: how can it be measured, objectively?

The experiment was designed to be simple and was introduced once the participant was done with the SED questionnaire and the distance assessment. The participant was asked to do a bogus task, answering multiple choice questions about colours of objects they could see in the environment they were in (virtual or real, corridor or lecture hall). After 15 seconds of starting the task, an alarm bell went off. Hand-written notes were taken about their visible reaction. Then the experiment was interrupted to ask a set of follow-up questions, and the experiment ended.

The bogus task consisted of questions about the colours of objects they could see in the environment they were in. This bogus task was intended to keep them busy, so that the alarm would go off while they were in the middle of something, and an interruption in the action could be seen as a reaction to the alarm. The origin of the alarm sound was placed at ca. 150 degrees to the right from the forward direction they were looking at. That location was chosen so that it will require them to turn their heads more than 90 degrees to find it, if they were to search for it. In addition, they were wearing eye-trackers, so that it would be possible to assess whether they located the origin of the sound or not. The objects selected for the colour assessment were placed rather in front of the participant to prevent them to look around in search for the object they were asked the colour of. This was meant to reduce the chance of attributing the search for the object to a reaction to the alarm, since the head movement was also an indicator of them looking for the source of the alarm. Therefore, if the participant was mostly just looking ahead, instead of around for the bogus task, once the alarm went off it would be clear they were searching for it if they sharply turned their heads to the right.

The alarm was triggered by a script, starting the bell sound 15 seconds into the bogus task. Participants were asked about three questions at that time. A small Bluetooth speaker was used in the real corridor and the real lecture hall. The speaker was placed before the participants would arrive, and while it was relatively inconspicuous (a black box, ca. 9x7x3 cm^3), it was not hidden, fully visible from the position participants were standing in.

A 3D model of the speaker was included in the virtual scenarios in the same location, so that participants exposed to the same room would consistently have the sound coming from the same location. A decibel meter was used in reality to measure the volume of the alarm, but in VR it was based on the audio characteristics that could be manipulated in Unity. This is because it was not possible with the available equipment for this experiment to measure the sound each side of the headphones delivered to the participants' ears. Factors such as the shape of the ears, the distance between the headphones and the ears, the participants' hair covering their ears, and even the participant adjusting the headphones mid experiment, could not be controlled for.

The alarm was triggered in the first part of the experiment for each participant, independently of the realm or the scenario they were in (see Figure 12). The point was to have them react to the alarm only once, and to launch the alarm in all versions of both rooms. It was considered that launching the alarm twice would lead to learning behaviour. It was also considered that it would not make a difference whether the alarm was triggered in the first or second room the participant was in. The first one was selected due to convenience: it was easier to prepare the speaker ahead of time before the participant starts the experiment, as the real speaker has a feature that turns it off automatically if unused for a period predetermined by the manufacturer.

The data on the colour answers provided by the participants was not recorded as it was fully irrelevant to the objectives of this study. The reaction that could be observed by the researcher in place was recorded in hand-written notes. The notes were an answer to the question "Did they react?". The possible answers were "yes, immediately", "yes, later", or "not at all". After the reaction was assessed, the experiment was stopped, and the follow-up questions were asked:

a. "What was that sound?" – this question was meant for them to describe the sound, to assess if they identified it correctly, independent of the realm they were in.
b. "Where did it come from?" – this question intended to have them locate the direction of the sound in the 3D space, independent of the realm they were in.
c. "Was it in VR or in reality?" – this question was meant to make sure they correctly identified the sound as coming from the VR space, and it was not asked to participants who were exposed to the alarm in the real environment.
d. "Why didn't you look for its origin?" – this last question was asked only to those who did not react at all, based on the observations made when the alarm started.

Their answers were written down, and the experiment ended.

3.3.4 Experimental settings

As detailed in Figure 12, the experiments were conducted in two parts and participants could be assigned to start either in VR or in reality, and either in the corridor or the lecture hall. In the first part, participants were first asked to complete an SED questionnaire, in either realm or room they started in. The SED questionnaire was always answered first. Then, in the case of the corridor (either real or virtual), participants were asked to assess the distance to three different objects. Next, they were asked to perform a bogus assessment of colours of objects in the room (see Reaction to alarms) and the alarm was triggered. In the case of participants starting in the lecture hall, no assessment of distances was performed, but the SED assessment was performed, and the alarm was triggered.

In the second part of the experiment, participants were moved to the second room. The tasks they were asked to complete in the second part depended on those completed in the first part. If the participant started in the corridor, in the second part they did the SED assessment of the lecture hall, and no bogus task or alarm was included. If they started in the lecture hall, in the second part they did the SED assessment of the corridor, followed by the assessment of distances to the three objects in the corridor, and again no bogus task or alarm was included.

The crossing of participants between realms and rooms meant to avoid repetition in their assessment of the SED questionnaire or the distances to the three objects in VR and in reality, keeping the assessment performed of each aspect between subjects without needing to double the number of participants.

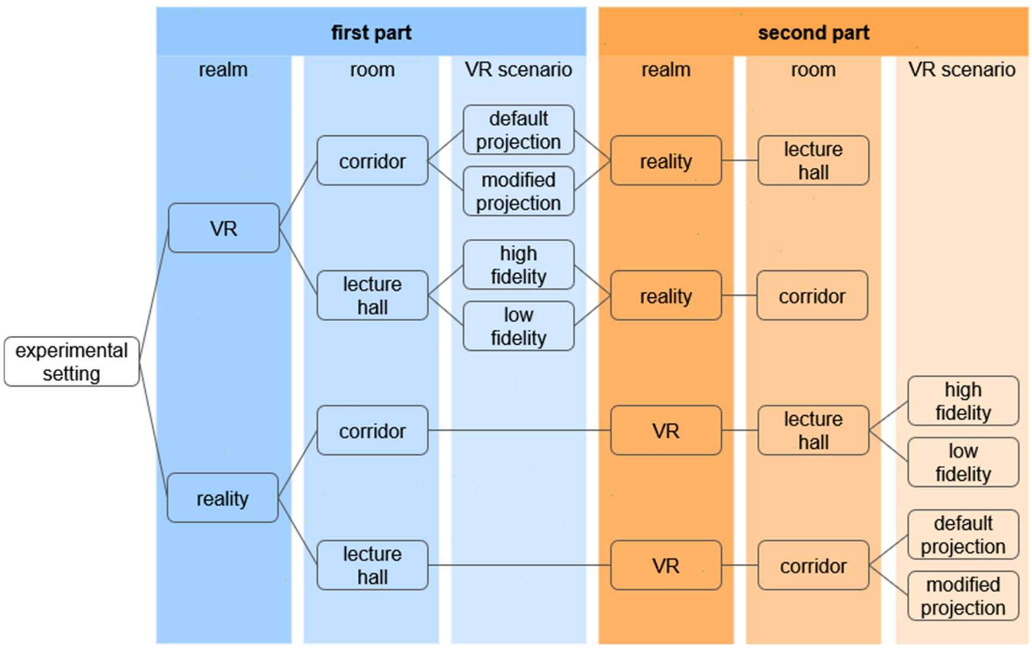

Figure 12 – Overview of the different experimental settings participants were exposed to. In every case the realm and the room were alternated between the first and the second part. This prevented testing within participants and at the same time, each participant produced two sets of data: one for VR and one for RE. There were two scenarios for each virtual room, but no scenarios for the real rooms.

3.4 Equipment

The equipment used is described in Table 5. The VR environments were created as described in section 2.1, and a script in Unity launched the different tasks for the participants. Their answers were recorded in a csv output file. A similar script was used to create an app to be launched in the tablet, for participants to provide their answers while doing the experiment in reality. Analogously, a csv output file was created with their answers.

The head-mounted display (HMD) and corresponding controllers used were HTC Vive Pro Eye (2448 x 2448 pixels per eye, 5K resolution, 120° field of view, 120 Hz refresh rate). The framerate was kept at 90 Hz or higher throughout the participants' experience. This piece of equipment includes eye-trackers made by Tobii (www.tobiipro.com), which is the same manufacturer of the eye-trackers used in the real environment: Tobii Pro Glasses 2 (*Tobii Pro Glasses 2 Wearable Eye Tracker - Discontinued*, n.d.). Tobii's products are not open source, which makes impossible to tell if the algorithms processing the data collected by the two sets of eye-trackers are identical, even if made by the same manufacturer. However, it was considered that the same brand name will likely handle the data in the same way, compared to the alternative of using different brands.

