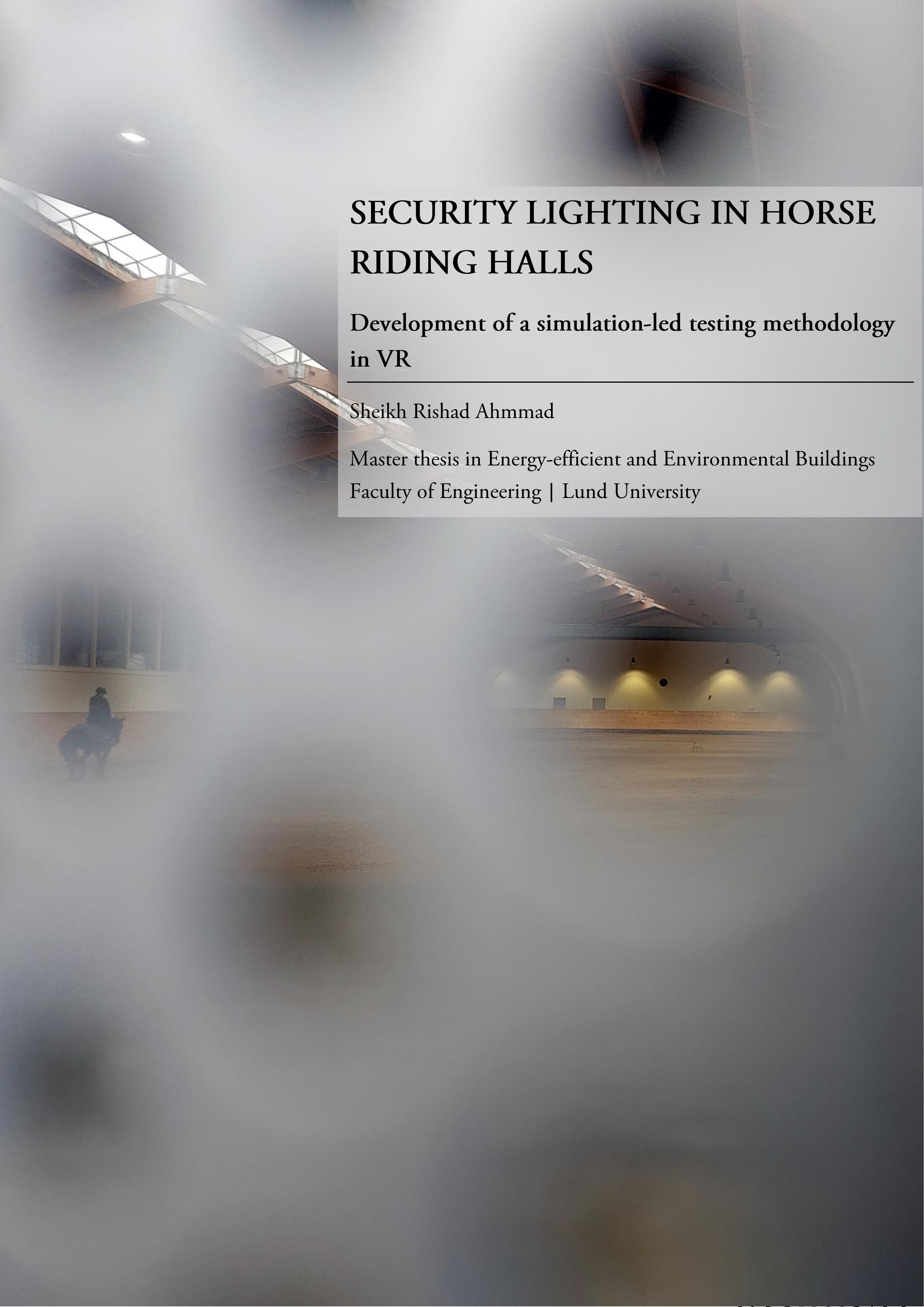

SECURITY LIGHTING IN HORSE RIDING HALLS

Development of a simulation-led testing methodology in VR

Sheikh Rishad Ahmmad

Master thesis in Energy-efficient and Environmental Buildings
Faculty of Engineering | Lund University

Lund University

Lund University, with eight faculties and a number of research centres and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 112 000 inhabitants. A number of departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 6 000 employees and 47 000 students attending 280 degree programmes and 2 300 subject courses offered by 63 departments.

Master Programme in Energy-efficient and Environmental Building Design

This international programme provides knowledge, skills, and competencies within the area of energy-efficient and environmental building design in cold climates. The goal is to train highly skilled professionals, who will significantly contribute to and influence the design, building or renovation of energy-efficient buildings, taking into consideration the architecture and environment, the inhabitants' behaviour and needs, their health and comfort as well as the overall economy.

The degree project is the final part of the master programme leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

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Keywords: Security lighting, horse riding halls, mesopic vision, Virtual Reality, object tracking

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Abstract

Security lighting plays a vital role for safe evacuation during an emergency such as power outage or a fire related incidence. Installing a security lighting system properly is more crucial for a horse riding facility for two reasons. Firstly, if a sports activity is ongoing at the exact moment of an emergency, the activity needs to be ended safely with the help of security lights to avoid injuries and accidents. Secondly, the security lighting is required so that horses stay calm and do not react from the sudden absence of light. Daylight is scarce between winter solstice to spring equinox in Sweden. This phenomenon makes scheduling events and competitions during completely daylit hours more difficult, especially during the winter, making the facility more dependent on electric lighting.

Emergency situations occur rarely in horse riding halls, thus the cost related to the energy use is not such a big concern. On the other hand, the large volume of occupied space makes it a costly affair to install the whole security lighting system, including cost for lamps, luminaires, controls, and batteries. This study investigates the possibility to introduce new security lighting solutions that can potentially reduce the lighting installation costs, while making the system safer, more secure, and efficient. However, the study does not go into details of the associated costs of the system, rather focuses on the design and visualization of the lighting system.

The main purpose of the study is to adapt a simulation methodology and develop a testing methodology that can be used to design security lighting systems. Installing a trial version of the system in situ to evaluate its performance can be costly and time-consuming. Alternatively, computer-based simulations and visualizations with Virtual Reality (VR) provide a cheaper solution to test and iterate different design solutions. This project focuses on developing a testing methodology in a VR environment that can provide lighting professionals with an immersive experience of their design. In real life situations, the VR environment can also be utilized to let the user group experience the environment and obtain their feedback. This exercise can be helpful in the design process to make informed decisions. To validate this process, the developed VR environment in this project is tested on volunteer participants to get their feedback.

The simulation results suggest that it is possible to provide same level of illuminance in the case building during emergency situations with fewer luminaires and less installed power according to the existing minimum lighting requirement. However, the participants' feedback as well as test data from the VR experiment suggest that the current minimum requirement for security lighting in the specific building type may not be enough for its occupants to be able to see everything properly and safely evacuate the space during an emergency. The eye tracking data obtained from this study can be analysed in future to get a better understanding of the test participant's gaze behaviour.

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Firstly, I express my gratitude to the Swedish Institute for funding my postgraduate education at Lund University. I am extremely grateful to Svenska Ridsportförbundet for financial support and for providing important documentation and general support, especially Anna Reiley and Marcus Lundholm. I express my deepest appreciation to Mats Molén at Fojab Arkitekter for sharing his expertise with me as well as providing the drawings of Malmö Civila Ryttareförening building. I thank Research Institute of Sweden, especially Cecilia Hagberg for being a part of the project. I am indebted to Kristin Kringstad for letting me access the Malmö Civilia Ryttaförening building and arrange a session with test participants there. I am indebted to Maria Hedin for letting me use the facilities of the VR lab at Lund University, and to Joakim Eriksson for his advice on the methodology in VR. I thank Jayedi Aman from the University of Missouri for his help and suggestions. I am indebted to Mikkel Kofod Pedersen from Ladybug tools for his help with the eye gaze visualization. I extend my sincere thanks to Jonathan Andersson for helping with the scripting in Unity. I am indebted to all the test participants who dedicated their time for my project. I am grateful to my wife, Ishrat Laila Nowrin for her unconditional support throughout the project. I also thank her for lending me her workstation to work on the renderings and assisting me with the final test on participants. Special thanks go to my supervisors who helped me with their guidance throughout the project. I am grateful to my examiner Niko Gentile for his thoughtful comments, suggestions, and appreciation. I thank my co-supervisor Hillevi Hemphälä from Lund University for her guidance as well as providing me her test equipment. I am grateful to my co-supervisor Mandana Sarey Khaney from Technical University of Denmark for her continuous support and involvement. I am also indebted to her for lending me the VR headset and workstation which made it possible to bring the test to the participants. Last but not the least, I sincerely thank my supervisor Marie-Claude Dubois for envisioning and initiating the project, believing in me and supporting me throughout the project.

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1 Introduction

1.1 Background

Security lighting in horse riding halls and stables is required in case of emergencies such as power outage, so that the horses, their human caretakers, and other occupants can leave the facility safely. This is crucial since caretakers and occupants can consist of teachers and a group of children, who could be in risk of accidents when lighting suddenly turns off. A horse could panic or move rapidly, with the risk of falling on a child and injuring him or her for life. The current requirement for security lighting in horse riding halls is to provide 15 lux of illumination (5% of the required illuminance level) on the entire horizontal surface for 20 minutes (Svenska Ridsportförbundet, 2020). However, the height at which the illuminance level should be measured was not mentioned. The cost of lamps, batteries, and luminaires to provide this security illumination is very high, considering the large size of these spaces.

It takes horses five minutes for cone cells and 20 to 30 minutes for rod cells to adjust to a dark environment ((Murphy, 2015). On the other hand, humans take about 30 minutes to fully adapt to a dark environment (Dubois et al., 2019). Horses have a better sense of smell and a much better vision in low light conditions than humans (Hörndahl et al., 2013) and can probably find their way out under power outages. However, sudden change in light to a very low level can make the horses nervous and cause accidents. Five lux of illuminance is sufficient for humans to see in outdoor environments (European Committee for Standardization (CEN), 2014). However, the long dark adaptation time may make it difficult for humans to adjust to a security lighting condition suddenly in an emergency.

These issues call for research on this topic, for developing a cheaper and more appropriate security lighting solutions in horse riding halls, which ensure a safe lighting environment for both humans and horses, at the same time reducing the total cost compared to the current situation. The project proposal was initiated based on practical problems faced by Svenska Ridsportförbundet who have some set requirements for security lighting in horse stables. However, the requirements are seemingly arbitrary, leading to expensive solutions, and there is scope for revising them.

1.2 Research objectives

The main objective of this project is to simulate and visualize different general and security lighting conditions and develop a testing methodology based on Virtual Reality (VR). The purpose of the VR test is to assess the object and colour identification capability of test participants in different lighting condition based on object tracking and eye gaze direction tracking technology. One hypothesis is that the higher number of object recognition by the test participants correspond with the ability to navigate in the riding hall during an emergency lighting condition. The test method is expected to demonstrate low risk with security lighting with lower installed power and better lighting design in horse riding halls, although further research is required in order to come to a definitive conclusion. This research investigates the possibility to reduce the cost of security lighting while providing a better lighting solution and safe environment. Simultaneously, it explores the possibility of using the proposed testing methodology as part of the design workflow for real projects.

2 Literature review

Before starting this study, a brief literature review was conducted to gather all relevant information about horse riding halls, including previous research as well as regulatory framework. The following sections present key information found in this literature review.

2.1 Lighting requirements in horse riding facilities

2.1.1 Electrical lighting requirements

Electrical lighting requirements for horse facilities are outlined by Brandskyddsföreningen in their handbook (Brandskyddsföreningen, 2019). These requirements state that the lighting should be sufficiently uniform with satisfactory brightness. The lighting should be safe from an electrical as well as a fire safety point of view. Luminaires should be correctly directed in order to avoid glare and shading, so that horses' vision is not compromised by their own shadow. The luminaires should not be placed directly above the horses, nor in a place where the horses can reach them (Horse and Hound, 2019). The lighting fixtures should be easy to clean, weatherproof, and resistant to corrosion for an environment such as a horse riding facility. The fixtures should be covered by a cage which will prevent them from breaking in case a horse reaches one of them. The luminaires should have a plastic safety cover to protect the horses from injury in case the light shatters. The wires should be covered and concealed so that horses or rodents cannot damage them by chewing. Incandescent lamps such as halogen bulbs are not suitable for indoor spaces as they might get too hot and cause fire incidents. LED lights are currently recommended due to their long lifespan, low temperature, energy-efficiency, and cost-effectiveness.

