Developing VR Technology Tools for Lighting Research in Architecture in Compliance With Daylight Recommendations From the Standard EN 17037

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21 June, 2024

GDAŃSK UNIVERSITY OF TECHNOLOGY

WYDZIAŁ ARCHITEKTURY

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Scientific discipline: Architecture and Urban Planning

DOCTORAL DISSERTATION

Title of PhD dissertation: Developing VR Technology Tools for Lighting Research in Architecture in Compliance With Daylight Recommendations From the Standard EN 17037

Title of PhD dissertation (in Polish): Rozwijanie narzędzi technologii VR do badań nad oświetleniem w architekturze zgodnie z zaleceniami dotyczącymi światła dziennego z normy EN 17037

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Gdańsk year 2024

Acknowledgements

This work is dedicated to the memory of my grandparents, Anna Łucja and Wacław Bladowski, and Helena and Henryk Bednarek. Their loving guidance, wisdom, and support have been the foundation of my personal, professional and academic growth.

I also wish to extend my deepest gratitude to my supervisor, Professor Justyna Martyniuk-Pęczek, for seamlessly introducing me to the academic world.

Contents

Acknowledgements 3

I Subject of the study 1

1 Introduction 2

1.1 Motivation . . . 2
1.2 Justification of the Research Topic . . . 3
1.3 Identification of the Research Problem and the Subject of Research 4
1.4 Research Questions . . . 5
1.5 Goals . . . 5
1.6 Thesis Statements . . . 6
1.7 Scope of Work . . . 6
1.8 Methodology . . . 7
1.9 Structure of the Thesis . . . 9
1.10 Glossary . . . 11

2 Virtual Reality in the Context of the Evolution of Informational Media 16

2.1 History and Development of Virtual Reality . . . 16
2.1.1 From Cave Paintings to Virtual Reality . . . 16
2.1.2 Brief history of VR technology . . . 23
2.1.3 VR as a Milestone in the Development of the Media Used in Education . . . 27
2.1.4 Accelerating Digital Transformation: The Role of VR and AR During the COVID-19 Pandemic . . . 27
2.2 Conceptualizing and Defining Virtual Reality . . . 30
2.2.1 Milgram's Continuum of Reality . . . 31
2.2.2 Burdea's Triangle: Interaction, Immersion, and Imagination . . . 31
2.2.3 VR Taxonomy Approach . . . 31
2.3 The Multifaceted Applications of Virtual Reality . . . 32

2.4 Conclusions 37

3 Key Aspects of EN 17037: Daylighting in Buildings **39**
3.1 Introduction 39
3.2 EN 17037: Daylighting in Buildings 42
3.2.1 Key Sections and Annexes of EN 17037 42
3.2.2 Detailed Section on View from the Window 44
3.3 Categories of Measurements in Daylighting 48
3.4 Survey on the Usage of VR in Lighting Research and Lighting Design Practice Under
IEA SHC Task 70 50
3.5 Conclusions 50

II Research and Analysis: Utilizing VR Tools - An Overview of Practices and Technologies **52**

4 Utilizing VR in Lighting Research and in Practice **53**
4.1 Introduction to VR in Research and in Practice 53
4.2 Focus on VR in Daylight Research 58
4.2.1 Comparison Between VR and Traditional Daylighting Analysis Methods 60
4.2.2 Overview of the SHC IEA Task 70 Survey 62
4.3 Conclusions 63

5 Hardware and software for VR in Research **65**
5.1 Wider Analysis of VR Devices and its Development 65
5.1.1 Evolution of VR Devices 66
5.1.2 Meta Quest 2 66
5.1.3 PlayStation VR2 66
5.1.4 HTC Vive Cosmos 67
5.1.5 Emerging VR Devices 67
5.2 VR Software and Examples 69
5.2.1 Development Platforms 69
5.2.2 VR Software Examples 70
5.3 Uncanny Valley in VR 70
5.4 Conclusions 73

III Building and Testing the Author's VR Tools for Daylighting and Architectural Research **74**

6 Pilot tools - from the most common to perfect scenario **75**
6.1 Introduction 75
6.2 Walkthrough Tool - Most Common Scenario 76
6.2.1 Background 76
6.2.2 Features 78
6.2.3 Methodology 81
6.2.4 Conclusions 83
6.3 ALTO VR - Perfect Scenario 86
6.3.1 Background 86
6.3.2 Features 87
6.3.3 Methodology 89
6.3.4 Conclusion 91