Table 5 – Equipment used for the different types of data collected in the experiment

	Equipment	
Data collected	VR	RE
SED evaluation	HMD, hand controllers, VR computer	Tablet
Assessed distances		
Eye-tracking data		Eye-trackers
Video recording		
Reaction to alarms	Hand-written notes	

3.5 Data collection

Different sets of data were collected from the participants. The data collected is detailed on Figure 13 The SED assessment was done twice by the participant: once in VR and once in reality, which also meant once in the corridor and once in the lecture hall. The distance assessment was performed in the corridor, either real or virtual. The reaction to the alarm was only collected in the first part (i.e., the first room the participant was placed in), to avoid the learning effect.

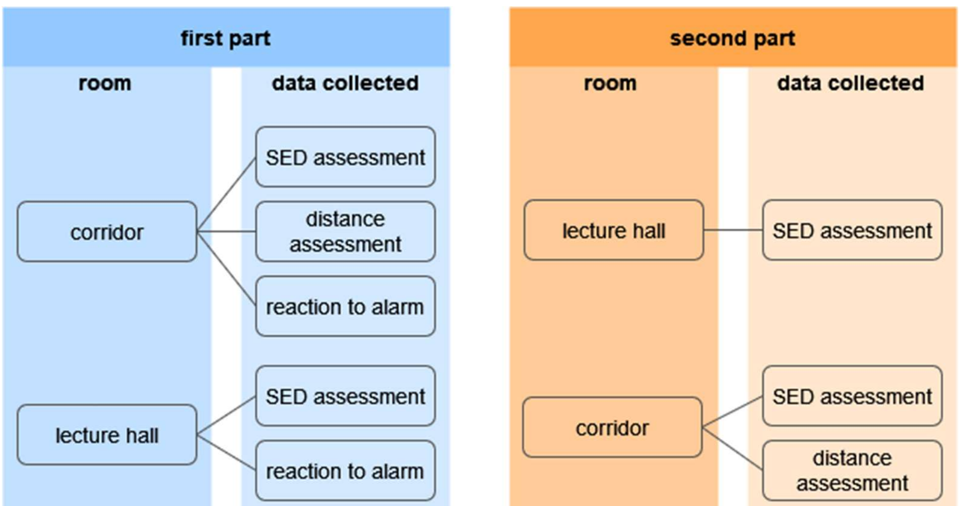

Figure 13 – Data collected in each part of the experiment, per participant, independent of the realm the participants assessed each room in.

3.6 Experimental procedure

Participants showed up at the pre-established meeting point at the V-building, one at a time. Once there, they were guided to the experimental room: either the real corridor, the real classroom, or the VR lab. In that room, they were asked to sign the informed consent form, and they were given time to read the participant information which included the consent form in case they did not read it ahead of time. They were specifically informed about the right to terminate the experiment at any time.

They were then told that the experiment is about perception of environments in VR and in reality, and that the experiment would take place in two types of settings: one real, and one virtual. They were given a brief explanation of the SED questionnaire, which included that they were going to be shown words, one by one, for them to assess the room they were looking at in a scale from “not at all” to “very”. They were told there is no right or wrong answer, and that it was expected from them to give an answer quickly, based on their gut feeling. They were then told that one or two more tasks will be presented to them (either in the tablet or in the HMD), “one about distances, and the other one about colours”, in reference to the bogus task. Once any questions were cleared, they were helped to fit the equipment, either the HMD or the eye-trackers. They were then guided through the calibration process for the eye-trackers, either in VR or in reality. Once the calibration was successful, the experiment was launched.

The order in which the data was collected was always the same, for all participants in all scenarios in both realms. Participants in reality followed the instructions given to them in the tablet. Participants in VR did the same with the instruction given to them on a canvas in the virtual environment. The first task was always the SED assessment of the room they were in. After they finished the SED assessment, the next task showed up automatically. That next task was the one on assessment of distances if the participant started in the corridor, or the bogus task (reaction to the alarm) if they started in the lecture hall, after which the first part ended. Participants starting in the corridor had the bogus task as a third and last task in the first part as the second one was about estimating distances.

Having completed the first part, the participant was then guided to the second experimental room: the VR lab if they started in the real corridor or the real lecture hall; or the real corridor or the real lecture hall if they started in the VR lab. Then they were given instructions to follow the instructions presented to them, which were to do the same SED questionnaire in the second room, and in addition the distance assessment if they were then in the corridor (whether virtual or real). With that, the second part ended. The reaction to alarm was not included in the second part as the person had already been exposed to this test in the first part.

Lastly, participants were asked to fill in a form with demographic information (age, gender), their own assessment of the realism of the rooms they were shown in VR, what their occupation is and whether they were familiar with the rooms they saw. This last part was meant to separate replies from those in the general public, who may not have ever been in the V-building, from the replies from students and staff who are very familiar with the lecture hall.

Once the demographic questionnaire was completed, participants were given an explanation about the tasks they performed and what was the point of collecting that data from them. Then, participants were given the opportunity to ask any further questions, and with those cleared, they were handed their preferred reward (two movie tickets or a supermarket voucher) and were guided out of the experimental room.

3.7 Data analysis

As stated before, the data was collected from different sources depending on whether the participant being in VR or in reality. After the data collection was finished, the csv files that were the output in either case were aggregated for the analysis. However, a couple of issues emerged: incomplete data sets and the presence of extreme values. Some csv files were corrupted (no data could be accessed in them), or were incomplete (e.g., in the assessment of distances, one of the three objects had no entry in the distance column, meaning no data was recorded there). The files with incomplete datasets were not included in the analysis.

When assessing the extreme values, Tukey's fences method (Tukey, 1977) for the detection of outliers was performed. The method identified values in the distance assessment that were either too high or too low. Upon close inspection, it became clear that those values were indeed too far out to be trusted. From the total sample of 465 assessments among all three corridors (the real one, the scenario with the default projection, and the scenario with the modified projection), 25 outliers were removed based on the results of the test, with 22 of them being assessments of distances in the real corridor. With the outliers removed, one more evaluation was performed: some of the assessments of the distance to the fire extinguisher or the traffic cone were between 0 and 2 m. Those were deemed a deeply flawed assessment of the egocentric distance. As indicated in Figure 11, the distance to the fire extinguisher was measured as 6.84 m, while the distance to the traffic cone was 12.89 m. Moreover, there was a double-leaf swing door on the right-hand wall that could serve as reference (i.e., even when its width was unknown, less than one meter is highly unlikely for a double-leaf door). Therefore, the researchers made an arbitrary decision that anything below 2 m could not be a reasonable assessment of the distance between the participant and the extinguisher, and by extension to the traffic cone. This meant that four additional datapoints were removed for being shorter than 2 m.

4 Results of the Experimental studies

4.1 Impact of the level of fidelity

The mean scores of the eight SED factors for the lecture hall are presented in Table 6 and Figure 14.

Table 6 – Mean scores of SED factors for lecture hall

	M (SD)							
	pleasant-ness	*complexity*	*unity*	*enclosed-ness*	*potency*	*social status*	*affection*	*originality*
Reality (n = 99)	4.32 (0.80)	3.51 (0.80)	4.91 (0.97)	3.85 (1.17)	4.73 (0.69)	3.76 (0.91)	4.30 (1.17)	2.64 (1.22)
Hi-fi (n = 35)	4.11 (0.88)	3.43 (0.68)	5.01 (1.18)	3.71 (0.99)	4.86 (0.75)	3.66 (0.91)	4.40 (0.94)	2.49 (1.07)
Lo-fi (n = 29)	3.98 (0.75)	3.53 (0.78)	4.89 (0.67)	3.94 (1.03)	4.67 (0.65)	3.72 (0.93)	4.32 (1.38)	2.56 (0.85)