Olympic sports halls require 1 400 lux of illuminance for all the televised events (Fitt & Thornley, 2002). On the other hand, general public horse riding facilities with provision of more than 1000 audiences require an illuminance level of more than 750 lux on horizontal surfaces and 375 lux on vertical surfaces. Facilities with less than 1000 audiences require 500 lux on horizontal surfaces and 250 lux on vertical surfaces. The uniformity ratio (minimum/average) for both cases should be a minimum of 0.70. Local horse riding facilities on the other hand require 300 lux on horizontal surfaces and 150 lux on vertical surfaces. The uniformity ratio should be minimum 0.70 and 0.50 on the horizontal and vertical surfaces respectively (Sveriges Kommuner och Landsting, 2013). For the purpose of this study, a local horse riding facility in Malmö has been selected and applicable requirements have been considered. The height at which the illuminance level should be measured was not mentioned alongside the requirements. Hence, the simulations for this study were conducted assuming an average human eye level of 1 600 mm, which is also similar to horses' eye level.

2.1.2 Security lighting requirements

Security lighting should be available in the horse stables, riding halls, and along the transport routes as well as outdoor tracks if they have lighting provisions. Horse riding facilities in Sweden are required to have sufficient security lighting to fulfil two purposes (Svenska Ridsportförbundet, 2020). The first one is to provide reassuring security to continue an ongoing event in case of a lighting failure. The security lighting must be turned on immediately and last for at least 20 minutes so that the ongoing activity can be safely terminated. In this case, the illuminance level of the space must be at least 5% of the original requirement, which is 15 lux for local facilities for exercise, training, and competitions (Sveriges Kommuner och Landsting, 2013). The second purpose is to ensure that horses do not get nervous from the sudden absence of light and cause any accident.

2.2 Lighting and vision

The human perception of reality is not an actual representation of the physical world, as it is evident since humans have managed to come up with ways to measure different aspects of it (Russell, 1945). Sensory organs in human body work primarily as a filter that feeds human brain with a fragment of information that helps to construct a view of the world. Thus, the senses that humans can feel largely depend on circumstances and the humans themselves. The sense of vision or any other sense for that matter can vary to a large extent for the same person at different circumstances, or at a different physical condition or a different age (Schiffman, 1977).

Perceptions of different senses can vary to a large degree amongst different species, and humans and horses are very different in this regard. This study deals with spaces that accommodate both horses and humans, which is why it makes it more important to study how the sense of vision works for both humans and horses. A horse riding hall during its full operation can have children, instructors, parents, and other visitors present during the event of an emergency. Thus, it is also important to study the sense of vision in people of different age groups.

2.2.1 Human vision

Humans, like most other mammals have a frontal overlapping binocular visual field, where they have the highest visual acuity as well as depth perception (Saslow, 2002). Humans can see a wider range of the colour spectrum compared to the horses. However, humans have poorer low level light vision compared to many animals including horses. On the other hand, humans have better photopic or bright-light vision, which works best at higher levels of illumination.

2.2.2 Vision in mesopic range

Daylight and electric lighting design needs understanding of photopic adaptation as the main adaptation state during daytime (i.e. at high light levels) (Dubois et al., 2019). However, during an emergency, lower light levels is prevalent in horse riding halls, which makes it important to study mesopic adaptation for such cases. Mesopic vision is a combination of photopic vision and scotopic vision in low but not dark lighting condition (Viikari et al., 2008). Mesopic condition has a luminance level ranging from 0.01 cd/m^2 to 3.00 cd/m^2 (Li et al., 2020). Luminance level lower than this is considered to be scotopic range and higher levels are generally considered to be in the photopic range.

2.3 Virtual reality

The term Virtual Reality was first coined by Jaron Lanier of VPL research in 1989 (Paranandi & Sarawgi, 2002). The reason behind introducing the new term was to distinguish the immersive digital world that he was trying to create from regular computer-based simulations. VR technology is widely used today for entertainment, education, training, research, and many other purposes.

While most lighting design software can provide a quantitative analysis of the design, previous studies showed that VR technology can be utilized to perform a qualitative analysis (Lee & Lee, 2021). VR technology can provide the means to assess the impact of different lighting design iterations quickly on test participants (Scorpio et al., 2021). One of the biggest challenges of using VR technology for lighting design is to ensure that it can create a visually and photometrically correct reproduction of light (Scorpio et al., 2021).

3 Methodology

The study was initiated by conducting a physical survey to the case building. Architectural drawings and lighting design specifications were collected from the architectural firm commissioned to design the building (Fojab Arkitekter). The collected AutoCAD drawings and photographs from the site visit were used as the basis for the 3D modelling of the building. At first, a 3D model with a simplified geometry of the building was created in Rhinoceros 3D. The model was compatible to perform daylight and electric lighting simulations using the ClimateStudio plugin for Rhinoceros 3D. The existing lighting conditions as well as several proposed lighting conditions were simulated using this model. Based on the results of these simulations, a few instances were chosen for testing in VR. The model was used to create RADIANCE-based renderings for these lighting conditions from a fixed viewpoint. These renderings were used to create the testbed in VR environment in Unity. The test was conducted on volunteer participants where their responses were recorded through a questionnaire survey. The object tracking data and eye movement data of the participants during the test were extracted for further analysis. The overall methodology of the project is explained in Figure 1.

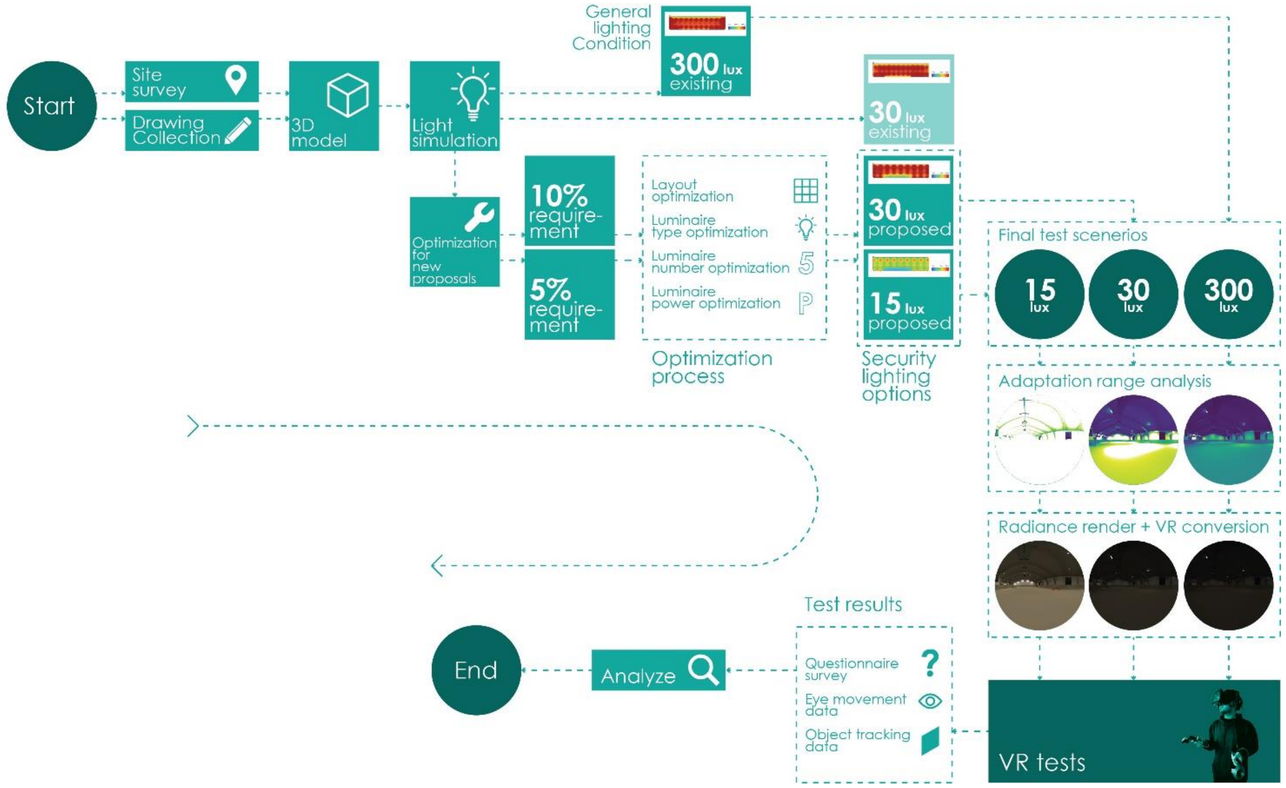

Figure 1: A figure illustrating the methodology of the project.

3.1 Building specifications

3.1.1 Building geometry

For the purpose of this study, the Malmö Civila Ryttareförening (Malmö Civil Riders Association) horse riding hall was taken as the study object. This building is located on Elisedalsvägen 1, in Malmö, Sweden (55°N 13°E). The whole facility consists of 5 500 m^2 of usable floor area, of which the riding hall roughly occupies almost 2 500 m^2. The riding hall measures almost 25 meters by 100 meters with a North-South elongated orientation, slightly inclined towards the West. The hall has a pitched roof with an angle of 15° with respect to the horizontal surface. The height of the riding hall is 10 meters along the central ridge, and 6 meters at the lowest point. The overall layout of the building highlighting the riding hall is shown in Figure 2.

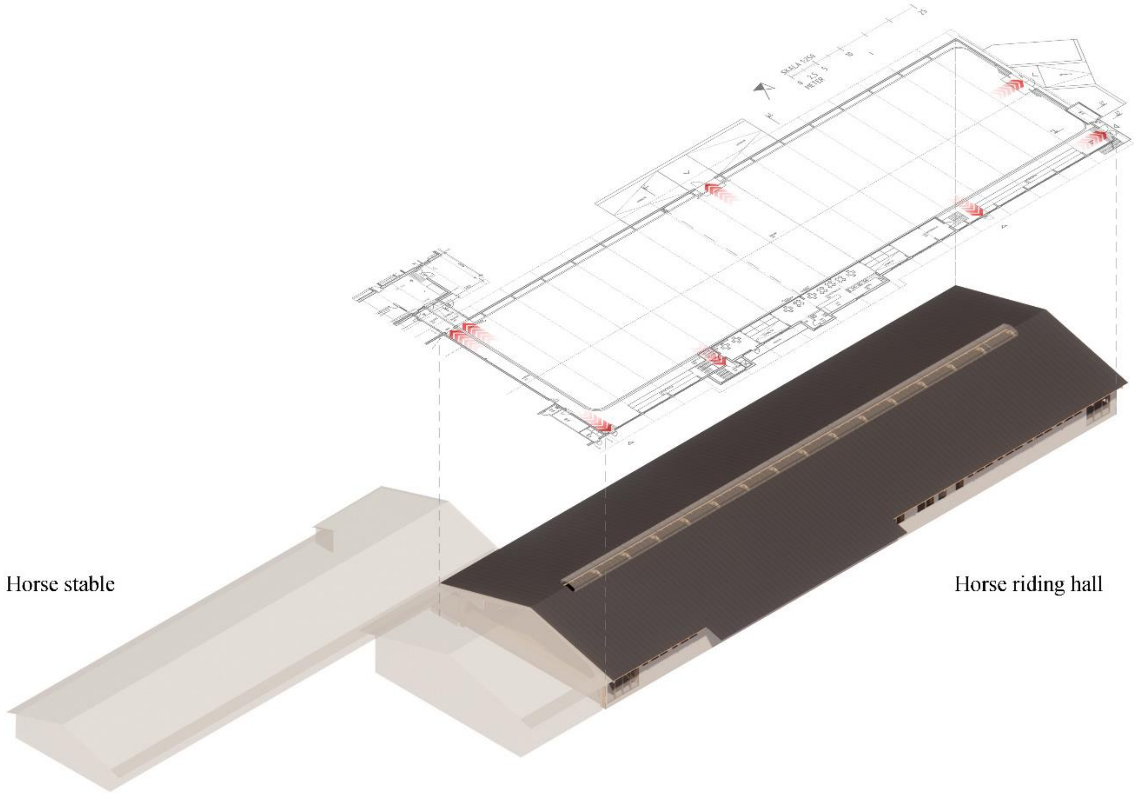

Figure 2: Axonometric drawing showing the Malmö Civila Ryttareförening building. Drawing courtesy (plan) of Fojab Arkitekter.