7 Arch ViewR **94**
7.1 Introduction 94
7.2 Features 97
7.2.1 Fully Implemented Features 97
7.2.2 Partially Implemented Features 97
7.2.3 Not Implemented Features 98
7.3 System Design and Modularity of the Main VR Tool 99
7.3.1 Key Components of the Main VR System 99
7.3.2 System Workflow 102
7.3.3 Benefits of a Modular VR System 102
7.4 Banks as a Data Repository 103
7.5 Overall Development Process Overview 104
7.5.1 Design Overview 104
7.5.2 Code Overview 106
7.6 Conclusions 116

IV Arch ViewR - Capabilities, Evaluation and Conclusions **117**

8 Results and Pilot Testing of the Arch ViewR **118**
8.1 Introduction 118
8.2 Tool as a Main Result 118
8.3 Need to Test the Tool 120
8.4 Gdańsk as a Case Study for the Arch ViewR Bank System 122

8.4.1 Location Bank 124
8.4.2 Urban Bank 125
8.4.3 Architectural Bank 129
8.5 Pilot Experiment Design Overview of the Arch ViewR 131
8.5.1 Methodology 131
8.5.2 Survey Design and Implementation 133
8.6 Pilot Testing Results of the Arch ViewR 134
8.6.1 Pre- and Post-experiment Questionnaire Comparison . . 135
8.6.2 Landmarks: The Lures of the Landscape 138
8.6.3 Questionnaire Answers and Experiment Results Comparison 140
8.6.4 Analysis of the Numerical Data Obtained During the Experiment 142
8.7 Conclusions 156

9 Summary **157**
9.1 Lessons Learnt for Designing VR Experiments in Research 159
9.2 Recommendations and Future Research 162

A Appendix **182**
A.1 Complete Code Listing 182

B Result Screenshots **199**

Part I

Subject of the study

Chapter 1

Introduction

I could either watch it happen or be a part of it.

Elon Musk

1.1 Motivation

As I embark on this PhD journey, I reflect on my professional and academic experiences, which have been deeply intertwined with my passion for architecture and cutting-edge technology. My background is rooted in architecture, having earned both a Master's and an Engineering degree from the University of Technology in Gdansk. Over the years, this foundation has evolved, merging with my growing interest in virtual reality (VR) and its potential applications in various fields.

My career began with a series of roles that honed my skills in 3D visualization and graphics development. Working as a Junior 3D Generalist at Motion Imaging Ltd. and later at EON Reality, I developed a keen understanding of how virtual environments could be used to simulate and visualize architectural designs. These early experiences were pivotal, exposing me to the fast-paced, innovative world of VR and 3D development.

At EON Reality, I took on increasingly complex responsibilities, eventually managing global teams and developing AVR content. It was there that I recognized the transformative potential of VR in not just gaming or entertainment, but in practical, everyday applications such as architectural design and education. This realization inspired me to explore further, leading me to found my own VR company, AB2, where I spearheaded projects that ranged from immersive learning tools to firefighter training simulations.

My work with VR technology in these diverse applications laid the groundwork for my current research. As a VR expert of the IEA SHC Task 70 initiative, I have been actively involved in promoting low-carbon lighting and passive solar strategies. This experience has provided me with a unique perspective on how VR can contribute to sustainable architectural practices.

My PhD research at the Faculty of Architecture in Gdansk aims to bridge the gap between traditional (not VR methods) architectural methods and modern VR technology. By evaluating the view from windows in compliance with European Standard 17037, and exploring how VR can enhance this evaluation. My initial studies, involving various VR experiences and their impact on architectural design perception, have already yielded promising insights.

The journey of developing VR tools - from typical walkthrough simulations to advanced, interactive environments - has been both challenging and rewarding. These experiences have solidified my hope in the power of VR to revolutionize architectural design and evaluation.

Through this thesis, I aim to not only contribute to academic knowledge but also provide practical tools and methodologies that can be used by architects and designers globally. My professional journey, marked by continuous learning and adaptation, has prepared me well for this challenge. I am excited to delve deeper into this research, driven by a passion for innovation and a commitment to advancing the field of architecture through technology.