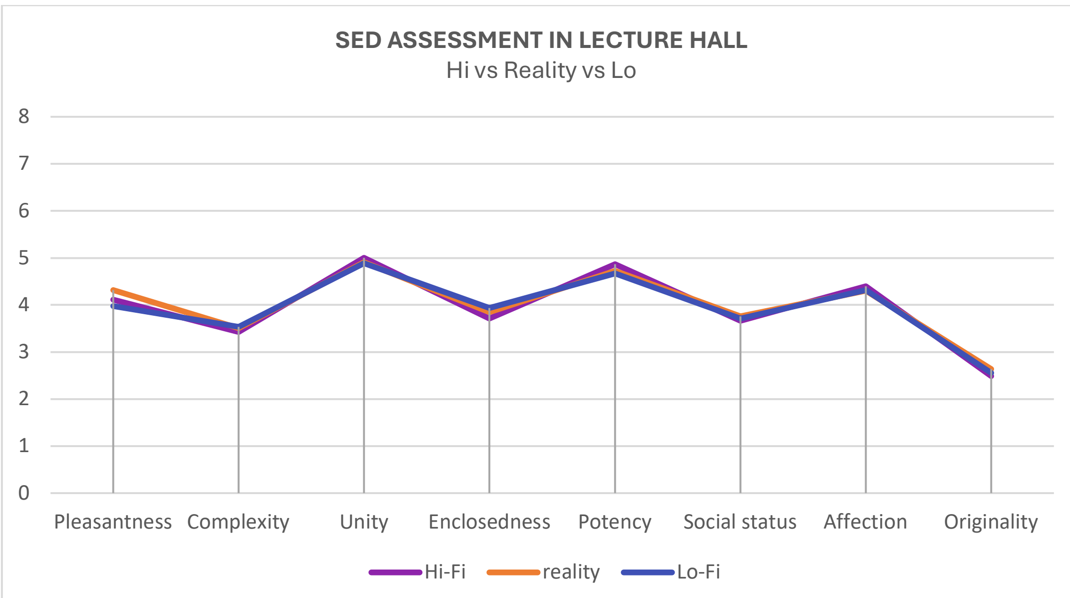

Figure 14 – Results of the SED assessment made by the participants in the three versions of the lecture hall

In general, all three lecture hall scenarios were perceived as rather neutral with regard to complexity, enclosedness, social status, and the scores of perceived pleasantness were slightly higher than neutral. The scores for perceived originality were low whereas the scores for perceived unity, potency, and affection were relatively high. It is noted that the real lecture hall was rated as slightly higher than the virtual scenarios for perceived pleasantness, social status and originality, and the virtual scenario with high levels of details was rated as higher than the other two scenarios for perceived unity, potency and affection. Surprisingly, the Lo-Fi scenario was rated slightly higher than the other two scenarios for perceived complexity. However, a Kruskal-Wallis test resulted in no significant differences across the three scenarios of the lecture hall for SED factors.

The mean scores of the SED factors for the corridor are presented in Table 7 and Figure 15.

Table 7 – Mean scores of SED factors for corridor

	M (SD)							
	pleasant-ness	*complexity*	*unity*	*enclosed-ness*	*potency*	*social status*	*affection*	*originality*
RE (n = 67)	3.28 (0.86)	3.14 (0.79)	4.37 (1.14)	4.68 (1.02)	4.90 (0.91)	3.35 (0.93)	4.40 (0.97)	2.69 (1.15)

VR natural (n = 44)	3.37 (0.83)	3.47 (0.84)	4.54 (0.88)	5.22 (0.95)	5.01 (0.72)	3.39 (0.90)	4.42 (1.11)	2.56 (0.99)
VR scaled (n = 44)	3.42 (0.95)	3.35 (0.81)	4.45 (0.80)	5.35 (1.10)	4.98 (0.83)	3.30 (0.89)	4.47 (1.18)	2.52 (1.09)

The same data analysis was performed for the corridor scenarios. Since there was no difference in fidelity between the default projection and the modified projection, the SED questionnaire should show no difference between the two VR scenarios, which can be observed on Figure 15.

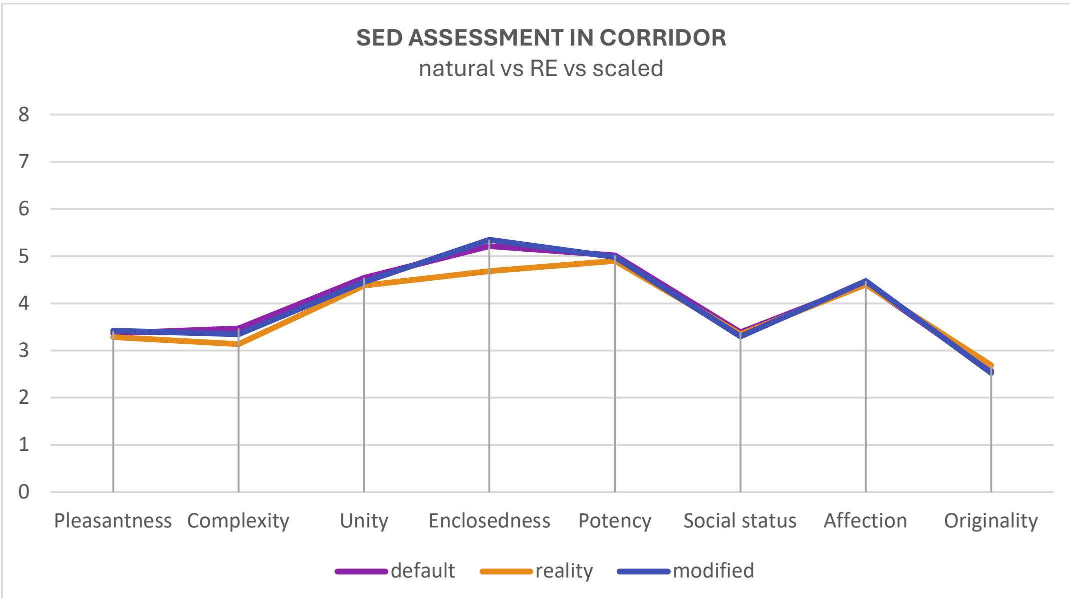

Figure 15 – Results of the SED assessment made by the participants in the three versions of the corridor. There is a tight overlap between the two VR version, with a clear difference between them and the real corridor in "enclosedness".

The three versions of the corridor were generally perceived as rather neutral with regard to pleasantness, complexity, and social status, whereas the scores for perceived originality were relatively low. On the other hand, the scores for perceived affection, unity, enclosedness and potency were higher than those of other factors. The highest score corresponded to perceived enclosedness of the VR modified projection scenario followed by that of the VR default projection scenario.

A Kruskal-Wallis test resulted in no significant differences across the three scenarios of the corridor for SED factors except 'enclosedness' ($H(2) = 15.99$, $p < 0.001$, $N = 155$) which refers to '*a sense of spatial enclosure and demarcation of the environment*'. Further, Mann-Whitney U tests resulted in differences in perceived enclosedness between the three versions of the corridor as:

- There was a significant difference in perceived enclosedness between the VR default projection corridor scenario ($M = 5.22$, $SD = 0.95$, $n = 44$) and the real corridor ($M = 4.68$, $SD = 1.02$, $n = 67$): ($U = 974.500$, $z = - 3.021$, $p < 0.005$, $N = 111$)
- There was a significant difference in perceived enclosedness between the VR modified corridor ($M = 5.35$, $SD = 1.10$, $n = 44$) and the real corridor ($M = 4.68$, $SD = 1.02$, $n = 67$): ($U = 887.500$, $z = -3.547$, $p < 0.001$, $N = 111$)
- There was no significant difference in perceived enclosedness between the VR default corridor ($M = 5.22$, $SD = 0.95$, $n = 44$) and the VR modified corridor ($M = 5.35$, $SD = 1.10$, $n = 44$): ($U = 862.500$, $z = -0.885$, $p = 0.376$, $N = 88$).

In conclusion, there were no differences in the environmental perceptions between the two VR corridors for all the eight factors whereas the differences found between the two VR corridors and the real corridor for enclosedness.

4.2 Perception of distances

Table 8 presents the descriptive statistics of the data. The unequal number of assessments per sample is due to the removal of extreme values and the incomplete datasets as discussed in section 3.7. Figure 16Figure 16 presents the boxplots of the assessments performed by the participants by object and scenario.