The building has a wooden structure that creates an uninterrupted space, as shown in Figure 3. A linear opening is created along the central ridge of the roof which lets natural light inside the building. The building façade mostly comprises glass, wooden louvres, perforated metal sheets, and wooden panels. The Northern façade is mostly open towards the outside. However, the Southern façade is partially blocked by a mezzanine level housing some supporting facilities that potentially reduce the amount of daylight coming from the South.

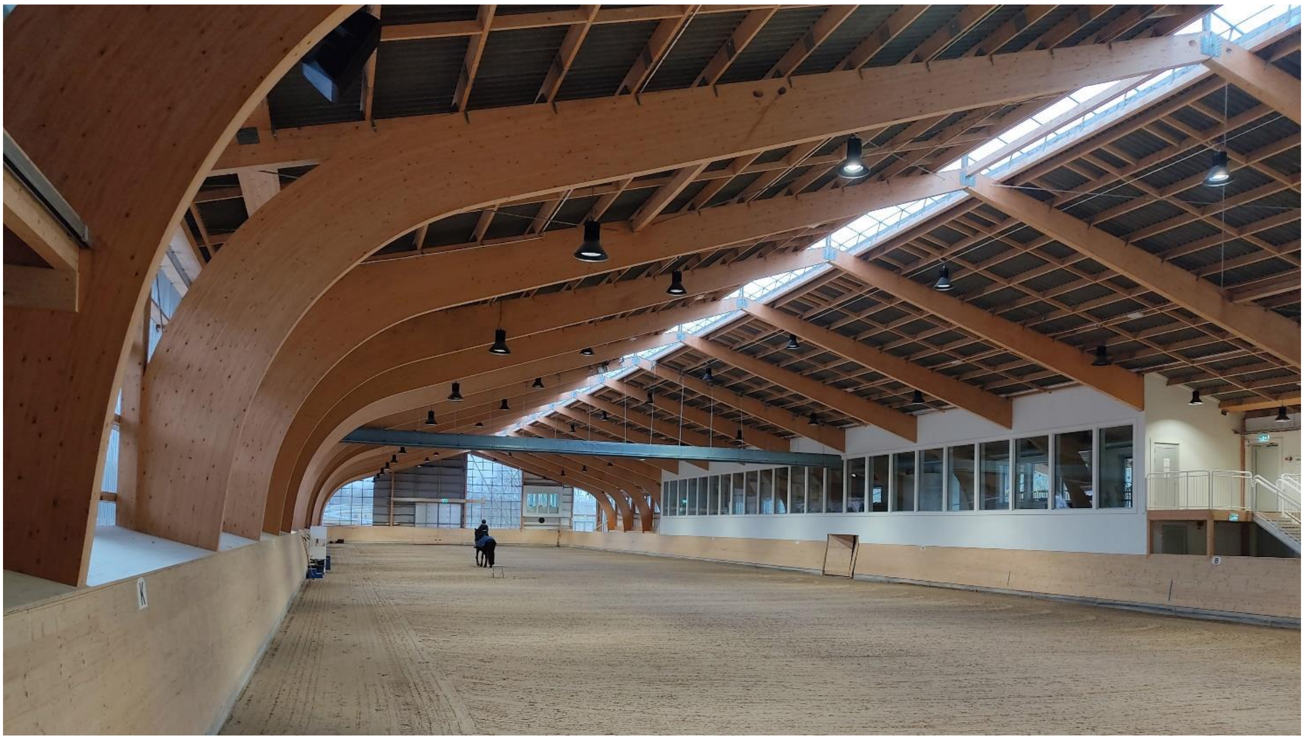

Figure 3: A photograph showing the interior spaces of the riding hall. Photo: author.

3.1.2 General and security lighting in the building

The existing space has two different sets of lighting systems installed according to two different grids. The first system includes 60 Luminaires that provide lighting to the building for general use and the second system includes 43 luminaires that are only used in case of emergencies (Figure 4). The overall lighting layout of the riding hall is illustrated in Figure 5. The lighting layout does not follow the same grid as the structural members of the building, causing unwanted placement of luminaires leading to light losses.

Figure 4: A photograph showing a general luminaire (in green rectangle) and a security luminaire (red rectangle). Photo: author.

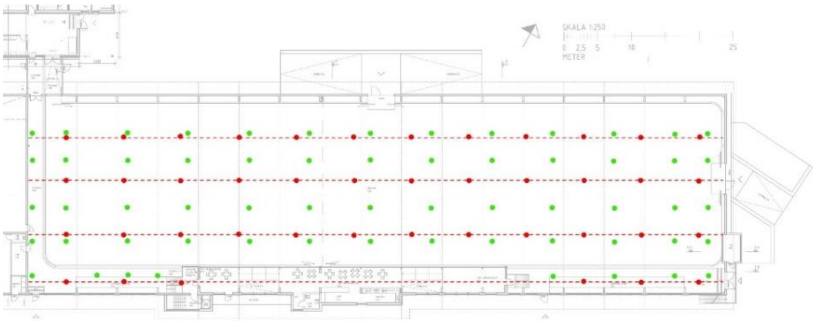

Figure 5: Floor plan of the riding hall with the regular lighting system marked with green circles and security lighting system marked with red circles and dotted lines.

3.1.3 Escape routes

The riding hall has eight exit points located in different places, among which three are directly accessible from the riding area. The other exit points are located near the gallery, cafeteria, entrance from the stables, and other public entrances. The exit points are properly marked, and escape plans are available in different places. However, the riding area is very large and there is possibility that finding the nearest exit can be challenging in an emergency for people who are not too familiar with the building.

3.2 Modelling and simulation: software and hardware

3.2.1 Drawing preparation

The first program used in this study was AutoCAD, which is a computer-aided design software developed and marketed by Autodesk. AutoCAD is widely used in architecture, engineering, and the construction industry for 2D and 3D drafting. AutoCAD was mostly used in this project to review the existing building drawings as well as generate new drawings for the project.

3.2.2 3D modelling

Rhinoceros 3D was used to create the virtual model of the case building. Besides its traditional function as a 3D modelling software, Rhinoceros 3D is also used as the base software for many simulation and visualization plugins such as ClimateStudio, Grasshopper etc. Rhinoceros 3D was used to construct the three-dimensional model of the case building (Figure 6). Compatibility with different software and plugins was one of the motivating factors for selecting Rhinoceros 3D as the 3D modelling software in this study.

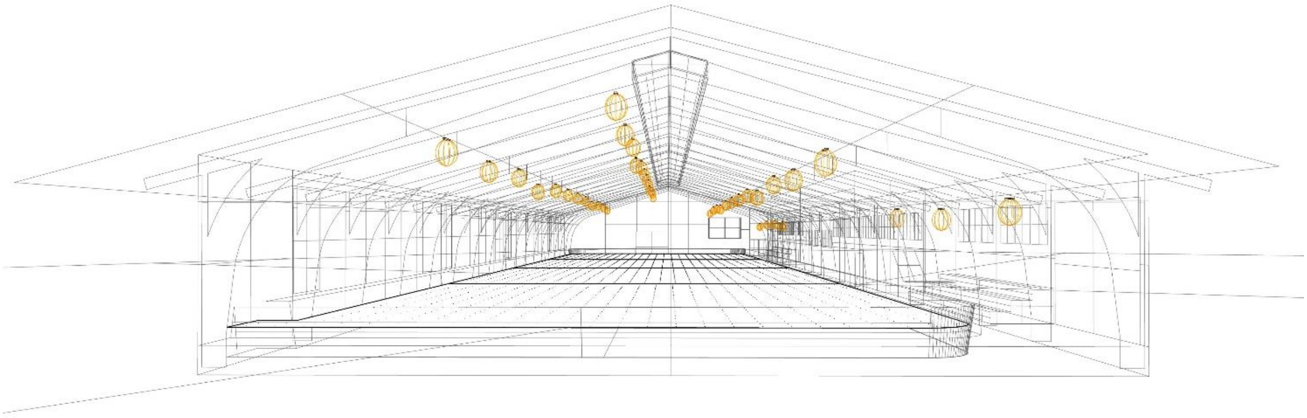

Figure 6: 3-dimensional model of the study area constructed in Rhinoceros 3D.

3.2.3 Lighting simulation

For the light simulations, ClimateStudio was selected as it is an environmental performance analysis software compatible with Rhinoceros 3D. ClimateStudio was used to perform photometrically accurate lighting simulations. The software is built on EnergyPlus and a RADIANCE-based hybrid deterministic-stochastic raytracing technology. ClimateStudio is developed by Solemma, and free for educational and research purposes.

3.2.4 VR conversion and visualization

Finally, Unity was used as the main cross-platform game engine for the VR simulations. This software has also been adopted by other industries including Architecture, Engineering, and Construction (AEC). Unity can be used to visualize the models from the software mentioned previously towards a VR environment. Unity is free for educational use, and the hardware for running it including VR headset and controllers were accessed through the Virtual Reality Lab at Lund University as well the Department of Civil Engineering at DTU. The VR Head Mounted Display (HMD) used for this study is a Vive Pro eye (Vive Developers, 2019), which is the first of its kind that can provide eye tracking data. Other features include SteamVR Tracking, G-sensor, gyroscope sensor, proximity sensor, IPD sensor etc. Vive pro eye has a Dual OLED 3.5'' (diagonal) screen with 1 440 x 1 600 pixels per eye (2 880 x 1 600 pixels combined). The refresh rate is 90 Hz while the gaze data output frequency (binocular) is 120 Hz. The ergonomic design of the headset includes eye relief with lens distance adjustment, adjustable IPD, headphones, and head strap. The eye tracking is accurate up to 0.5°–1.1° (within field of view of 20°). It has a 110 degrees trackable field of view. The data outputs include timestamp, gaze origin, gaze direction, pupil position, pupil size, and eye openness. The user guide (Vive Developers, 2019) further points out that the eye tracking performance may be affected due to eye surgery, eye disease, high myopia, and heavy makeup among other reasons.

3.3 Experiment methodology

3.3.1 Validation method

The security lighting system of the building is mostly available during an emergency; thus, it was not possible to turn the lights on during the survey. Moreover, determining the illuminance level of the space using physical light measurement tools would have required the security lights to be turned on during a nighttime environment, as the experiment should be done without the presence of sunlight and only in the presence of electric lighting. As it was not possible to recreate such a scenario, physical measurements were not taken into consideration for this study. It is to be mentioned that for real projects and practical applications of this methodology, physical measurements will be required to validate the simulation results. For the purpose of this study, it was done by taking the luminaire data from the site survey as well as the specifications provided by Fojab Arkitekter. These data were then used to conduct the simulations.

3.3.2 Case selection

Different lighting conditions were simulated to select the appropriate cases for final investigation in VR. Different lighting fixtures (.ies files) were used to simulate different lighting conditions. The specifications of the luminaires are shown in Table 1.

Table 1: Comparison of different luminaires used for the simulations.

	Existing general lighting (300 lux)	Existing emergency lighting (30 lux)	Fewer luminaires with higher power (30 lux)	Same luminaires in fewer numbers (15 lux)
Number of luminaires	60	43	23	23
Luminaire model	Silversun HBG100CWD	Silversun FX615NWE	Silversun FX230CWE	Silversun FX615NWE
Standard consumption (W)	100	15	30	15
Battery duration (h)	-	3	3	3
Colour temperature (K)	5000	4000	5000	4000
Luminous flux: (lumen)	15000	2200	4200	2200
Efficiency (lm/W)	150	147	140	147

The results of the simulations are visualized and discussed in this section. The simulations were represented with a heatmap, and the colour scale is shown in Figure 7.