1.2 Justification of the Research Topic

As technology continues to evolve and permeate various aspects of our lives, it is transforming traditional modes of operation across a wide range of fields. One such field experiencing this transformation is architecture. The advent of Virtual Reality (VR), an immersive, interactive experience, has begun to redefine the approach and methods applied in architectural design and representation.

Practitioners and researchers are increasingly integrating Virtual Reality (VR) into architecture, moving beyond basic applications like virtual walkthroughs to explore its full potential (Wang, Li & Kho 2018). VR's ability to simulate real environments in three dimensions offers innovative opportunities in architecture, a field constantly seeking improved visualization and interaction methods (Wang et al. 2018). Studies have shown the evolution of VR technologies in architecture education, from desktop-based VR to immersive VR and Building Information Modelling (BIM)-enabled VR (Wang et al. 2018). VR has been identified as a key tool for enhancing experiential learning in architecture education (Asad, Naz, Churi & Tahanzadeh 2021).

This research, therefore, seeks to delve deeper into the specific application of VR in evaluating daylight and views from windows in residential design, adhering to the standards set by EN 17037. By doing so, the research hopes to identify potential new applications and methods in architectural design and representation using VR, expanding the horizon of possibilities in the field.

Given the rapid advancement and adoption of VR, a thorough understanding of its capabilities and potential uses in architecture, particularly in daylighting standards, is both timely and necessary.

1.3 Identification of the Research Problem and the Subject of Research

Throughout the course of utilizing different applications and learning about their characteristics and limitations, a consistent issue began to emerge: the optimization of views from windows in architectural design, specifically in terms of daylighting. The perception and utilization of natural light within a space is not just a component of aesthetic preference but has considerable implications on energy efficiency, user comfort, and overall architectural quality. Consequently, it stands as a significant yet complex issue in architectural design.

The subject of this research is the creation of a VR tool that facilitates architectural and urban research for individuals who are not VR developers. This tool aims to investigate and leverage the factors contributing to the optimal quality of the view from a window using VR technology. In a field where the manipulation of light and space is crucial, understanding how daylighting influences the perception of a view can lead to significant enhancements in architectural design and user satisfaction.

The research problem that underpins this study revolves around the lack of comprehensive understanding and application of the Daylighting standard EN 17037. While this standard provides guidelines for daylighting in buildings, its implementation often falls short of optimal due to a lack of in-depth knowledge on how various factors influence the quality of a view, such as the size and placement of windows, the orientation of the building, and the specific uses of different spaces within the building.

Through the use of VR, this study intends to simulate various scenarios and conditions to identify the key factors that contribute to the optimal quality of a view from a window, as dictated by the standard EN 17037. In doing so, the research aims to bridge the gap between theory and practice, enabling architects to make more informed design decisions and better implement the daylighting standard.

1.4 Research Questions

The main research question for this study is:

> What is the impact of virtual reality on evaluating window views for architectural design in compliance with European Standard 17037?

In order to further understand the effects of virtual reality on daylight perception in residential design, the following sub-questions were also addressed in this study:

1. How does VR influence the design and placement of windows in residential buildings to optimize daylight and comply with European Standard 17037?
2. Does the use of virtual reality improve the decision-making process for residential design with regards to daylight?
3. What elements influence the creation of a VR tool for assessing window views according to the European standard EN 17037?
4. What are the factors that contribute to the optimal quality view from a window and if VR is an effective medium to leverage these factors into practice?

These sub-questions aimed to further explore the potential benefits and limitations of virtual reality in residential design and its impact on daylight perception. The answers to these questions will provide valuable insights for designers, architects, and researchers in the field of residential design and virtual reality.

1.5 Goals

The objectives of this thesis are twofold:

1. **To conduct a comprehensive analysis of the utilization of Virtual Reality (VR) technology in research applications.** This entails evaluating the current state of VR technology, its integration within various research disciplines, and its effectiveness in enhancing data collection, analysis, and overall research outcomes. The analysis will also encompass an exploration of the benefits and limitations associated with the use of VR in research contexts.

2. **To develop a set of VR research tools that are accessible to a broader audience.** This objective focuses on the creation and dissemination of VR tools designed to be user-friendly and cost-effective, thereby promoting widespread adoption among researchers from diverse fields. The goal is to democratize the use of VR technology in research, ensuring that it is not limited to specialized or well-funded institutions but is available to any researcher seeking to leverage VR for their investigative work.