Table 8 – Descriptive statistics of the assessment of distances performed by the participants.

	fire extinguisher			traffic cone			end of the corridor		
	default	reality	modified	default	reality	modified	default	reality	modified
Valid	42	58	42	43	61	44	42	60	44
Mean	4.917	5.340	5.298	8.814	10.259	9.227	18.119	20.700	16.682
Std. Deviation	1.379	1.030	2.178	3.170	2.584	4.040	7.219	5.817	7.609
Minimum	2.000	3.000	2.000	2.500	5.000	4.000	4.000	9.000	5.000
Maximum	9.000	7.500	10.000	15.000	16.000	20.000	35.000	32.000	35.000

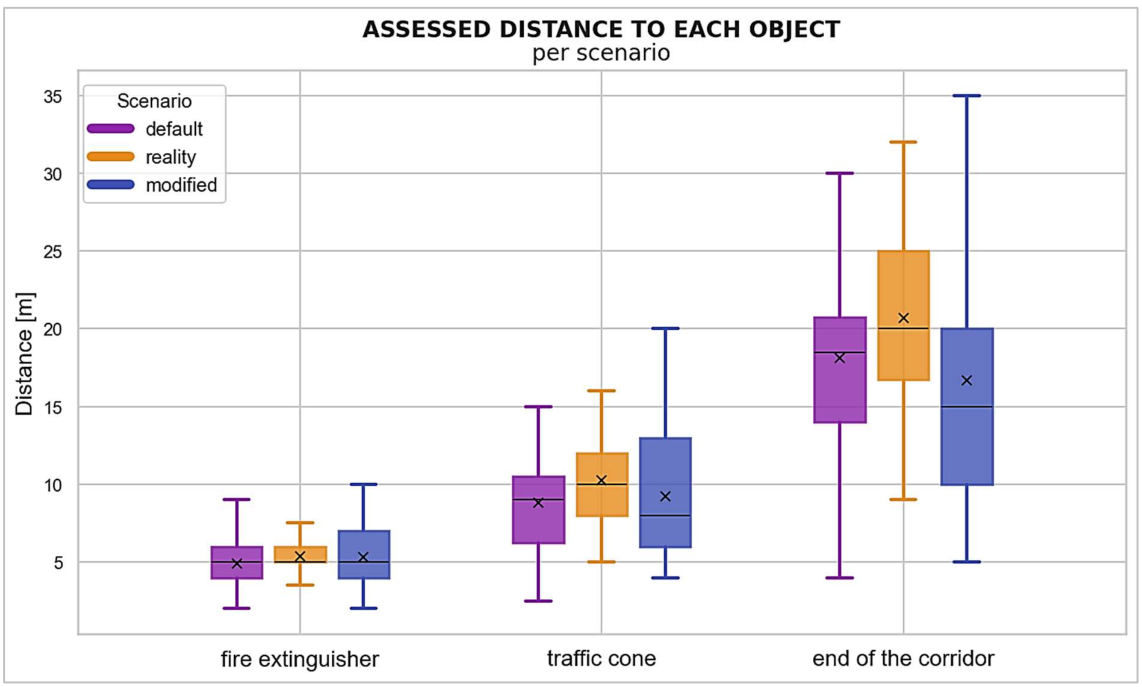

Figure 16 – Boxplots of the egocentric distance assessment to each of the three objects

A one-way ANOVA test was conducted for each of the three objects, to identify differences between the means of the samples per scenario. The results of the three ANOVA performed are shown on Table 9, Table 10, and Table 11. For the fire extinguisher, a homogeneity correction was needed due to inequal variances. Table 12 and Table 13 present a post-hoc test for the assessment of the distances to the end of the corridor.

Table 9 – One-way ANOVA test results for the fire extinguisher in each of the three scenarios

Homogeneity correction	**Cases**	**Sum of Squares**	**df**	**Mean Square**	**F**	**p**
Brown-Forsythe	Scenario	4.902	2.000	2.451	0.924	0.401
	Residuals	332.947	87.238	3817		

Note: Type III Sum of Squares

Table 10 – One-way ANOVA test results for the traffic cone in each of the three scenarios

Homogeneity correction	**Cases**	**Sum of Squares**	**df**	**Mean Square**	**F**	**p**
Brown-Forsythe	Scenario	58.498	2.000	29.249	2.597	0.079
	Residuals	1524.486	112.099	13.600		

Note: Type III Sum of Squares

Table 11 – One-way ANOVA test results for the end of the corridor in each of the three scenarios

Cases	**Sum of Squares**	**df**	**Mean Square**	**F**	**p**
Scenario	433.073	2	216.537	4.676	0.011
Residuals	6622.550	143	46.312		

Note: Type III Sum of Squares

Table 12 – Tukey's post-hoc test on the assessment of distances for the end of the corridor

			95% CI for Mean Difference				
		Mean Difference	Lower	Upper	SE	t	p_{tukey}
default	reality	-2.581	-5.824	0.662	1.369	-1.885	0.147
	modified	1.437	-2.040	4.914	1.468	0.979	0.591
reality	modified	4.018	0.819	7.217	1.351	2.975	0.010**

** p < .01

Note: P-value and confidence intervals adjusted for comparing a family of 3 estimates (confidence intervals corrected using the Tukey method).

Table 13 presents the letter grouping performed for the assessment of distances to the end of the corridor. It shows different symbols for reality (a) and the modified projection (b), while the default projection had both (ab). This means that the default projection could not be shown to be either different or the same to the other two, while reality and the modified projection were clearly different.

Table 13 – Letter grouping for the assessment of distances to the end of the corridor

Scenario	**Letter**
default	ab
reality	a
modified	b

Note: If two or more means share the same grouping symbol, then we cannot show them to be different but we also did not show them to be the same

A statistically significant difference was found in the distance assessment for the end of the corridor (p=0.011). Tukey's post-hoc test showed that the difference was between the real corridor and the modified projection. Therefore, the distances assessed in the "corrected" corridor were different than those assessed in the real corridor.

Figure 17Figure 17 presents the average distance assessment made by the participants in each scenario, as a fraction of the measured distance in the corridor. As the figure indicates, participants consistently underestimated distances in every scenario. The estimated distances ranged between 64% and 80% of the measured distances. The underestimation in the real corridor was about 80% of the measured distance; in the default projection it was between 68% and 72%, and in the modified projection it was between 64% and 78%. It should be noted that participants assessing the modified projection were better at assessing the distances to the two nearest objects (fire extinguisher and traffic cone), but the performance dropped substantially in the farthest object (end of the corridor).

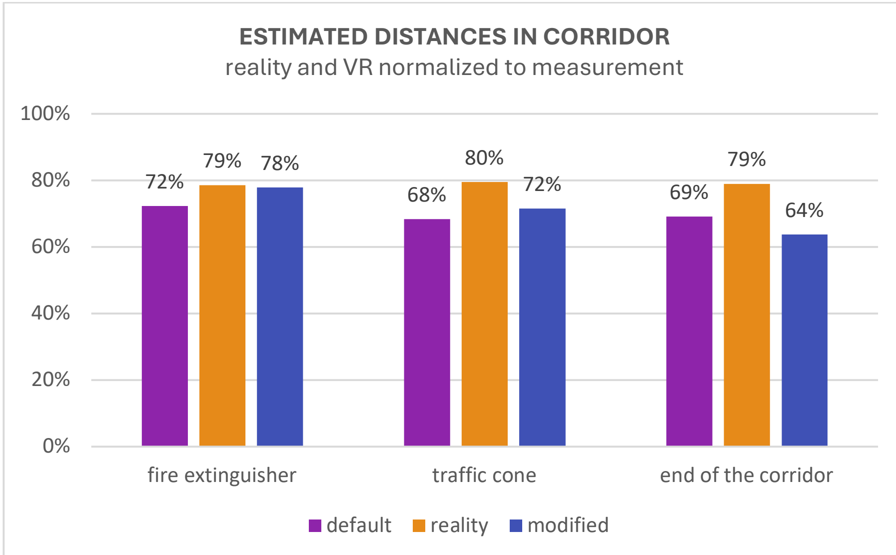

Figure 17 – Distances assessed compared to the measured distance to the target object, by scenario

As stated before, the point of this experiment was to compare assessments in VR to those made in reality, as it is known that people are bad at assessing distances visually. Therefore, a virtual scenario would perform best the closest the assessment of distances in it is to the assessment of distances in the real corridor. Figure 18Figure 18 presents the distances assessed in VR, normalized to the assessment made in reality. As the figure shows, the modified projection performed slightly better for the two closest objects (fire extinguisher and traffic cone), but it performed worse than the default projection for the farthest object (end of the corridor).