Figure 7: A colour scale showing different ranges of illuminance predominantly used in this study.

3.3.2.1 First scenario

Firstly, the general lighting condition of the building was simulated. This specific building type has a requirement of 300 lux mean illuminance on the horizontal surface. According to the surveys, the electric lighting system of the building is turned on during the daytime events. The building has provision of ample daylight from its facades and roof. Therefore, the luminaires coupled with natural light makes the illuminance level of the building considerably higher than the minimum requirement. Therefore, the lighting simulations were done without the presence of daylight. The simulation illustrated in Figure 8 for the existing luminaires show that the building has a mean illuminance of 288 lux and median illuminance of 280 lux on the horizontal surface. Considering that the lighting design consultants aimed to achieve 300 lux of illuminance, and that the simulation results had some inaccuracies owing to modelling imperfections, errors in material selection, and the general simplification made for the modelling, this case was considered to be the base case for the regular lighting condition. For easy understanding, this condition was referred to as the ‘300 lux environment’ for the remainder of the report. The purpose of selecting this as the base case is to compare how well a person can see in a security lighting condition compared to a regular lighting condition.

Figure 8: Illustration showing the simulation results of the existing regular electric lighting system of the riding hall. The black colour of the illustration suggests that all the simulation sensor points of the riding hall have an illuminance level higher than 30 lux.

3.3.2.2 Second scenario

As mentioned earlier, the minimum requirement for the security lighting is 5% of the regular light, which is equal to 15 lux for the case building. However, some guidelines (The Industry Committee for Emergency Lighting, 2008) suggest that for sensitive environments and where high level of precision is needed, emergency lighting equal to 10% of the regular lighting is required. For the case of this building, it is 30 lux. The existing security lighting system of the building was simulated, and the results show that the building has a mean illuminance of 29 lux and median illuminance of 30 lux on the horizontal surface. It is assumed that the lighting design professionals targeted to achieve 10% of regular lighting for the security lighting purpose. The simulation results are illustrated in Figure 9.

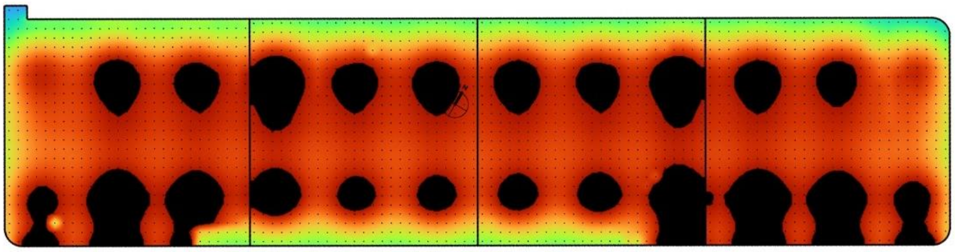

Figure 9: Illustration showing the simulation results of the existing emergency lighting system of the riding hall.

The first set of proposals for a different lighting system was based on the assumption that, a similar illuminance level can be achieved by reducing the number of luminaires while increasing their power. The proposal of a new layout was done considering the perceived problems of the existing layout. The layout does not follow the existing building structure and thus some of them fall in unwanted spaces. In many cases they are obstructed by the structures, therefore cannot provide the expected illuminance. Moreover, the layout not following the building structure is not aesthetically pleasing. The target of the new proposal was to solve these issues and provide a better layout while retaining the same level of illuminance with fewer lights. To do that, numerous simulations were done to achieve the optimized result. These simulations were performed by changing four different variables: lighting layout, type of luminaire, number of luminaires, and luminaire power. The results in Figure 10 show that, the newly optimized layout has a mean and median illuminance of 29 lux, which is considerably close to the existing condition. Thus, this scenario was selected to be the second test case, which can be called an improved layout with the same illuminance level as the existing one. For easy understanding, this condition will be referred to as the '30 lux environment' for the remainder of the study.

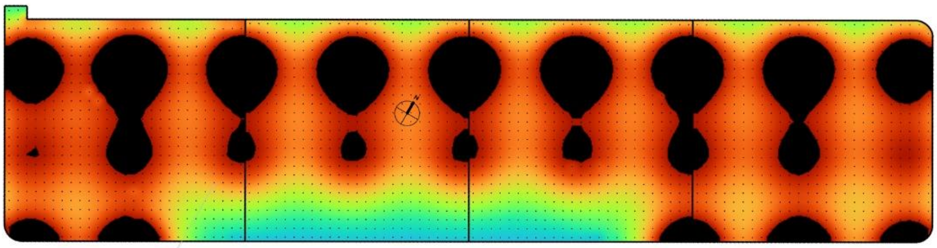

Figure 10: Illustration showing the simulation results of a proposed emergency lighting system of the riding hall having fewer luminaires with higher power.

3.3.2.3 Third scenario

Furthermore, a set of simulations were conducted to achieve an average illuminance level of 15 lux, which is equal to the minimum requirement of 5% of the regular lighting system. A similar approach to the previous scenario was taken to determine the most suitable combination of lighting layout, number, and type of luminaires. The optimized case of this set of simulations results in a mean and median illuminance of 15 lux as shown in Figure 11, thereafter known as the '15 lux environment'.

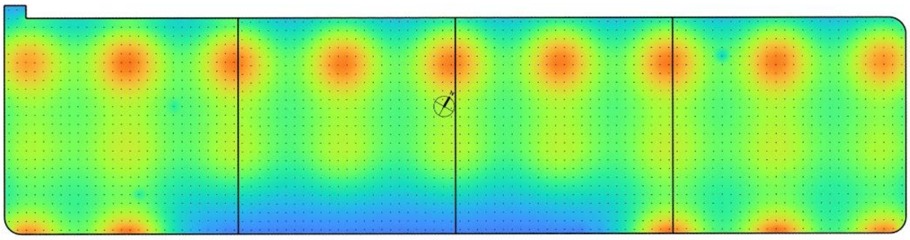

Figure 11: Illustration showing the simulation results of a proposed emergency lighting system of the riding hall having existing luminaires in fewer numbers.

The lighting layout used for the proposed second and third scenario is illustrated in Figure 12.

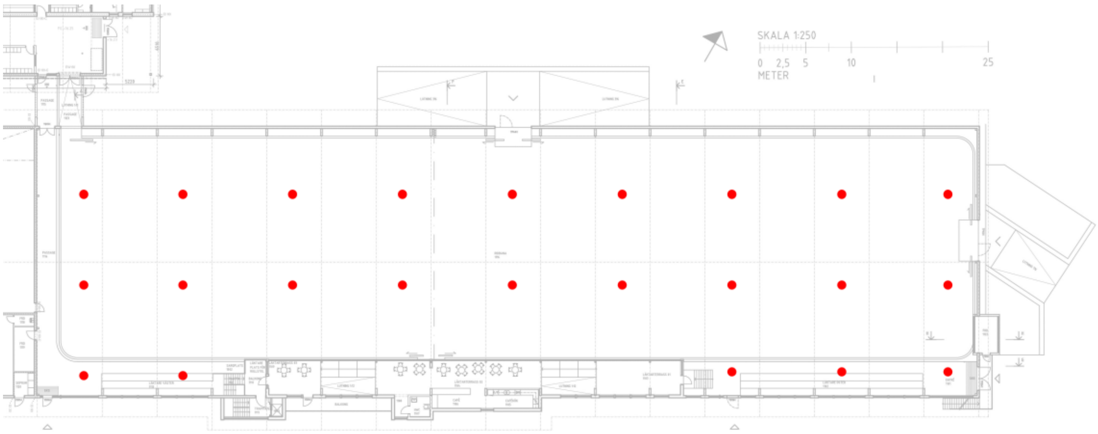

Figure 12: Proposed security lighting layout with reduced number of luminaires.

3.3.2.4 Comparison of the three different cases

The three final cases were chosen carefully so that they can reasonably indicate how well the participants can see in different lighting conditions. Comparing the 300 lux regular environment with the other two cases of emergency lighting can shed light on how well a person can see in an emergency compared to a regular lighting situation. Furthermore, comparing the test results of the 30 and 15 lux environments on participants can indicate if the requirement of 5% illuminance during an emergency situation is sufficient or not.

3.3.2.5 Adaptation range of the test scenes

The three cases were analysed to understand which light adaptation range they fall into. To do the analysis, false-colour RADIANCE renderings were performed in Climatestudio. The colour scale used for this study is depicted in Figure 13.

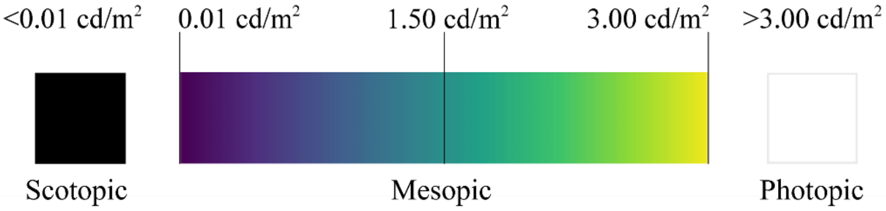

Figure 13: A colour scale showing the limits of mesopic range (shown in blue to yellow as a gradient). Scotopic range (values lower than 0.01 cd/m^2) is shown in black while photopic range (values higher than 3.00 cd/m^2) is shown in white.

The equirectangular rendering of the 300 lux environment (Figure 14) shows that the scene is completely within the limit of photopic range. Both renderings for the 30 lux environment and the 15 lux environment in Figure 15 and Figure 16 respectively show that they are predominantly within the range of mesopic adaptation. Some areas near and directly below the luminaires show that they have a luminance value of over 3 cd/m^2, however they do not have much impact on the overall space and can be neglected.

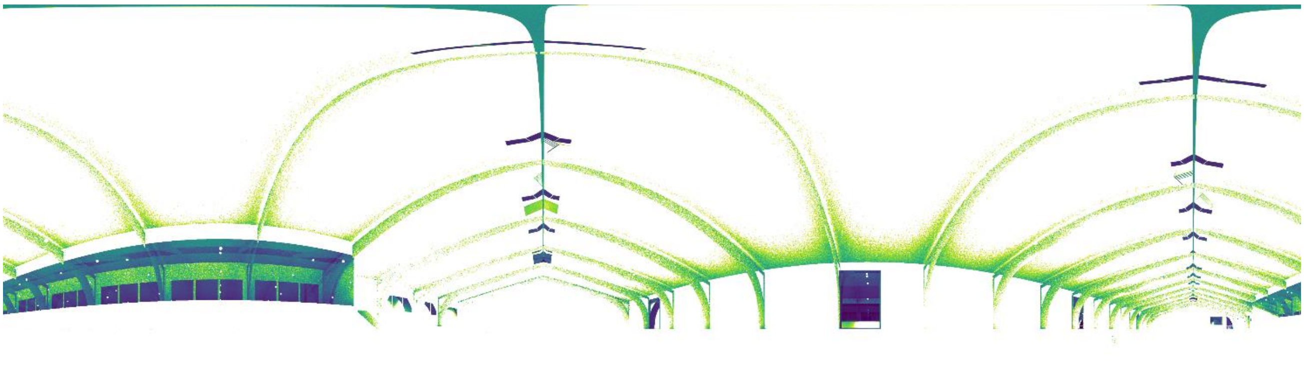

Figure 14: A false colour rendering showing the luminance level of the 300 lux environment, suggesting that it is mostly within the photopic range.