1.6 Thesis Statements

Over the years, technology has advanced significantly, bringing humanity to a point where it is now possible to render a sufficient number of frames per second to easily utilize VR technology. With VR technology, users can view everything from their own perspective and decide which direction to look, rather than being confined to pre-rendered views chosen by designers, as was the case not long ago. Users not only have the freedom to choose their view, but also can modify other important elements relevant to studies of daylight, such as the position of the sun, cloud cover, shadows, glare, and more. These aspects are also addressed by the European standard EN 17037.

Considering the above, this work was decided to focus on two thesis statements which are as follows:

1. **New technologies enable the expansion of research tools in the field of lighting to include VR tools.** This statement posits that the integration of VR technology can significantly enhance the capabilities and scope of research methodologies within the lighting domain.

2. **It is possible to create such tools that are easy to use and widely accessible for lighting research.** This statement emphasizes the feasibility of developing VR tools that are both user-friendly and broadly available, thereby facilitating their adoption by a wide range of researchers in the field of lighting.

1.7 Scope of Work

1. **Thematic Scope:** This thesis focuses on the development of a tool to support research in architecture and urban planning, specifically in the area of lighting and particularly the view from the window. It explores the application of VR in lighting research, in accordance with the European Standard EN 17037. Given that the developed tools will be designed for

use on a European scale, the author does not refer to the geometric matrix (from PL: "linijka słońca").

2. **Temporal Scope:** The literature review covers the period from 1960 onwards, encompassing the early developments and milestones in VR technology. The actual work on developing the tools for this thesis began in 2019.

1.8 Methodology

The primary focus of this study is on the utilization of Virtual Reality (VR) in lighting research, specifically exploring methods and techniques of window view evaluation that comply with EN 17037 standards. This central theme is emphasized throughout the research process.

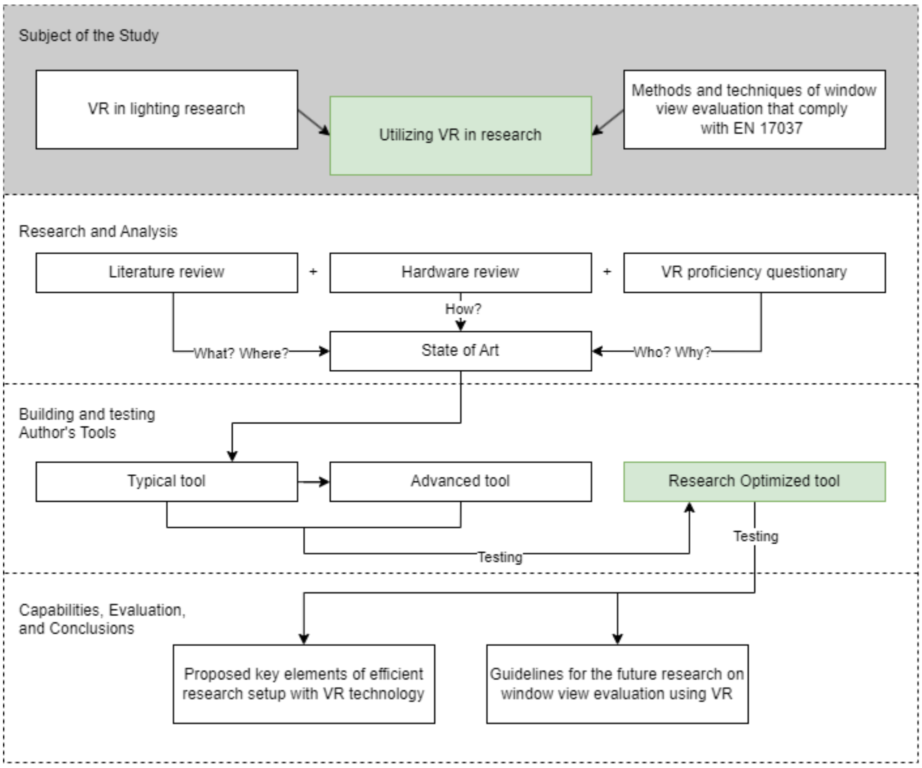


Figure 1.1. Method and structure. Source: Author

The research and analysis phase comprises three main components: a comprehensive literature review to determine the existing knowledge base (addressing the questions "What?" and "Where?"), a hardware review to evaluate the necessary technology for VR implementation (answering "How?"), and a VR proficiency questionnaire to assess the users' expertise and reasons for using VR (considering "Who?" and "Why?"). These components collectively contribute to understanding the current state of the art in VR research.