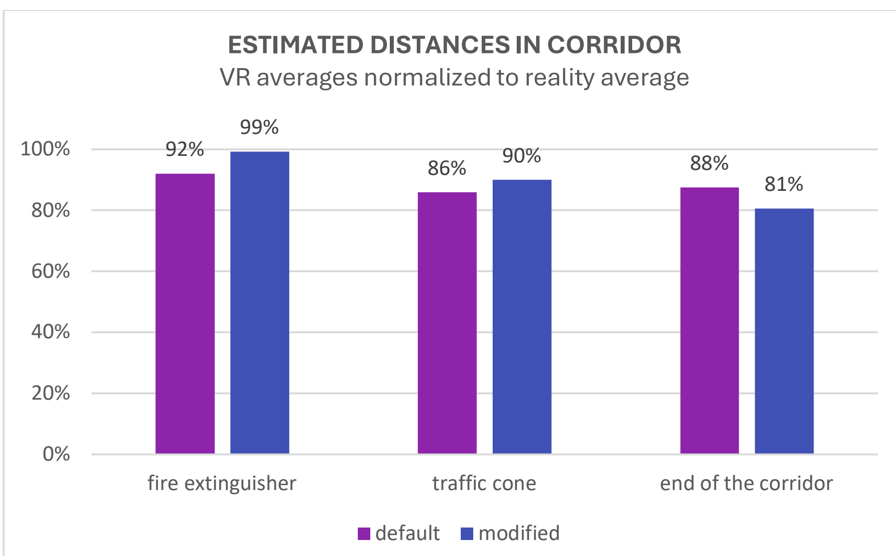

Figure 18 – Distances assessed in the virtual scenarios, normalized to the distance assessed in the real corridor

4.3 Reaction to alarms

The reaction to the alarms was recorded as hand-written notes made by the researchers while observing the participant, and are therefore subjective assessments. The reaction is based on noticeable actions (looking around the room and/or asking what that sound is), with a classification on how fast the reaction was noticeable ("yes, immediately", "later" or "not at all"). The results are presented in Figure 19.

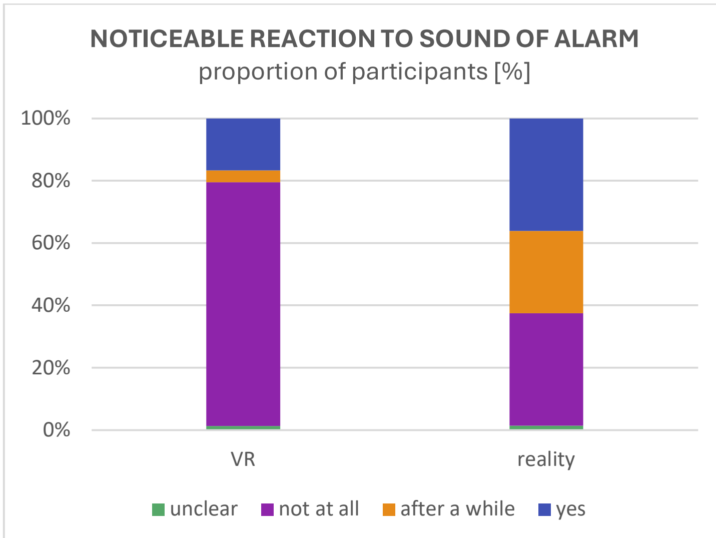

Figure 19 – Reaction to the sound of the alarm noticeable in participants in each realm. These results are based on subjective observations made by the researcher in the room.

In total, 74 participants were exposed to the sound while being in a virtual room (any of the two virtual corridors, or any of the two virtual lecture halls). From those, 92% correctly identified the sound as coming from the VR scenario they were in, and the rest estimated that the sound came from their real surroundings, and not from VR. When asked where the sound came from, independently of whether they looked for the origin or not, the answers were mostly that it came from somewhere in the back, to the right, which was the overall correct location. Participants gave their answer about the location in their own words, which were then grouped together for clarity. Figure 20Figure 20 presents the proportion of participants giving each of the answers. The correct answer was "back right". However, many participants answered "behind" or "right". Therefore, it was considered that it was not possible to determine the level of precision they put in their answer. To address this uncertainty, all three answers (i.e., "back right", "behind" and "right") were classified as "correct", while "front", "left", "above", "everywhere" and "outside the room" were considered "incorrect". Figure 21Figure 21 presents this lumping of the answers.

It is clear that participants were much more accurate when pinpointing the origin of the sound in reality than in VR. This is evident by the overwhelming majority of them answering "back right" as shown in Figure 20Figure 20, with only few of them saying "behind" or "right". In VR, larger proportions gave those answers. When lumping all "correct" answers together, participants in VR still lagged behind those in reality. Moreover, many more participants in VR gave "incorrect" answers compared to participants in reality. A Fisher's exact test showed a significant difference between VR and reality comparing "correct" and "incorrect" responses, with p=0.0006 for the corridor and p=0.0177 for the lecture hall (significance level of 0.05).

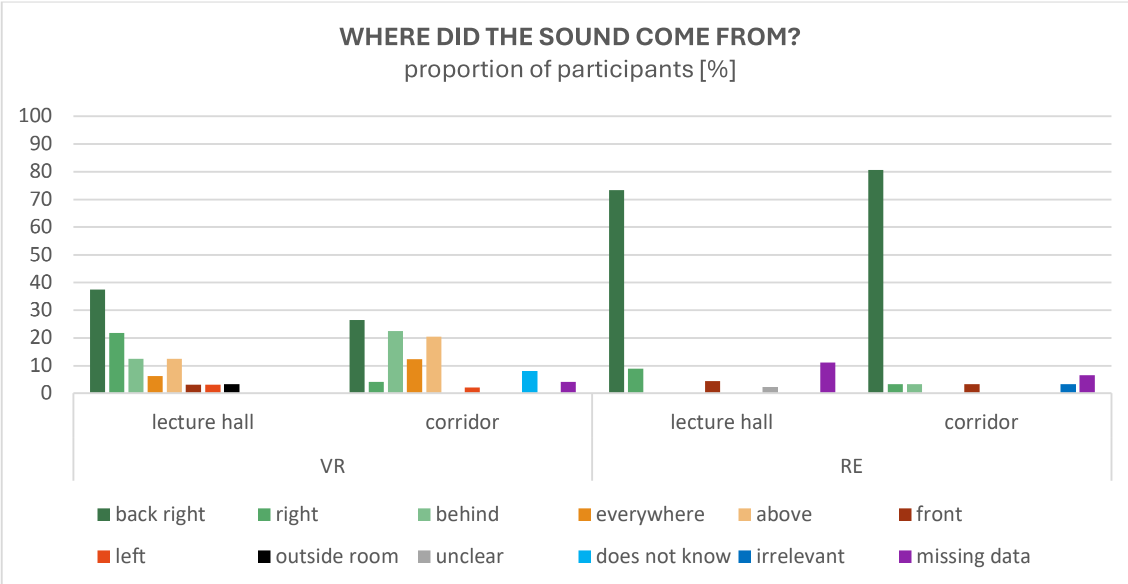

Figure 20 – Location participants indicated for the origin of the sound when answering the question "Where did the sound come from?".

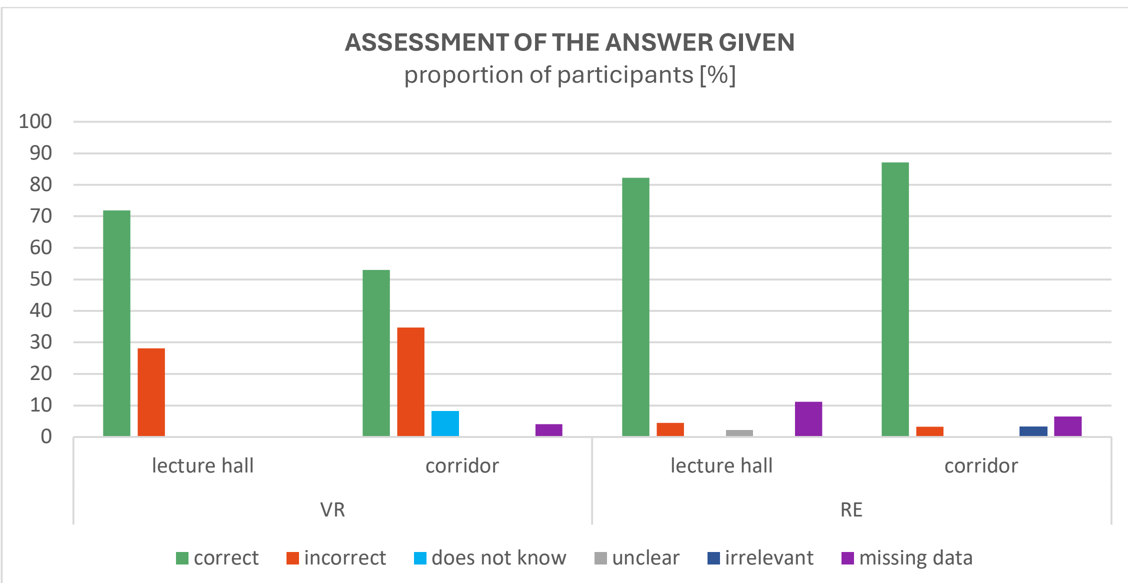

Figure 21 – Lumped answers that could be considered "correct" or "incorrect", based on the data presented on Figure 20Figure 20

Participants who did not respond to the sound at all were asked why. Their answers were that either they already knew it was a fire alarm, or they thought it was part of the experiment (e.g., to add stress to the task they had at the time), or they were just busy with the task at hand.