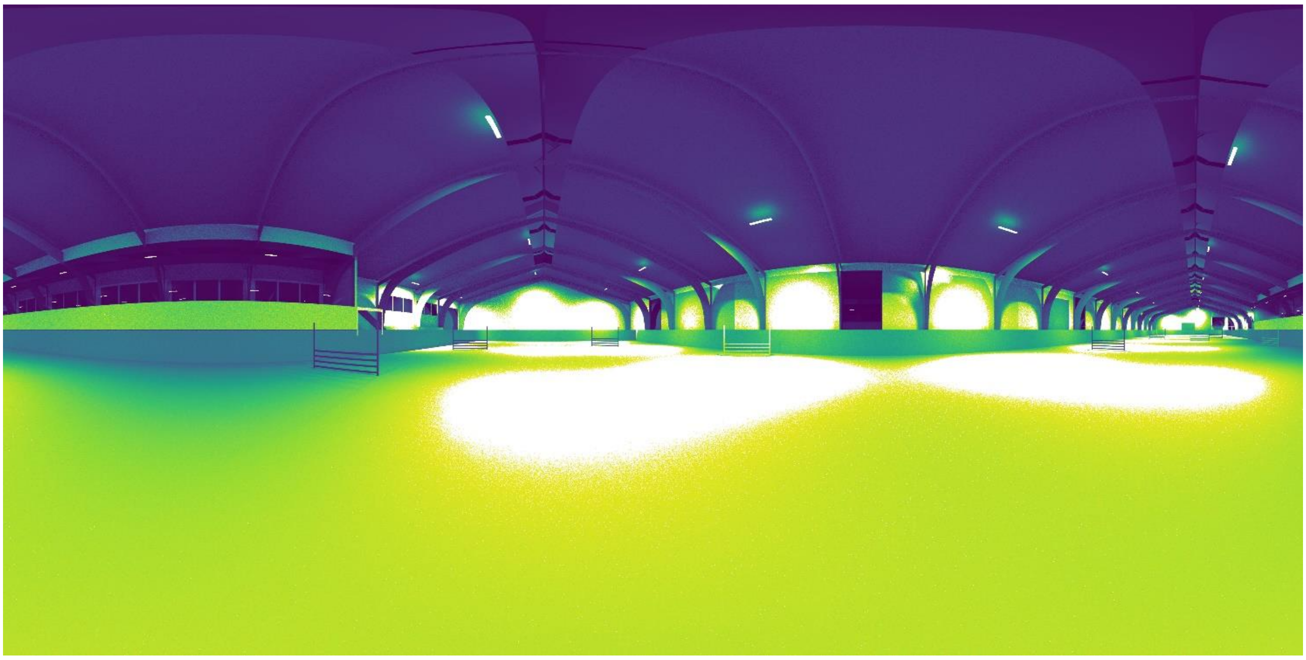

Figure 15: A false colour rendering showing the luminance level of the 30 lux environment, suggesting that it is mostly within the mesopic range.

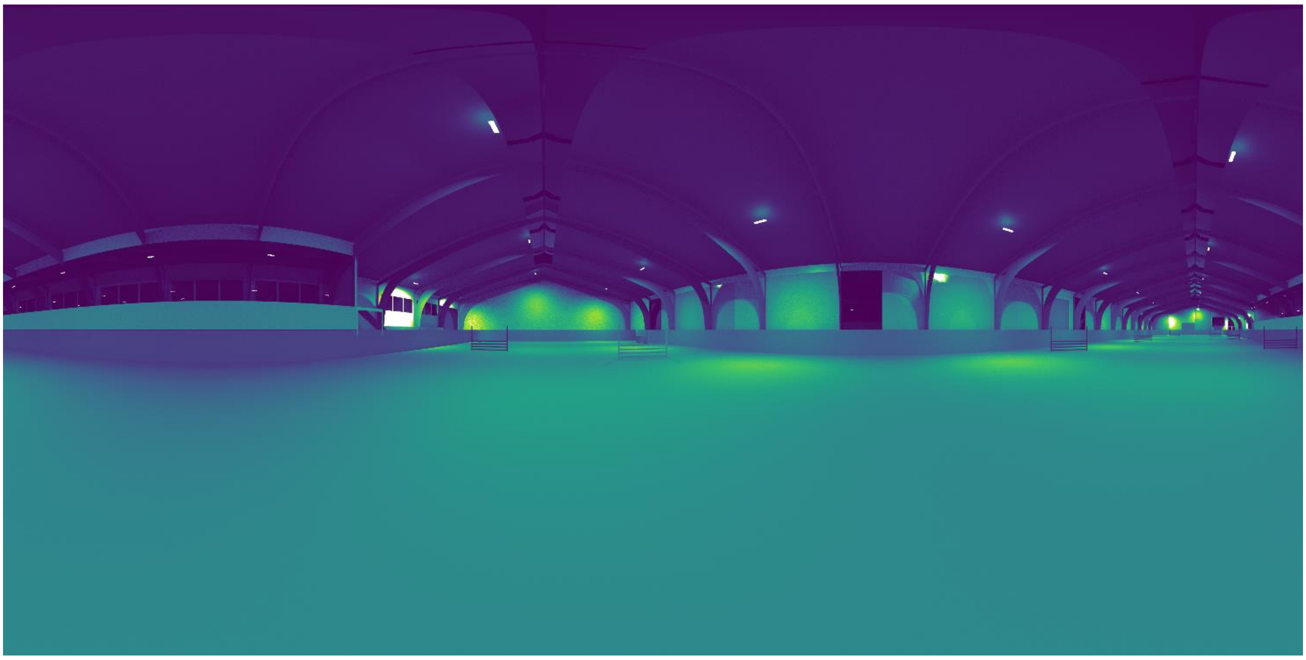

Figure 16: A false colour rendering showing the luminance level of the 15 lux environment, suggesting that it is almost completely within the mesopic range.

3.3.3 Static versus dynamic renderings

The Unity game engine was used to create the VR environment for the experiment. Unity has the capability to create fully immersive experiences, where the participants can move around the space freely. For this purpose, 3D models can be brought into the Unity environment from most 3D modelling software. However, dynamic rendering of the whole model is still not fully possible to achieve with RADIANCE and only static renderings can be extracted. According to Ward (2021), the developer of RADIANCE, there is a workflow to provide immersive experience for simpler 3D models. In this process, all surfaces need to be rendered individually as parallel projections, and these renderings can be used as textures for the same building geometry in Unity. However, this workflow is only possible for small projects with simple geometry, and has some limitations when windows are involved. This workflow was not possible in this particular project as the horse riding hall is an exceptionally large building with a complex geometry of the roof and wooden structural members. Although there are some other market-standard software that can do lighting simulations, RADIANCE is the most reliable one to provide scientifically validated lighting simulations (Jarvis & Donn, 1997) and therefore was used for the purpose of this study. Moreover, the 3D model of the horse riding hall is too complex for such software to manage which are predominantly designed to work with simpler buildings and interior spaces.

3.3.4 RADIANCE renderings for VR environment

The final renderings of the scenes were performed with RADIACNE engine embedded in the Climatestudio plug-in for Rhinoceros 3D. Equirectangular renderings were created for each scene where a single viewpoint was taken for all the scenes. The viewpoint was set to be (0,0,0) to simplify the process in later phases. Different coloured objects similar to the obstacles in horse riding halls were placed inside the scenes. Each of the scenes had a fixed number of objects with different colours: Red, Blue, and Yellow. The placement of the objects was randomized for each scene and these objects were used in the later phases for object identification inside the VR environment. An instance of object placement inside the building model is visualized in Figure 17. The final renderings for the three environments can be seen in Figure 18-20.

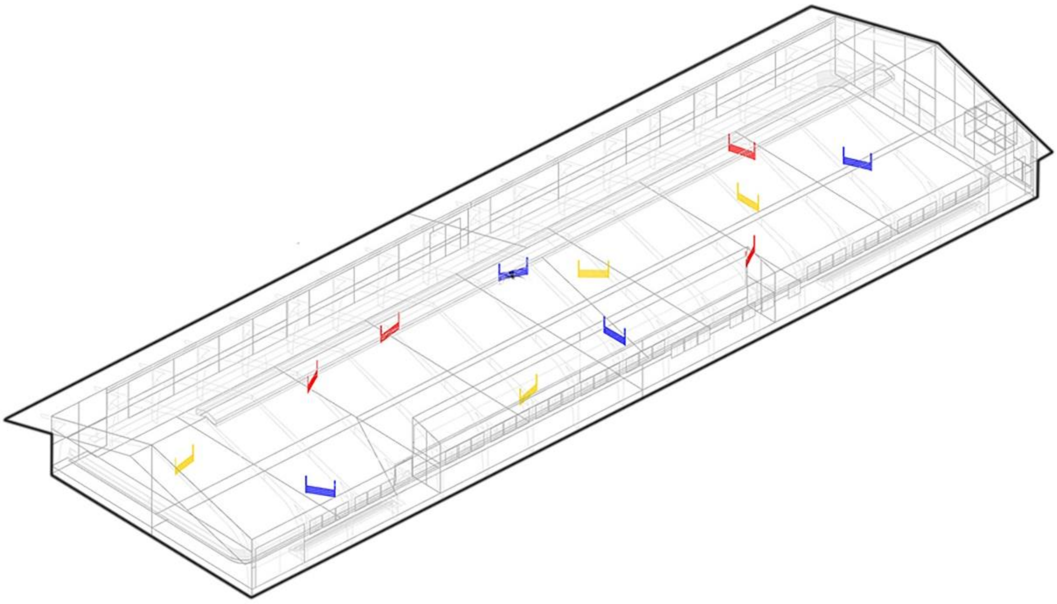

Figure 17: An illustration showing different coloured obstacles placed inside the 3D model of the building.

Figure 18: An equirectangular rendering with the existing electric lighting of the riding hall (300 lux environment).

Figure 19: An equirectangular rendering with the proposed security lighting of the riding hall by installing fewer luminaires with higher power (30 lux environment).

Figure 20: An equirectangular rendering with the proposed security lighting of the riding hall by installing the existing luminaires in fewer numbers (15 lux environment).

3.3.5 Creating the interactive environment

The equirectangular renderings for the three test cases were imported in Unity as a skybox material in three different scenes. These scenes can be experienced in 360° in the VR environment. As the obstacles inside the scenes are part of the rendered images, they cannot be interacted directly in the VR environment. To solve this issue, invisible Unity game objects were placed in front of the obstacles. This basically means that whenever the participants looked at the areas where the obstacles were in the renderings, they were actually looking at the invisible game objects (Figure 21*:*). A C# script from a previous study (Khanie et al., 2020) was modified and applied on the game objects so that when they were 'hit' by the eye gaze of the participants during the experiment, the object data and timestamp were recorded. Another C# script was written to save this data as a

.csv file format. The eye movement data of the participants were also saved as vector coordinates in a different .csv file. The C# scripts are presented in Appendix C.

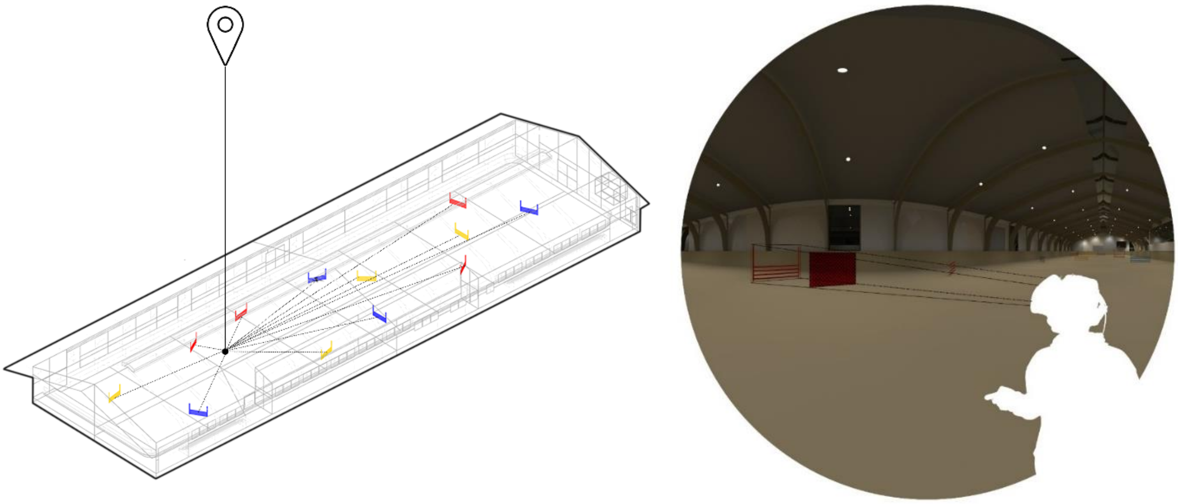

Figure 21: A schematic illustration showing the distance *of obstacle objects* from the viewpoint *(left) and the process of placing invisible objects (represented by the solid red surface) in Unity game engine in front of the areas of the rendering where the obstacles are located (right).*

3.3.6 Data outputs

Two sets of data were primarily extracted from the experiment. The first set of data includes the number and colour of objects that were 'hit' by eye gaze of the participants during the experiment. This data can be used to compare the visibility of objects in 3 different scenes based on their colour, distance from the observer, and number of identified objects. The second set of data includes the vector coordinates of the participants' eye movement during the experiment. This data can be merged with the renderings to visualize and analyse where the participants' gazes were directed towards while they were in the VR environment. Another source of data was the questionnaire survey from the experiments. This set of data provided insight into the demographic data and participants' feedback.