Following the initial research and analysis, the study progresses to the development and refinement of the necessary tools. This phase involves defining scenarios through brainstorming sessions, resulting in the identification of the Most Common Scenario, which led to the creation of the Walkthrough Tool, and the Perfect Scenario, which led to the creation of ALTO VR. This dual approach ensures that the tool is relevant in both typical use cases and ideal conditions, providing a comprehensive framework for its development.

As the research advances, technological constraints are acknowledged, guiding the creation of the Walkthrough Tool and ALTO VR. These two prototype tools serve as the foundational elements used initially, addressing specific needs within architectural design and urban planning. A rigorous evaluation and filtering process is then applied, aggregating features such as loading custom 3D models into a Feature Collective Bucket. This methodical approach involves value filtering for usefulness, learning curve filtering for usability, and EN 17037 filtering for industry compliance, systematically refining the most relevant features.

This culminates in the development of the Arch ViewR, optimized to enhance the efficiency and effectiveness of design and planning tasks. The final tool is subjected to comprehensive testing to verify its effectiveness and reliability. The outcomes demonstrate the tool's practical utility and potential for future improvements and broader applications in the field, providing valuable insights into user satisfaction, interaction patterns, and feature usage.

The the Walkthrough Tool, ALTO VR and the Arch ViewR are developed using Unity, Blender, Photopea, and Python.

The final phase of the study focuses on evaluating the capabilities of these developed tools and drawing conclusions. Key elements of an efficient research setup with VR technology are proposed, including essential components and configurations. Additionally, guidelines for future research on window view evaluation using VR are outlined, providing recommendations for continued exploration in this domain.

1.9 Structure of the Thesis

This thesis is meticulously structured to explore the multifaceted role of Virtual Reality (VR) in the evolution of informational media, with a particular emphasis on its applications in daylighting research. The following sections detail the organization of the content:

Part 1: Subject of the study

Chapter 1: Introduction

The first chapter sets the stage by introducing the author's personal motivations and background, defining key terms, and justifying the research topic. It further identifies the specific research problem and outlines the primary research questions guiding the study.

Chapter 2: Virtual Reality in the Context of the Evolution of Informational Media

This chapter delves into the historical development of VR, tracing its roots from early forms of media to its current state. It discusses key milestones in VR technology, its impact on educational media, and the accelerated adoption due to the COVID-19 pandemic. Conceptual frameworks and taxonomies for understanding VR are also presented, followed by an examination of the diverse applications of VR across various fields.

Chapter 3: Key Aspects of EN 17037: Daylighting in Buildings

The third chapter delves into the details of the tools and standards that are used in Poland and Europe for the daylight in buildings, focusing on the view from the windows.

Part 2: Research and Analysis: Utilizing VR Tools - An Overview of Practices and Technologies

Chapter 4: Utilizing VR in Lighting Research and in Practice

The fourth chapter focuses on the application of VR in lighting research, particularly in daylighting analysis. It compares VR with traditional (not including VR methods) daylighting method. This chapter highlights the advantages and limitations of using VR in this specific area of research.

Chapter 5: Hardware and Software for VR in Research

This chapter provides a comprehensive analysis of VR devices and software, detailing their evolution and current state. It examines various VR development platforms and software examples, discusses the phenomenon of the uncanny valley in VR, and explores the implications for research and development.

Part 3: Building and Testing the Author's VR Tools for Daylighting and Architectural Research

Chapter 6: Pilot Tools - from the most common to the perfect scenario

The sixth chapter presents pilot tools developed and designed by the author as part of the research. These include detailed case studies of a walkthrough tool and the ALTO VR tool. It covers the methodology, results, discussion, and tools used in these pilot studies, providing insights into their development workflows, user interactions, and potential future enhancements.

Chapter 7: Arch ViewR

The seventh chapter describes the development of the main VR tool created for this research. Arch ViewR is a tool that enables architects, urbanists, and daylighting researchers to utilize Virtual Reality (VR) for their experiments. This tool features a modular design, allowing for various input configurations and the generation of diverse results. Unique features, user interface, data processing, and security measures related to this tool are discussed. Arch ViewR operates within the scope of the researched area. This chapter demonstrates that new technologies can expand research tools to include VR and that it is possible to create user-friendly and accessible tools.