5 Discussion

5.1 Impact of level of fidelity

Overall, there were no significant differences between the SED evaluations of real-world and virtual scenarios for both corridor and classroom environments, thereby suggesting that the virtual environments could be perceived as similar to the real-world environments. This finding highlights the potential of VR methods to represent real-world conditions in the assessment and evaluation of educational environments and therefore, training in fire safety and emergency response.

The differences between the Hi-Fi scenario and the Lo-Fi scenario may not have been particularly noticeable to the participant because of the experimental design. Participants were standing in a reasonably unremarkable lecture room, in which they did not need to do much more than look around. The lack of textures in the Lo-Fi scenario would have been more noticeable if they had the need to do a close inspection of a particular object. As an example, the lack of texture on the walls may only become clear at shorter distances between the observer and the walls. Therefore, the results may not capture the effect of lack of textures. Nevertheless, the experimental design was based on the application of the results for fire evacuation scenarios, in which detailed inspection of objects is rather irrelevant. If needed, a high level of detail could be applied only to those objects that may require it, like the instructions on a fire extinguisher or the evacuation plan.

For the lecture hall, there were no significant differences in the SED evaluations across the three versions of the room. For the corridor, however, the significant differences were found for perceived enclosedness between the two virtual versions and the real room. This is in line with previous research on VR which suggested that virtual environments of small and/or narrow spaces are often perceived as smaller or narrower compared to the real-world ones (Rousset et al., 2018). For the training, however, this might be considered as an advantage (i.e. training to escape from the smaller or narrower environments than expected).

Further, the SED evaluations showed that the characteristics of these two types of environments were different to some extent. Besides the perception of being enclosed, the corridor was generally described as unpleasant, constant, quite forceful and unusual environment. The corridor was also perceived as quite familiar but rather not well-kept. For the lecture hall, the perceptions were rather neutral considering how pleasant, enclosed, status and familiarity of the environment is. It was also perceived as constant, forceful and unusual as described for the corridor environment. The similarities found in the SED evaluations may be because these two types of environments located in the same building (i.e., sharing an architectural style in general). Moreover, different features of each tested scenario were generally perceived as functioning together.

5.1.1 Differences between the curves

The ANOVA showed no statistically significant differences between the factors conforming the curves for the three versions of the lecture hall. A difference was observed in the case of the corridor, in which the real corridor was perceived as less enclosed than the two virtual versions of it, which shared the same level of enclosedness.

5.1.2 "Enclosedness" in VR

As stated above, participants in previous experiments have expressed before that the virtual version of a real building they were familiar with felt narrower (Rousset et al., 2018). Therefore, the higher rating on "enclosedness" in both virtual corridors compared to the real one is not surprising. The results obtained from the SED questionnaire and the subsequent statistical analysis support these claims. However, the same cannot be said in the case of the lecture hall. There was no statistically significant difference between the three versions of the lecture hall. Therefore, it is possible that the perception of narrowness is emphasized due to the geometric configuration of a corridor, which is much longer than it is wide or tall. In the lecture hall, the difference between length and width was smaller.

The virtual corridor felt significantly narrower than the real one. It is possible that the perception of narrowness is less in environments that are less one-dimensional than a corridor.

5.1.3 Differences between the two virtual lecture halls

No significant differences were observed between the SED output curves for the three lecture halls. This means that the Lo-Fi scenario gave a similar impression to the participants rating it to that given by the Hi-Fi scenario and the real corridor to the participants assessing them. It can then be concluded that time, effort and computational resources saving measures may not have a large impact on the perception participants have of a virtual environment. Using a low-fidelity virtual environment may mean a more efficient use of resources, and more effort could be put in other aspects as, for example, interactions or animations if needed.

5.1.4 Low-fidelity is not poor

The Lo-Fi scenario got very similar results from the SED method to those of the Hi-Fi scenario and even the real room. The Lo-Fi scenario was quicker to make, but it is in no way a subpar virtual representation of the real room. A trained eye can tell the simplified scenario was “flat”. To non-experts, the differences between the two scenarios may not be very noticeable. It is therefore important to highlight here that the Lo-Fi scenario not only was based on the Hi-Fi one, but it was still made by an expert, who made choices that favoured saving time and effort at the expense of photorealism. This means that there were many similarities such as light level, colours on objects and some other visual effects in order to look like the real room but with some aspects and components being simplified. The choices made were not uneducated or representative of bad practices, but a conscious compromise made by an expert. The results only show that cutting those corners did not come with a cost on the perception of the room, not that any beginner-level VR designer can do the same thing. This is to say: the simplifications do not seem to take a toll on the overall perception of the room, but they are only advisable in the case of expert VR designers who can make the simplifications wisely.

The experimental design had implicitly the ulterior motive to apply the results in future fire evacuation scenarios to be used for research purposes. It was expected a difference will be seen between the two virtual lecture halls, and between them and the real one. The scenario coming closer to the real lecture hall would be then adopted as the best representation of the real room. However, the results show a tight overlap between the three curves. This leads to the conclusion that either VR scenario could be used to represent the real lecture hall without large differences in the participants’ perception.

It is not possible to say if this outcome means that photorealism is unnecessary in any virtual environment representing a real one. It is also not possible to say that once the results are applied to a fire evacuation scenario, participants will not be able to tell any difference in realism either. However, the experimental conditions in the present study and future evacuation scenarios are different. In the present study, participants were unambiguously asked to stand still in a given spot and actively assess the room they were seeing based on a specific set of words. In a fire evacuation experiment, participants will be given a task (usually a bogus task), and at some point the emergency will start. It is therefore expected that participants in said fire evacuation scenario will pay less attention to the realism of the environment during the emergency, as their objective will then be switched to some sort of action. It is then unlikely that a simplified scenario will make them choose a different set of actions because of the lack of photorealism of some objects or the somewhat unrealistic shadows.

The decisions applied to the Lo-Fi scenario in order to reduce time and effort needed to generate did not produce a significantly different perception of it to the participants. They were not noticeable by the participants, based on the SED assessment they made of the rooms. It is not expected that in a future fire evacuation study these differences will affect their response to an emergency.

5.1.5 Reliability of the SED assessment

The SED questionnaire designed by Küller (1972) has not been extensively used. A single paper was found that used the method to assess perceived differences in the interior design of cars (Karlsson et al., 2003). No other applications of the method were found, but no alternative method that could suit the needs of the experiment could be found either.

Even if the reliability of the method is challenged, the comparison between the three versions of the rooms can still be useful, as it comprises relative differences. Anything that the SED method may over or underestimate is also over or underestimated in each assessment, and the relative differences would account for that. Whether the SED method is good at assessing enclosedness or not, the VR versions of the corridor were different than the real corridor, and that difference was statistically significant and is in line with the results from previous experiments about the difference in perceived narrowness between virtual and physical reality of building spaces (Rousset et al., 2018).

The SED questionnaire was developed to assess any environment, which is a reasonable approach. However, the nature of the rooms used in the experimental studies may render the words the method relies on questionable. For example, "idyllic" is hardly applicable to a corridor, and "toned-down" may need an object of reference (toned-down compared to a given benchmark).

Moreover, the implications of certain words may have changed since 1972, when the SED questionnaire was published. What exactly "feminine" and "masculine" implied in the design of a room back then may not be applicable in modern times. Yet, even with the changed perceptions, it is hard to tell how feminine or masculine a corridor in a maintenance basement can be. The same applies to the lecture hall, which is largely unremarkable by design.

Additionally, based on observations during the experiment, participants did not always seem to know what the words meant. There was a dictionary to provide definitions, and participants were made aware they could ask for help, but not all participants did. Some of them could claim "I don't know what that means", right at the moment of giving a rating, and the program did not allow for corrections. Also, some participants gave high ratings to some words that hardly apply to said corridor, such as "idyllic" or "lavish", making their understanding of the word dubious.