3.3.7 Experiment process

The experiment was conducted in an indoor space with ample daylight. The experiment started with two pre-tests- a colour deficiency test followed by a visual acuity test. The main test was performed by playing the three different scenarios to the test participants in the VR environment. The sequence of the scenes was determined using a balanced order of presentation, using the Latin square system (Fisher, 2008). In each scene, the participants were asked to identify how many objects of a specific colour they could see inside the VR environment. This process was subsequently repeated for the other two colours. The sequence in which the different coloured objects were to be recognized was also set by a Latin square system. After the three scenes were shown to the participants, the experiment concluded with a questionnaire survey. The experiment process is visualized in Figure 22.

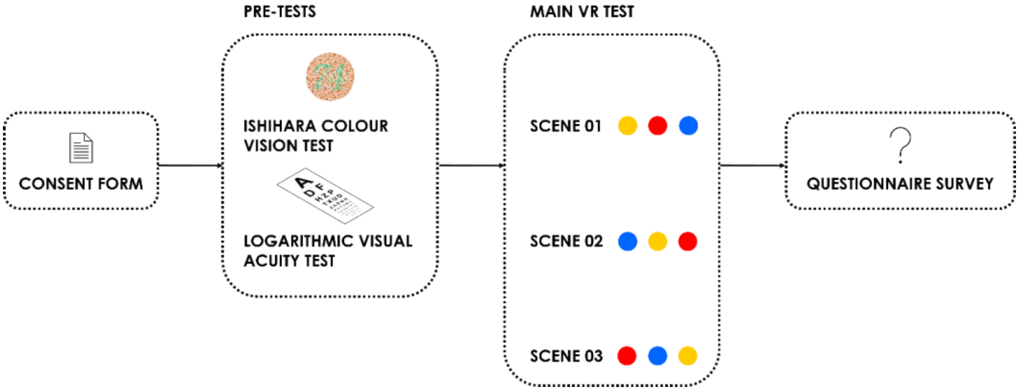

Figure 22: An illustration showing the VR experiment process.

3.3.7.1 Subject selection

The initial experiment was performed on students of Lund University to ensure the workability of the system. Subsequently, instructors of riding schools and a representative from Svenska Ridsportförbundet were selected as subjects for the final experiment. Participants of different age and gender were selected for the study to avoid any bias.

3.3.7.2 Equipment

Experiments were conducted with a mobile VR setup that can be easily taken to different riding schools. The setup consisted of a Dell Precision 7550 mobile workstation and a Vive pro eye VR HMD including a VR headset and two base stations. The colour vision deficiency test was achieved using an Ishihara Colour Vision Test (Clark, 1924) while the visual acuity test was done by a Logarithmic Visual Acuity Chart (Bailey & Lovie, 1976), which are standardized tests in optometry.

3.3.7.3 Performing experiments

The initial experimental setup was carried out in one of the study rooms in a student housing in Helsingborg, where the building occupants were invited to take part in the study. On the second day of the test, the setup was taken to a study house of Lund University called Helsingborgen. On the third day of the experiment, the setup was finally taken to the Malmö Civilia Ryttareförening building, which is the case building for this project. Riding instructors as well as one representative from the Svenska Ridsportförbundet were invited to take part in the experiment and give their feedback.

The same experimental procedure was followed for all nine test participants. The test started by greeting the participants and have a brief discussion explaining the project and its objectives. The discussion continued and the whole experimental process was described in verbal form. The participants were then asked to read and sign the consent form presented in Appendix A. As first pre-test, the participants were shown the Ishihara Colour Vision Test to determine if they had any level of colour vision deficiency. Afterwards, their visual acuity was tested individually for both eyes using a Logarithmic Visual Acuity Chart.

For the main experiment, the participants were asked to wear the HMD and adjust it according to their preferences. The lens distance was adjusted when needed to match with the eye pupil distance of the participants. The participants were asked if they could see the default VR background scene. The first test scene was then played, and the participants were asked to identify objects of different colours in a pre-determined sequence. The participants were allocated one minute to identify all the objects in a particular scene. Their responses were recorded, and test data was automatically saved on the computer. The participants were asked to close their eyes for one minute before the start of the next scene. The same process was followed until all three scenes were shown in a randomized order of presentation and the test data was recorded. The scenes were shown in a pre-determined order which was unique for each participant. Visual adaptation time while experiencing a dark scene right after experiencing a bright scene was not taken into consideration. This is due to the fact that such situation may also occur in real-life emergency situations and the occupants of the building may not get any time to adapt to the dark environment.

After the successful conclusion of the test, the participants were asked to take part in a questionnaire survey with the aim to get their feedback on the test.

4 Results

The outcome of the project is discussed in this section. The primary results from the first phase of the study come from the simulations performed in Climatestudio. In the second phase of the study, VR test was conducted on participants, and the results were obtained and analysed from the object tracking data, eye movement data, and the questionnaire survey.

4.1 Initial simulations

The initial simulations comparing the different lighting conditions show that the regular lighting system of the building can possibly provide the required illuminance for the specific building type, 300 lux. The security lighting system provides 29 lux of mean illuminance, which is 10% of the regular lighting system. Although the requirement stands at 5% of the regular lighting system, an overestimation in this case may prove to be beneficial, as it was mentioned before that some building regulations require 10% security lighting for critical spaces. The simulations further show that the proposed lighting layout with fewer luminaires and higher power can successfully match the existing lighting system. Thus, reducing the number of luminaires can be an option to reduce the overall installation cost for the emergency lighting system. Furthermore, keeping the same luminaires while reducing their number can bring down the illuminance level to the minimum requirement of 5% security lighting. This can further reduce the installation cost. However, it must be ensured beforehand that this minimum requirement of security lighting is appropriate for occupants to see in an emergency condition. This was further investigated in this project by doing the tests on participants in the VR environment.

4.2 Test participants: Demographic data

The test was conducted on a total of nine participants. The list of participants included three students of Lund University, one architect, four riding school instructors, and one representative from Svenska Ridsportförbundet. Among the nine test participants, four were male. Most of the participants were in the age group of 18-40, while only two participants were in the range of 40-55. Four participants had spectacles during the experiment. One participant joined the test without spectacles, but he confessed that he uses a prescription glass from time to time. The other participants do not require spectacles for regular use. None of the participants had any lenses while performing the experiment. Three of them have experienced a VR environment before.

4.3 Pre-tests: colour deficiency test and visual acuity test

Two pre-tests were conducted before running the final VR test on participants. The results from the colour deficiency test show that eight of the participants had normal colour vision, while one of the participants had a Red-Green colour deficiency. The visual acuity test was done on participants while wearing the spectacles for those who used the same spectacles in the VR environment. The results show that four of the participants had perfect vision in their left eyes, while five of them had perfect vision in their right eyes. Two of the participants had difficulty recognizing letters from a three meter distance with their left eyes, while one of the participants struggled to see with his right eye. It is to be noted that many of the participants were riding school instructors, thus having very high functioning vision in the first place. A summary of the visual acuity test is shown in Figure 23. A 20/20 vision means that a person can see clearly at a 20 feet (six meter) distance that is supposed to be seen at this distance in regular conditions. A 20/40 vision means that the person needs to be at a 20 feet (six meter) distance to see things that a person with normal vision can see from a 40 feet (12 meter) distance.

Figure 23: A graph showing the summary of the visual acuity test.

4.4 VR test on participants

4.4.1 Object identification

The participants were asked during the experiment how many objects of different colours they could see. At the same time, the eye gaze tracking technology was used to analyse how many objects the participants could see. Most of the participant could successfully locate most of the objects, although they mentioned facing some difficulties for specific scenes, specific colours, and distant objects. The difficulty to locate the objects was reflected in the object identification data derived from the eye tracking feature of the HMD. This indicates that the objects that the participants could see but found it difficult to do so, may not have been detected either during the eye movement tracking. Thus, object identification results from the eye movement data were lower than the verbal responses in most cases. Object identification data of one participant was kept out of study due to hardware malfunction.

Figure 24 illustrates the object tracking data of different scenes depending on their distance from the viewpoint. All the objects were located by at least three test participants irrespective of their distance. The blank triangular space on the left of the graph indicates that fewer number of object identification, i.e. identified by three or four participants, occurred only at a distance higher than 15 meters. The graph suggests that the longer the distance was from the viewpoint, the objects were less likely to be identified by the participants. The blank triangular space on the right of the graph indicates that higher identification of objects by the participants, i. e. identified by seven to nine participants, occurred only when the distance was lower than 20 meters. Objects identified by five or six participants were distributed almost evenly according to their distance from the viewpoint.

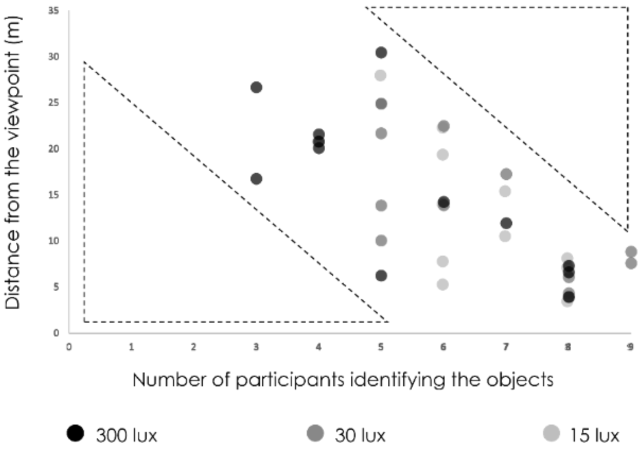

Figure 24: A graph showing the number of participants identifying the objects depending on the distance from the viewpoint.

Figure 25 illustrates the instances of occurrence of specific number of object identification in different scenes. It can be seen that one and two object identification instances were higher in 15 lux environment compared to the 300 lux and 30 lux environment. On the other hand, four object identification instances were similarly high for 300 lux and 30 lux environments, but it was low for 15 lux environment. It can be concluded that higher number of object identification was less frequent in the 15 lux environment while lower number of object identification was more frequent. Yellow and Red object identification was lower in the 15 lux scene while Yellow object identification had the lowest average value. Blue object identification seemingly did not get impacted much by the change of the lighting condition. This is expected as humans have a higher sensitivity for blue colours in the mesopic and scotopic range called Purkunje effect (Anstis, 2000), and the light sources for this study was rich in blue light.