Part 4: Capabilities, Evaluation and Conclusions

Chapter 8: Results and Pilot Testing of the Arch ViewR

The eighth chapter outlines the design and implementation of the study, including experimental setup, and survey design. It discusses the data gathering process, encountered challenges, and presents the study results, including detailed analysis and graphical representation of the data.

This chapter shows the impact of VR on design processes and the factors contributing to optimal window views.

Chapter 9: Summary

The final chapter recaps the background and motivation of the study, summarizes the research design and key findings, and discusses the broader implications of the research. It concludes with recommendations for future research, providing a directions for further exploration in the field.

Digital elements

This work incorporates supplementary digital elements. Following the final chapter, a QR code is provided, which serves as a means to request access to a Google Drive folder. This folder contains the Arch ViewR for download, as well as videos demonstrating two additional tools.

1.10 Glossary

3DoF (Three Degrees of Freedom)

A term used to describe VR systems where the user can look around in any direction (pitch, yaw, roll) but cannot move freely within the virtual space.

6DoF (Six Degrees of Freedom)

A term used to describe VR systems that allow users to move along three translational axes (up/down, left/right, forward/backward) in addition to looking around, providing a more immersive experience.

ALTO VR

A tool developed for this research to simulate daylight and allow users to customize building setups, lighting, and perform daylight analysis in a virtual environment.

Augmented Reality (AR)

A technology that overlays digital information onto the real world, enhancing the user's perception of their environment.

Augmented Virtuality (AV)

A variation of augmented reality where real-world elements are incorporated into a predominantly virtual environment.

Burdea's Triangle

A theoretical model for VR experiences defined by three components: interaction, immersion, and imagination.

COVID-19 Impact on VR

The pandemic accelerated the adoption of VR and AR technologies as remote work and online learning became necessary, highlighting the practical applications of these technologies across various generations.

Cuneiform Scripts

One of the earliest systems of writing, developed by the Sumerians of ancient Mesopotamia, used to record information on clay tablets.

Daguerreotype

An early photographic process invented in 1839 by Louis Daguerre, which used a silver-plated copper sheet to create a highly detailed image.

Daylighting

The practice of placing windows, skylights, and other openings in a building to utilize natural light to illuminate the interior.

Degrees of Freedom (DoF)

Refers to the number of axes along which a user can move or look in a virtual environment. Commonly used in VR to describe the range of motion available to the user.

European Standard EN 17037, Daylight for Buildings

A standard that provides guidelines for daylighting in buildings, covering aspects like the quality of view, exposure to sunlight, and availability of daylight.

Extended Reality (XR)

An umbrella term that encompasses all forms of computer-altered reality, including VR, AR, and MR (Mixed Reality).

Haptic Feedback

Technology that provides tactile feedback to the user through touch, enhancing the immersive experience of VR by simulating the sense of touch.

Head-Mounted Display (HMD)

A device worn on the head that provides a visual display directly in front of the eyes, commonly used in VR systems to create an immersive experience.

Immersion

The sensation of being physically present in a non-physical world, often achieved in VR through high-quality visual, auditory, and sometimes haptic feedback.

Immersive Learning Tools

Educational tools that use immersive technologies like VR to provide interactive and engaging learning experiences.

Interaction

In the context of VR, it refers to the extent to which users can interact with and manipulate the virtual environment.

Main Tool also known as Arch ViewR

The VR tool that is the result of this paper. It is the effect of testing and evaluation of Walkthrough Tool and ALTO VR.

Milgram's Continuum of Reality

A framework that categorizes experiences from completely real (real environment) to completely virtual (virtual environment), including augmented reality and augmented virtuality.

Mixed Reality (MR)

A blend of physical and digital worlds where physical and virtual objects co-exist and interact in real-time.

Oculus Rift

A VR headset developed by Oculus VR, known for providing an immersive VR experience with 6DoF capabilities.

Photorealistic Visualization

Creating images or environments in VR that are highly realistic and indistinguishable from real life.

Pilot Tools

Initial, small-scale implementations of VR tool used to test and refine the concepts and methodologies before developing the Arch ViewR.

Sensorama

An early example of multi-sensory, immersive technology created by Morton Heilig in 1962, which combined sight, sound, vibration, and smell to simulate a real-world experience.

Sword of Damocles

The first head-mounted display system, created by Ivan Sutherland and Bob Sproull in the 1960s, featuring simple wireframe graphics.