5.2 Perception of distances

No statistically significant differences were found in the distance assessment to the fire extinguisher or the traffic cone among the three scenarios. For both objects, the assessment of distance was slightly better in the modified scenario, but not significantly better. A significant difference was found in the assessment of distances to the end of the corridor, in which the modified scenario underperformed, compared to the default scenario.

Based on the statistical analysis, the modified projection performed significantly worse than the default projection only in the case of the end of the corridor. This may imply that the shader applied in the modified projection improved the perception of distances at closer range from the observer. The distance to the end of the corridor was 26.2 m, while the traffic cone was at 12.9 m and the fire extinguisher was at 6.8 m.

5.2.1 Reality vs the default projection

5.2.1.1 Assessments in VR were not as bad as expected

No statistically significant difference was found between the default projection and the real corridor. This result differs from the literature consulted. The available literature claims that participants tend to underestimate distances in VR compared to reality (Maruhn et al., 2019; Renner et al., 2013; Rousset et al., 2018), with the underestimation being the assessments in VR around 74% of the assessment made in reality. While an underestimation was observed in each case, the assessments done in the default projection were 85% of the distance assessed in reality, as shown in Figure 18Figure 18. Therefore, the present study did not replicate the expected underestimation in VR.

5.2.1.2 The underestimation was not significantly worse in VR

The differences between reality and the default projection were not shown to be statistically significant. Naturally, absence of evidence is not evidence of absence. One typical explanation for the lack of a significant difference is the sample size. Although not too small, the sample size of 44 participants is not particularly large. Therefore, it is possible that the effect size was too small, and no differences could be observed. However, in the consulted literature, the samples were smaller: 26 to 30 participants for Mahrun (2019), 14 participants for Rousset (2018), and while Renner (2013) does not refer to the sample sizes in the studies they reviewed, they mention the study by Ziemer (2009), which recommends "larger samples" than what they had (52 participants subdivided in 4 scenarios with 13±1 participants per scenario). Therefore, the sample size in the present experiment may not have been an issue, and the expected underestimation of 74% should have been observed in this experiment.

5.2.1.3 Disparities between observations on site

The lack of a statistically significant difference between the default projection and the real corridor is remarkable, as the visual inspection performed before and after the conduction of the experiment shows a clear elongation of the corridor in the default projection compared to the real one. Therefore, it was expected that the distances in the default corridor would be assessed as longer than in the real corridor. This expectation was not supported by the results.

5.2.2 Reality vs the modified projection

The results varied when comparing reality to the modified projection. The assessment of the distances to the extinguisher was almost identical. Participants underestimated distances in the modified projection when compared to participants in the real corridor, but this underestimation was not statistically significant in the cases of the fire extinguisher and the traffic cone. In the case of the end of the corridor the assessments in the modified projection were significantly worse.

5.2.2.1 The default projection worked better a shorter distance

As shown on Figure 18Figure 18, the average assessment made in the modified projection were 99%, 90%, and 81% of the average assessment made in the real corridor to the fire extinguisher (6.8 m away), the traffic cone (12.9 m away) and the end of the corridor (26.2 m away) respectively. The shader used the distance between the user and the object as variable, so it is not surprising that the effect was affected by the distance.

5.2.2.2 The modification factor in the shader

The modification factor applied in the design of the modified projection scenario was subjective. As explained on section 3.3.2, the factor was selected using a trial-and-error approach. Three of the researchers involved were standing in the corridor and looking at the end of it in VR and in reality, by moving the mask of the HMD up and down. The objective was to make sure that the architectural lines (floor line, ceiling line, wall line) aligned in both realms. The factor selected, according to them, made those lines in the modified projection match their reality counterparts best. That also means that the enlargement of the door at the end of the corridor in VR was, according to them, aligned with what they could see in the real corridor. Independently on what the literature read may say about under or over estimation of dimensions in VR, the factor was selected based on this visual inspection. Again, this visual inspection is subjective, but no alternative, more objective method could be identified.

After the analysis of the data, the result being the significant difference between the modified projection scenario and the real one, a doubt emerged whether the chosen factor was correct. The VR equipment was installed again in the real corridor, and a new visual inspection was performed. According to this post-hoc visual inspection, the modified projection was still considered the most accurate replication of the architectural lines used before. In comparison, in the default projection, the end of the corridor looked farther ahead, which could be appreciated in the mismatch of the architectural lines and the door at the end of the corridor looking smaller.

5.2.3 The modification factor

The puzzling problem is that the modified projection visually resembles the real corridor better than the default projection, and yet the distances assessed by the participants in the modified projection were significantly different than those assessed by the participants in reality. That is: the authors could not pinpoint a difference between the modified projection and the real corridor in terms of dimensions, while according to the authors, the default projection seemed clearly farther. No hypothesis could be found to explain this contradiction. It is clear now that the matching of architectural lines was not the right approach to select the modification factor, but why that was not enough is unknown.

5.2.4 The contradictions

It is hard to find an explanation to how come upon visual inspection the modified projection aligns better with the real corridor and yet participants consistently underestimated the distances in it compared to in the real corridor. Moreover, no statistically significant difference was observed between the real corridor and the default projection. Lastly, both were perceived as more enclosed than the real corridor, which means that there is a different perception of space, an apparent reduction of it.

5.3 Reaction to alarms

The assessment made on whether participants reacted or not still needed a subjective interpretation to be classified. The eye-trackers were largely unnecessary in the real rooms, as most participants did turn their heads around enough to see the speaker. None mentioned the speaker in their responses, they just pointed in the general direction of it.

The data collected shows that participants in VR mostly do not search for the origin of the alarm, while participants in reality sometimes search for it. This means that “ignoring” the alarm is more likely in VR but not unlikely in reality. So, participants in VR may disregard the alarm more often than participants in reality, but participants in reality also disregard it. Therefore, there is a discrepancy between the behaviours observed in VR and in reality, but it is smaller than the initial expectation that the vast majority of people in reality would react to the alarm. While the discrepancy is there, its impact in the validity of the VR data is unknown.

The effect of the researcher standing in the room cannot be disregarded. Many participants said that they ignored the alarm because the researcher did so too, as they were not given instructions to stop the experiment. Since in this experiment the researcher was present in the real room the participant was in, it is possible that participants in VR were less sensitive to the presence of the researcher in the real room, as they knew they were “alone” in VR. Nevertheless, the effect of the researcher in the room means that the results cannot be extrapolated to a real-world emergency.

The results show that participants were worse at pinpointing the direction of the origin of the sound. This means that VR may not be a good tool to conduct experiments in which the location of audible cues plays an important role.

It is also possible that participants were worse in VR because they were asked about the origin of the sound right after stopping the simulation. Probably they should have been asked while being still in VR, but this was not identified as a source of bias during the design phase of the experiment.

The results measured differences between VR and reality when it comes to the reaction to the alarm. No solution to it is proposed, as the experiment was designed to answer an “if” question based on anecdotal observation, rather than “why”.

Lastly, it is possible that the problems with the perception of sounds in VR (lack of reaction and to some extent also directionality) can be solved by the use of voice alarms. In a previous experiment by

Arias et al. (2022), a voice alarm was used. The alarm consisted of a series of beeping sounds, followed by a message in Swedish, a new series of beeping sounds, and a message in English. That sequence was repeated constantly. Anecdotally, participants seemed less prone to ignore the alarm. The evacuation of the English speakers was clearly delayed by the time it took for the English message to start playing. In comparison, in an experiment with the sound of a domestic smoke detector going on (Arias, Nilsson, et al., 2020), participants took a long time until they reacted to the alarm. This is also anecdotal as the time it took until reaction was not collected. Therefore, future studies could look into the performance of voice alarms compared to non-voice alarms in the time for reaction. If voice alarms work better in VR than alarms not using voice messages, it is possible that a suitable compensation for the lack of directionality of the sounds in VR compared to reality could be a voice message giving information to the participant. This is not necessarily a realistic alarm system but rather a compensation for the drawbacks with audible cues in VR.

6 Conclusions

The results of the project were able to measure differences between the same experiments conducted in VR and in reality, as it was intended. Some differences were expected, in which case the results provided a numerical assessment of said differences. Some differences were unexpected, in which case the results were inconclusive.

6.1 Impact of level of fidelity

- No statistically significant difference was found between the results of the SED assessment obtained in both virtual versions of the lecture hall and the real one. This means that the Lo-Fi virtual environment was not perceived as different from the Hi-Fi version or the real lecture hall based on the SED assessment. Therefore, the simplifications introduced in the Lo-Fi version were not detrimental to the overall perception of the room for the participants.
- Those simplifications were meant to save time and effort in producing the virtual environment, but they need to be carefully assessed by an experienced VR designer, as calculated compromises rather than bad practices.