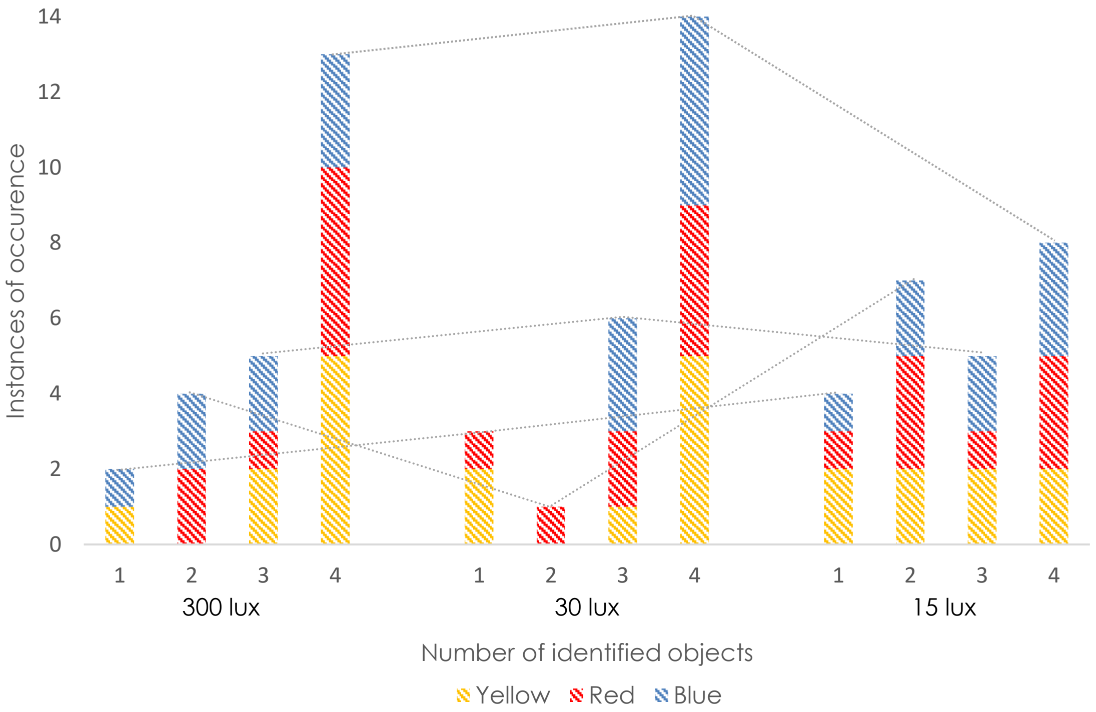

Figure 25: A graph illustrating the instances of occurrence of specific number of object identification in different scenes.

Figure 26 suggests that average total object identification did not differ significantly between the 300 lux and 30 lux environments. However, total object identification was lower in the 15 lux environment compared to the other ones.

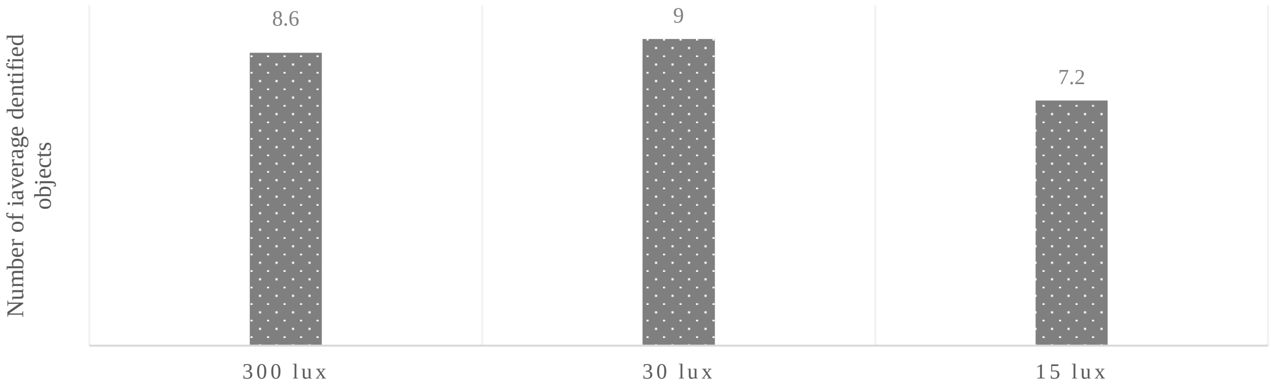

Figure 26: A graph showing the number of average total identified objects in each scene.

Figure 27 shows comparison of total object identification by each individual test participant. Object identification in 30 lux environment was higher than or equal to 300 lux environment for six out of eight participants. This indicates that their vision may not have been compromised in spite of the low light level. Three out of four participants wearing spectacles identified fewer objects in 15 lux scene compared to the 300 lux scene. Six participants identified fewer or equal objects in 15 lux scene compared to the 30 lux scene. The participant having colour vision deficiency (P04) evidently did not face any major problem to identify objects. However, he mentioned afterwards that it was harder for him to distinguish blue and red objects in darker environments. It is to be mentioned that the participant in question is used to gaming and VR HMDs, therefore it may have been easier for him to adjust to the test setup.

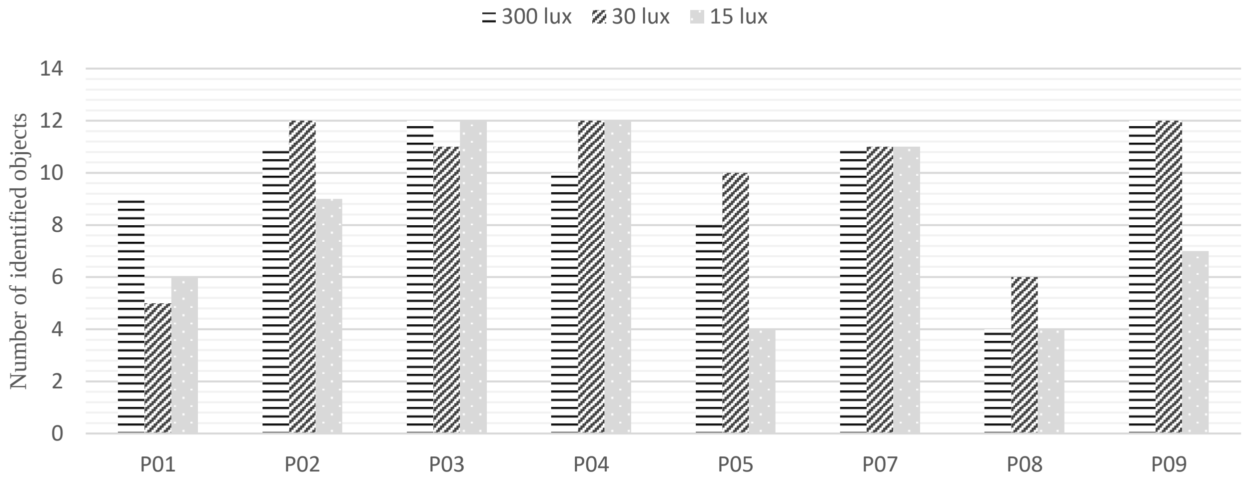

Figure 27: Total object identification by individual test participants.

4.4.2 Questionnaire survey

4.4.2.1 Feedback on side effects

Wearing VR HMD for a longer period can cause dizziness, nausea, and eye fatigue (Lavoie et al., 2021) among other symptoms. The VR part of the test required the participants to wear the HMD for approximately five minutes, with two one-minute breaks between three scenes. The participants were asked to close their eyes while changing scenes. Most participants did not mention any side effects. The first participant reported mild headache and dizziness, who was also the person who found it hard to focus while inside the VR environment. It is to be mentioned that the first participant volunteered to set up the VR scenes and experienced it for a longer period compared to the other participants. It can be concluded that, the experiment process was less likely to cause any serious side effects for the participants if they are using the VR HMD for a shorter period.

4.4.2.2 Feedback on VR experience

Six participants found it harder to find objects located farther away, while seven participants reported that it was harder to find objects of a specific colour. While all of them mentioned yellow objects to be the hardest to find, two participants also reported that red objects were harder to locate as well. All participants could understand that one of the three scenes was very bright compared to the other two scenes. When asked if it was harder to locate objects in the darker environments, five participants agreed. Four participants could find a difference between the two darker environments, most of them answering that one of them was darker than the other. This indicates that the 30 lux environment and 15 lux environment were distinguishable by almost half of the participants. The participants rated the experience of using the VR headset out of 10, and the average was 7.9. When asked how realistic the VR environment was, the participants gave an average rating of 7.9.

4.4.2.3 Individual responses

The individual feedback of the participants was recorded for further analysis. The first participant mentioned that the VR HMD was heavy and harder to manage while wearing spectacles. While the Vive Pro Eye is the most suitable HMD for doing research involving eye movement data, the model is indeed comparatively heavier than other market standard HMDs. The second participant felt that it was easy to identify and locate objects of different colours in all the scenes. The third participant pointed out that the objects that are not perpendicular to the observer were harder to identify. The participant pointed out that the screen went completely white a few times during the experiment, which was fixed for the subsequent tests. The participant also brought up the topic of adapting to different lighting conditions, which was discussed in this report in detail. The fourth participant suggested that a pre-test could be designed to check if everything was okay with the VR HMD before starting the real experiment. The participant also pointed out that low resolution of the rendered images can cause problems to identify objects. While the scenes were rendered in a reasonably high resolution, the Unity game engine and the VR HMD reduced it to some extent. The fifth participant felt comfortable in all three scenes and liked taking part in the experience. The sixth participant pointed out that as the main objective was to find out the objects, the lighting conditions were overlooked. Thus, it was difficult to answer if they could find any difference between the lighting conditions. The seventh and eighth participant found the bright scene to be the most comfortable. The ninth participant was curious to know how low the lighting needs to be before it gets difficult to leave the riding hall, which is one of the main objectives in this study.

5 Discussion and conclusions

This thesis investigated security lighting in horse riding halls by using a methodology based in VR. The study showed that although there are some standard guidelines to follow regarding the security lighting design of agricultural and sports facilities, the handbooks and building codes did not refer to any scientific research behind the requirements. The study indicates that better security lighting conditions can be achieved by informed decision making in the design process gained from a proper and functioning simulation and visualization methodology. Such initial studies can help avoiding unforeseen complications and mistakes during the building construction and operation phase. Furthermore, installation cost can be reduced with lower installed power and better lighting design.

The results of this study indicate that some of the existing requirements are not sufficient in test environments, and thus require further full-scale scientific research. The existing security lighting system was found to have two times more illuminance than the minimum requirement mentioned in the handbook. The study investigated visibility of objects of different colours in varying distances in different lighting conditions. The test results show that object recognition by the participants for the higher threshold of 10% security lighting compared to the general lighting condition of the building did not differ to a high degree. On the other hand, the minimum security lighting requirement of 5% resulted in lesser object identification. Although literature studies suggest that 5% (15 lux for the case building) illuminance is sufficient for the building occupants, the unavailability of required adaptation time made it difficult for the participants to locate and identify objects. Furthermore, many test participants found it difficult to locate objects of specific colours, objects located at a distance, and in the darker environments. The methodology can be further developed, and the outcomes can be utilized to get a better understanding about the appropriateness and performance of lighting design iterations.

The major limitation in this project was not being able to measure the illuminance level of the study building in accurate conditions, which would have helped to validate the model and solidify the decision-making process. Another major limitation of not being able to make the VR environment completely immersive was imposed by the software used in this study. The ability to test the lighting conditions in VR using a scientifically validated software while the participants can move around freely through the spaces might be the next innovation to develop for lighting professionals. As this was intended as a pilot study, there were very few test participants. However, more test subjects are needed for practical implementation of the methodology. Statistical analysis conducted for a higher number of test subjects may present new insights. Moreover, the study did not exclusively investigate and incorporate tone mapping for the VR environment and relied mostly on the default settings of the render engine and regular calibration of the VR HMD. Further study into this can help to get more reliable and realistic results from the test methodology.

VR technology is mostly used in lighting design for qualitative research in recent times. This study emphasizes on the possibility of utilizing VR technology in lighting design process through quantitative research. As a fairly new field of study, software-related limitations are a major hurdle to cross here. However, recent development in technology has shown great promise for the future. The AEC industry has been experiencing a major shift towards emerging technologies in the recent decades, and it can only be assumed that it will continue to grow in an ever-changing manner. The industry has incorporated advanced Computer Aided Design (CAD), Building Information Modelling (BIM), computational design, digital fabrication, Building Performance Simulation (BPS) among countless technologies. Virtual Reality is a comparatively new but promising technology for the future of the industry. Technology companies have started to prepare for an immersive virtual world in near-future, and AEC industry will surely follow. It can only be assumed that more and more practices will put emphasis on adapting virtual reality in the design and construction process. This is an exciting time to work on the use of VR in AEC industry, and more research is required to remove the technological obstacles.

6 Future work

This project was primarily focused on the requirements for security lighting in horse riding halls and how well humans can see in a simulated VR environment under these conditions compared to a general lighting condition. The study did not go into detail about the horses' vision and behaviour during such emergency conditions, which is also crucial to come to any decision or conclusion. Further studies must include experts from hippology to understand the impact of security lighting conditions on horses, and a completely different type of methodology must be developed for that.