Traditional daylighting analysis methods

Methods for daylighting analysis that are used on regular basis not including Virtual Reality.

Uncanny Valley

A concept in robotics and 3D computer graphics describing the discomfort or eeriness experienced when a humanoid object appears almost, but not exactly, like a real human.

Virtual Boy

An early VR system developed by Nintendo, released in the 1990s, known for its 3DoF capabilities and limited commercial success.

Virtual Environment (VE)

A computer-generated, three-dimensional environment in which a user can interact and experience a simulated presence.

Virtual Reality (VR)

A computer-generated simulation of a three-dimensional environment that can be interacted with in a seemingly real or physical way by a person using special electronic equipment.

VR Taxonomy

A classification system for VR experiences based on the type of reality (ranging from entirely real to entirely virtual) and the degree of interaction, immersion, and imagination they offer.

Walkthrough Tool

A VR tool that allows users to navigate through a virtual environment, commonly used in architectural design to visualize and experience a building or space before it is built.

Chapter 2

Virtual Reality in the Context of the Evolution of Informational Media

2.1 History and Development of Virtual Reality

2.1.1 From Cave Paintings to Virtual Reality

Human history is replete with the desire to record experiences and share information. The evolution of these processes has been monumental (Neștian, Tiţă & Guță 2020), moving from rudimentary wall drawings to complex digital simulations like Virtual Reality (VR). This section traces the captivating journey of how humans have progressed in the creation, storage, and dissemination of experiences and knowledge.

The Dawn of Sensory Recording: Lascaux Cave Paintings

Around 18,000 years ago, the Lascaux cave paintings [fig. 2.1] in France signaled one of humanity's first attempts to capture and share experiences (Genty, Konik, Valladas, Blamart, Hellström, Touma, Moreau, Dumoulin, Nouet, Dauphin & Weil 2011). Primitive yet profoundly eloquent, these drawings on the walls of caves served as a community memory, perhaps even a form of storytelling or ritualistic expression. While far from the 'virtual' experiences we know today, these paintings represent a foundational moment in the human endeavor to recreate the world around us.

Figure 2.1. Lascaux Cave Paintings. Source: https://archeologie.culture.gouv.fr/lascaux/en/access-walls. Accessed on 20 March 2024.

The Written Word: Manuscripts and Books

The invention of writing systems ushered in a new era for information storage and dissemination. Sumerian cuneiform scripts on clay tablets [fig. 2.2] are among the earliest examples (Dittmar 2011). Manuscripts, painstakingly copied by hand, came next and were usually the preserve of religious or academic institutions. However, the real revolution came with Gutenberg's invention of the printing press in the 15th century. The printing press democratized information, making books more affordable and accessible, thereby setting the stage for the Renaissance, the Scientific Revolution, and eventually, the Enlightenment. For the first time, information could be mass-produced and disseminated widely, affecting every aspect of society from religion to politics to science (Lewis 2021).

Figure 2.2. Proto-Cuneiform tablet. Source: https://www.metmuseum.org/art/collection/search/329081. Accessed on 20 March 2024.

The Daily Record: Newspapers and Journals

The emergence of newspapers in 17th-century Europe, particularly in England and the Netherlands, marked a significant shift in the dissemination of information. These publications provided regular updates on current events, financial matters, and gossip, serving as platforms for public discourse and debate. The democratization of information through newspapers significantly influenced the formation of public opinion and the advancement of democracy. By transcending the limitations of traditional books and manuscripts, newspapers became the first mass media, enabling the widespread delivery of timely information to a broad audience. The influence of newspapers extended across various societal domains, impacting politics, science, and public discourse, thereby shaping the fabric of society (Fortunati, Taipale & Farinosi 2014)(Fleming & King 2009).

From Static to Dynamic: Photography and Film

Photography, invented in the early 19th century, allowed for an unprecedented capture of reality. The Daguerreotype [fig. 2.3] and later technologies could fix a moment in time in a way that paintings and written descriptions could not. However, it was the invention of motion pictures at the end of the 19th century that brought a new dynamism to storytelling (Klein-Avraham & Reich 2014) (Osiyevskyy & Dewald 2015). Films added the elements of movement and time, providing a more immersive experience. Over the 20th century, the art of film making evolved to include sound, color, and special effects, creating ever more engaging and realistic representations of stories and events.