6.2 Perception of distances in VR

- No statistically significant difference was found in the perception of distances between the real corridor and the default projection. This result contradicts the literature that indicates an underestimation of distances in VR
- A statistically significant difference in the perception of distances was found between the real corridor and the modified projection. This is an unexpected result, as according to the researchers involved in this project, the architectural lines of the modified projection aligned well with those in the real corridor. An explanation for this could not be found.

6.3 Reaction to alarms

- Participants in reality showed a form of reaction to the alarm more often than participants in VR. Nevertheless, the proportions of participants reacting to the sound of the alarm in each were not largely different. While less participants in VR may visibly react to the alarm, lack of visible reaction can also be expected in reality. These results are unlikely to be reasonably extrapolated to reality, as the presence of a researcher in the room may imply an expectation of control by the participant, meaning that no reaction from the researcher may mean to the participant that they do not need to react either.
- Participants were clearly worse in VR than in reality when asked to indicate the origin of the alarm sound they heard. This means that VR may not be recommended to study behaviour in experiments in which the participant is expected to react based on a correct identification of the origin of an audible cue.

6.4 Recommendations for the application of the results

This project allowed for developing a deeper understanding of the differences in perception of environments in VR and in reality. The conclusions of this project can help VR researchers to make more robust experimental designs by saving time in the generation of the environment, being aware of limitations in distance perception and possibly working around in the limitations in the reaction to alarm sounds in VR. When designing a VR experiment, much thought needs to be put in the advantages and disadvantages the method has, in order to evaluate whether the shortcomings of it could affect the data to be collected.

The results presented in this report are based on the experiments conducted and are not exempted from the limitations of each experiment. While they may be used as a general guideline in future VR experiments, an analysis needs to be performed first to determine if they may work against the purposes of the specific experimental design. As an example, while our results show that the absence of shadows may be detrimental to the perception of realism for the participant, in cases in which real-time lighting is not possible due to constraints in the computational power, no shadows may be the only way to go.

Furthermore, the present project did not study the perception of realism of the virtual environment while the participant was busy conducting actions in said environment. In a fire evacuation scenario, it is unlikely (although not impossible) that the lack of shadows in objects would be noticeable enough while the participant is making decisions on their way out of the virtual building, let alone have an effect in said decisions. Therefore, the results can be used if an assessment of advantages and disadvantages deems a net benefit.

Lastly, it is important to consider that there is no one-size-fits-all solution in the design of VR experiments. The many limitations of the technology, and the wide spread of possible experimental designs with their focus on special aspects make a blanket solution for all cases unlikely. Therefore, the main recommendation is a careful consideration and a deliberate implementation of these results, with a clear understanding of their implications in the experimental design.

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Appendix A. Modified projection for corridor scenario

Multiple methods can be used to manipulate how a final image is rendered on a screen, the most common are *vertex and fragment (pixel) shaders* and *full-screen post-processing effects*. An example of manipulation is that lenses in a head-mounted display often cause barrel distortion, which is addressed by pre-warping the image so that the barrel distortion corrects the resulting image a user sees. Each approach has its pros and cons.

The post-processing approach is attractive as it can be done in image-space when everything is rendered. However, image manipulation can lead to regions of lower pixel density which means that oversampling of pixels must take place and later be down-sampled or discarded. Also, the image manipulation applies for every single pixel on the screen, both of which can be taxing computationally. Image space generally lacks full 3D awareness, meaning some information might have to be rebuilt as needed, e.g. by using depth buffer information. An advantage of the post-processing approach is that any calculations of light and shadows can be done efficiently using rectilinear projections as the distortion happens after light and shadows are computed.

The vertex and fragment shader approach can be applied to triangles of interest only, in contrast to the post-processing approach. However, in the specific case of environment distortion this has less value as the entire virtual environment must be affected by any manipulation. Of bigger importance is the fact that the vertex shader (and to some extent the fragment shader as well if needed) often has full 3D space awareness from object space to clip space, with view space and world space in between. This can vastly simplify or even enable distortions that might not be otherwise possible in other approaches, such as post-processing. One disadvantage is that any change to world projection will also have an effect on light and shadow projection (as they are assumed to be rectilinear) for them to be visually synchronized. This can vastly complicate the implementation of the final effect.

One commonly used projection correction for wide field of view images is the Panini projection (*The General Panini Projection - PanoTools.Org Wiki*, n.d.). It is a cylindrical projection which aims to reduce peripheral view distortion, compared to rectilinear projection, while keeping vertical straight lines straight, as opposed to spherical or fish-eye projection. A built-in post-process implementation of the Panini projection exists in Unity (*Panini Projection | Universal RP | 7.1.8*, n.d.), and as such was pilot tested with a few people. Unfortunately, it was quickly evident that the world distortion that occurs when moving one's head (as the projection centre is moving) induced nausea and the correction did not feel natural as the environment noticeably deforms. The Panini projection seems more suitable and natural when projected onto a plane such a traditional monitor, as the observer has multiple alignment points besides the monitor.

Another technique that seemed attractive was inspired by the Google Cardboard vertex displacement based approach to VR headset lens pre-warping (Kehrer, n.d.). However, instead of warping space to correct for lens distortion, the general idea is to warp space around the camera to change the perception of distance/size, and the space warping follows the camera (player) around as it moves. In the specific case of distance assessment it was of interest to make distant objects appear closer or further away than the standard rectilinear projection, and this can be achieved by either moving objects (specifically vertices) closer to the camera (compress space) or enlarging the object based on distance by stretching them in the plane parallel to the forward view vector, making them appear large rand therefore closer. The latter approach was chosen after testing as it gave the most stable image with the least graphical artifacts, such as z-fighting.

A code snippet of the vertex shader can be seen below. The vertex displacement requires a set normalizing distance (_NormalizingDistance), which is the distance that a desired scale (_FarScale) is achieved. E.g. if the normalizing distance is set to 12 meters and the scale is set to 1.4 any vertex at 12 meters away will be enlarged/displaced by 40% in each direction in the plane that is parallel to the current forward direction of the camera. This process is not necessarily linear, and the user can manipulate this by changing the _PowerExponent value to any desired value larger than 0, the default being 1.0 which creates a linear scaling from _StartDistance to _NormalizingDistance. The value _StartDistance allows the effect to be offset to any distance away from the camera. The default is 0 which again creates a linear change over distance from observer to whatever is observed.

```
VertexPositionInputs GetVertexPositionInputsAlt(float3 positionOS)
{
    VertexPositionInputs input;
    input.positionWS = TransformObjectToWorld(positionOS);

    float3 camRelativePos = input.positionWS - _CameraPos;
    float xNorm = max(0.0, abs(camRelativePos.x) - _StartDistance) / _NormalizingDistance;
    xNorm = pow(xNorm, _PowerExponent);
    float zNorm = max(0.0, abs(camRelativePos.z) - _StartDistance) / _NormalizingDistance;
    zNorm = pow(zNorm, _PowerExponent);
    float2 camFlatForward = _FlatCameraForward.xz;
    camRelativePos.yz *= lerp(_CloseScale, _FarScale, xNorm);
    camRelativePos.xy *= lerp(_CloseScale, _FarScale, zNorm);

    input.positionWS = camRelativePos + _CameraPos;
}
```

An illustrative example of the modified projection is presented in Figure 22 , where a) is the standard rectilinear (default) projection, and b) is using the vertex displacement shader and a _FarScale of 2.0 at a _NormalizingDistance of 25 meters, approximately the end of the corridor.

Figure 22 – Illustration of the differences in the projections used for the scenarios. This is not the participants' view. The camera is located on the far left indicated by the green arrow. a) Side view of a corridor scenario using default projection. b) Side view of a corridor scenario using the vertex displaced projection using a _FarScale of 2.0 at a _NormalizingDistance of 25 meters

The resulting view from the camera can be seen in Figure 23 and Figure 24. Figure 23 represents the view the participant would have in the default projection. Figure 24 represents the view the participant would have in the modified projection, with the _FarScale factor of 2.0 and _NormalizingDistance of 25 meters, meaning that the end of corridor occupies two times the number of pixels in each of the lateral and vertical directions.

Figure 23 – View from the camera downwards the corridor using default projection.

Figure 24 – View from the camera downwards the corridor using the vertex displaced projection using a _FarScale of 2.0 at a _NormalizingDistance of 25 meters.