The study can be broadened to include more building types facing similar issues such as museums, auditoriums, warehouses etc. A methodology similar to the one developed for this project can be replicated for other building types. Considering the importance of the optimization process of the security lighting system, it can be investigated further to be able to implement in real projects.

Moreover, this study developed a process to generate eye movement data of the participants under the test conditions. This data can be further analysed to understand the participants’ gaze direction behaviour. The analysis can shed light on occupant behaviour in low-light conditions, which can be crucial to make informed design decisions.

The test conducted for this project was created as a simple testbed in Unity. It is possible to potentially develop this into a lighting design application or game by integrating a User Interface (UI) with it. The developed application can be used by lighting design professionals to test their design iterations on test participants in a VR environment.

7 Popular science summary

Human eyes as living optical devices can do amazing things such as being able to see to some extent in a moonlit night even though the illuminance is lower than 1 lux most of the times. However, this is mostly true when human eyes are properly adapted to the dark environment, which may take up to 30 minutes. The lack of adaptation time in low light conditions in a building during an emergency such as a fire incident or power outage makes it a difficult affair for the occupants to see properly and safely evacuate the space as soon as possible.

Sweden, being situated very close to the Arctic Circle, experiences early sunsets during a major part of the year. The absence of sunlight makes electric lighting in buildings more important even in regular working hours. Local horse riding facilities in Sweden require 300 lux of average illuminance in the horizontal surface of the building during general lighting condition and 5% or 15 lux illuminance for 20 minutes during emergency. If such a situation occurs during an ongoing sports event after the sunset, the building occupants must rely on the security lighting system to evacuate safely.

The main objective of the project was to develop a methodology to test if such a lighting condition is sufficient or not during an emergency. Although the building occupants include both humans and horses, only human visual perception was taken into consideration for this study. Testing how well humans can see in an emergency lighting condition in the case building in reality is a time consuming and costly affair. On the other hand, computer-based simulations and testing can be done in Virtual Reality (VR) in relatively shorter time and minimal cost. Furthermore, this opens up the possibility to develop several lighting design iterations and test them to achieve a comparative analysis. Therefore, the scope of the project was to adapt a simulation methodology and develop a VR testing methodology to test different lighting conditions of the Malmö Civila Ryttareförening building on human subjects. For the purpose of the study, it was hypothesized that the ability to locate objects in different lighting conditions in VR is proportional to the ability to see in those lighting conditions in reality.

While the requirement for security lighting is set at 5% of the required general lighting according to the handbook by Svenska Ridsportförbundet, some other guidelines suggest it to be 10% for certain critical spaces where there might be risk of injuries and accidents. The intention of this project was to test both requirements as well as the general lighting condition of 300 lux to make a comparative analysis. The existing general and security lighting conditions were simulated, and two optimized design iterations were proposed to match the 5% (15 lux) and 10% (30 lux) requirements. Simulations also suggested that the general lighting condition was in photopic adaptation range while the security lighting conditions were predominantly in the mesopic adaptation range. The general lighting condition along with the two security lighting design iterations were chosen as the final three test conditions. These conditions were then rendered from a fixed viewpoint as equirectangular images in a scientifically validated lighting rendering software. The renderings were used to create the VR environment in a game engine. Invisible game objects were programmed and placed inside the virtual environment that can be coupled with eye gaze tracking technology to determine if the objects were seen by the participants.

The test was intended to be a pilot study for a future broader research and was conducted on nine participants for this project. The participants' feedback suggested that they faced difficulty to locate distant objects, objects of specific colours, and objects in darker scenes. Their feedback was in line with the eye gaze tracking and object identification data gathered from the tests. The test data suggests that the participants could identify more objects in 300 lux and 30 lux environments compared to the 15 lux environment. The results of this test indicate that the minimum requirement of 5% security lighting may not be enough for the participants to identify objects in a test environment. More test subjects and further work on the methodology is required to get a definitive answer.

The project can be further developed to conduct broader research for different building types. VR technology has already showed great promise in Architecture, Engineering, and Construction (AEC) industry, and the possibility to incorporate it in lighting design, simulation, and testing process is worth investigating. There are still major technological barriers to overcome, which requires intense research in the upcoming years.

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Appendices

Appendix A: Contents of the consent form

Informed consent under the Act (2003:460) on ethical review of research relating to humans, regarding voluntary participation in research on security lighting conditions in horse riding halls.

Please read all the information about the research below:

Background and purpose
The research aims to develop a Virtual Reality based simulation methodology for testing different lighting conditions in horse riding halls including regular lighting conditions in photopic range and security lighting in mesopic range i.e., low-light condition.

Participation in the research
Participation in this research is voluntary and not remunerated. The participants are chosen based on their expression of interest upon the researcher's request.

How does the research study work?
The study takes approximately 30 minutes for a single participant. The study is initiated by two simple pre-tests followed by the main test in a Virtual Reality environment. The first one is a colour deficiency test using the Ishihara Colour Vision Test. The second one is a visual acuity test using a Logarithmic Visual Acuity Chart. The main test is done using a Vive Pro Eye Head Mounted Display for Virtual Reality. The participants are shown different lighting conditions inside the virtual environment ranging from 15 lux to 300 lux of illuminance. The participants are asked to identify different coloured objects inside the virtual environment and their responses are recorded. While the participants are wearing the headset, their eye movement is also tracked and recorded for analysis. After successful completion of the tests, the participants are asked to fill up a questionnaire survey.

What are the risks?
Using VR headsets may cause some side-effects including and not limited to dizziness, eyestrain, headache, and nausea.

Are there any benefits?
Participation as a research person in this study provides an opportunity for increased insight into the importance of lighting conditions in an indoor environment.

Data and privacy management
The personal data of the participants will only be processed after their written consent. The participants' names will not be a part of any publication while demographic data such as gender or age group might be used for analysis and publication(s). The participants' responses and eye tracking data will also be used for analysis and publication(s) related to this research. The participants can refuse to answer any question or provide any personal data. Even if the participants agree to participate in the experiment, they can withdraw any time during the experiment if they are not comfortable with it. The participants can withdraw their permission to use data from the experiment that relates to them within two weeks after the test, in which case the material will be deleted.

Informed consent under the Ethical Review Act (2003:460)
- I confirm that I have received necessary written and other oral information about the research study.
- I give my consent to participate in the study and know that my participation is completely voluntary.
- I am aware that I can terminate my participation at any time during the test and without explanation.
- I allow my personal data to be recorded according to the information I have received and that collected data about me is stored and handled electronically by the researcher.

Name and date: Signature:

Appendix B: Contents of the questionnaire survey form

Name/Anonymous ID:

Age group: 18-40 40-55 55+ Prefer not to answer

Gender: Male Female Non-Binary Prefer not to answer

Did you have previous experience of using VR headsets? Yes No

Did you wear prescription glasses/lens during this experiment? Yes No

Specification of glasses/lens if any (power, progressive/single vision/bi-focal):

Do you have colour vision deficiency to the best of your knowledge? Yes No

Did you experience any dizziness, eyestrain, headache, or nausea, or any other symptom(s) during the experiment? Yes No

Specify if answered yes (optional):

Did you struggle to focus your eyes during the experiment? Yes No

Could you find any difference between the two low-light condition scenes? Yes No

Specify if answered yes (optional):

Did you feel it was harder to see/identify the objects in the low-light environments compared to the regular lighting environment? Yes No

Did you feel it was harder to see/identify objects of a specific colour? Yes No

Specify if answered yes (optional):

Did you feel it was harder to see/identify objects that are located farther away? Yes No

Specify if answered yes (optional):

Rate your experience of using the VR headset in a scale of 1-10 with 10 being the best.
1 2 3 4 5 6 7 8 9 10

In your opinion, how realistic was the virtual environment in a scale of 1-10 with 10 being the most realistic?
1 2 3 4 5 6 7 8 9 10

Briefly express your experience of the lighting conditions in the VR environment:

Additional comments and suggestion

Appendix C: Programming scripts

Script 01

```
using System.Collections;
using System.Collections.Generic;
using UnityEngine;

public class SimpleGaze : MonoBehaviour
{
    public Camera viewCamera;
    public GameObject cursorPrefab;
    private ToExcel toExcel;
    public float maxCursorDistance = 30;
    int objectCount = 12;


    private float tickSpeed = 0.2f;
    private float timer = 0f;
    private float timeToHit = 0f;
    private bool hasSentEye = false;
    private bool hasSentObject = false;

    private GameObject cursorInstance;

    private List<Vector3> vectorList = new List<Vector3>();
    private List<string> nameList = new List<string>();
    private List<float> timeToHitList = new List<float>();
    // Start is called before the first frame update
    void Start()
    {
        cursorInstance = Instantiate(cursorPrefab);
        toExcel = FindObjectOfType<ToExcel>();
    }

    // Update is called once per frame
    void Update()
    {
        tickSpeed -= Time.deltaTime;
        timer += Time.deltaTime;
        timeToHit += Time.deltaTime;
        if (tickSpeed <= 0)
        {
            UpdateCursor();
            tickSpeed = 0.2f;
        }

        if (timer >= 60 && !hasSentEye)
        {
            toExcel.WriteEyeCSV(vectorList);
            hasSentEye = true;
            Debug.Log("Has sent eye");
        }

        if (timer >= 60 && !hasSentObject || objectCount == 0 && !hasSentObject)
        {
            Debug.Log("Has sent object");
```

```
            toExcel.WriteObjectCSV(nameList, timeToHitList);
            hasSentObject = true;
        }
    }

    private void UpdateCursor()
    {
        Ray ray = new Ray(viewCamera.transform.position, viewCamera.transform.rotation * Vector3.forward);
        RaycastHit hit;
        if (Physics.Raycast(ray, out hit, Mathf.Infinity))
        {
            cursorInstance.transform.position = hit.point;
            cursorInstance.transform.rotation = Quaternion.FromToRotation(Vector3.up, hit.normal);
        }
        else
        {
            cursorInstance.transform.position = ray.origin + ray.direction.normalized * maxCursorDistance;
            cursorInstance.transform.rotation = Quaternion.FromToRotation(Vector3.up, -ray.direction);
        }

        if (hit.collider != null)
        {
            if (hit.collider.CompareTag("Box"))
            {
                Debug.Log("Hit " + hit.collider.gameObject.name + " after " + timeToHit);
                string tempName = hit.collider.gameObject.name;
                float tempFloat = timeToHit;
                nameList.Add(tempName);
                timeToHitList.Add(tempFloat);
                hit.collider.gameObject.SetActive(false);
                objectCount--;
            }
        }

        vectorList.Add(cursorInstance.transform.position);
    }


}
```

Script 02

```
using System.Collections;
using System.Collections.Generic;
using UnityEngine;
using System.IO;

public class ToExcel : MonoBehaviour
{
    string fileNameEye = "";
    string fileNameObject = "";

    private void Start()
    {

        fileNameEye = Application.dataPath + "/eye.csv";
        fileNameObject = Application.dataPath + "/object.csv";
    }

    public void WriteEyeCSV(List<Vector3> aVectorList)
    {
        TextWriter tw = new StreamWriter(fileNameEye, false);
        tw.WriteLine("X, Y, Z");
        tw.Close();

        tw = new StreamWriter(fileNameEye, true);

        for (int i = 0; i < aVectorList.Count; i++)
        {
            tw.WriteLine((int)aVectorList[i].x + ", " + (int)aVectorList[i].y + ", " + (int)aVectorList[i].z);
        }
        tw.Close();

    }
    public void WriteObjectCSV(List<string> aNameList, List<float> aTimeToHitList)
    {
        Debug.Log("ObjList has " + aNameList.Count);
        TextWriter tw = new StreamWriter(fileNameObject, false);
        tw.WriteLine("Name, Time");
        tw.Close();

        tw = new StreamWriter(fileNameObject, true);

        for (int i = 0; i < aNameList.Count; i++)
        {
            tw.WriteLine(aNameList[i] + ", " + aTimeToHitList[i]);
        }
        tw.Close();

    }

}
```


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