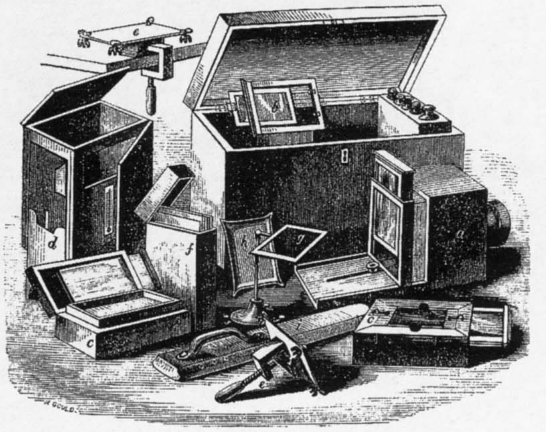


Figure 2.3. Apparatus and equipment for making daguerreotypes. Source: https://www.photohistory-sussex.co.uk/dagprocess.htm. Accessed on 20 March 2024.

A New Dimension of Interaction: Video Games and Interactive Media

The invention of video games in the latter half of the 20th century heralded a monumental shift in the media landscape. Early games like Pong were revolutionary, establishing that media could be interactive and directly engage the consumer. This interactivity evolved significantly with advancements in technology, including more powerful gaming platforms and computers. Multiplayer online games introduced complex virtual worlds, allowing not just interaction with the game environment but also real-time interaction among players. This was a significant leap that foreshadowed the immersive virtual environments we associate with modern VR.

One of the major challenges interactive media posed was the need for rapid frame processing. Unlike movies that were pre-rendered and took months or even years to produce, interactive media required real-time rendering to provide instant feedback based on user interactions. For example, Pixar's 1995 film "Toy Story" took years of development and an enormous amount of computational power to render its frames, a process that was possible because each frame could be pre-calculated and stored. On the other hand, James Cameron's "Avatar" (2009) incorporated some real-time feedback systems for the filmmakers but was still largely a pre-rendered film that took years to complete.

In contrast, video games like the early iterations of "Tomb Raider," featuring the iconic character Lara Croft, had to prioritize speed over visual fidelity [fig. 2.4]. The games had to render frames in real-time to allow for immediate player interaction, making it essential for the computing solutions to offer quick responses. As the gaming industry evolved, the balance between speed and fidelity became more refined. There is a significant difference visible when observing 2018 "Tomb Raider" [fig. 2.5]. A game like "The Witcher 3: Wild Hunt" became a watershed moment for the industry, demonstrating that games could offer both high-quality visuals and complex real-time interactivity. It presented detailed worlds and nuanced characters without sacrificing the real-time processing speeds necessary for seamless gameplay.

Figure 2.4. Early Tomb Raider game view. Source: `https://www.eurogamer.net/hard-core-a-look-at-the-original-tomb-raider-games`. Accessed on 20 March 2024.

These advancements in rapid frame processing and real-time rendering have been essential in pushing the boundaries of what is possible in VR. They allow for more natural and fluid movements, elevating the level of immersion and interactivity to new heights, and paving the way for future developments in this exciting medium.

Early Stages of Virtual Reality

Figure 2.5. 2018 Tomb Raider game view. Source: Rise of the Tomb Raider Gameplay

The term "Virtual Reality" was coined in the 1980s, and the subsequent decades were marked by incremental improvements in VR technology. Early VR systems were limited by hardware capabilities and were largely confined to academic and industrial applications. However, the groundwork was laid for the explosion of consumer VR in the 21st century.

One significant milestone in the development of VR technology was the differentiation between 3DoF and 6DoF [fig. 2.6], terms that refer to the Degrees of Freedom that a user has in a virtual environment.

In early VR systems, the user generally experienced what is known as 3DoF, meaning they could look around in any direction — pitch, yaw, and roll — but couldn't move freely within the virtual space. This was limiting in terms of immersion and interactivity. While 3DoF was a revolutionary step for its time, allowing users to change their point of view within a virtual world, it didn't capture the full range of human movement.

The advent of 6DoF systems marked a major leap forward. In addition to pitch, yaw, and roll, users could now also move along three translational axes — up/down, left/right, and forward/backward. This enabled much more natural interaction with the virtual environment. Users could now walk around, crouch, jump, or lean, offering a dramatically more immersive experience.

The transition from 3DoF to 6DoF has been crucial for applications be-

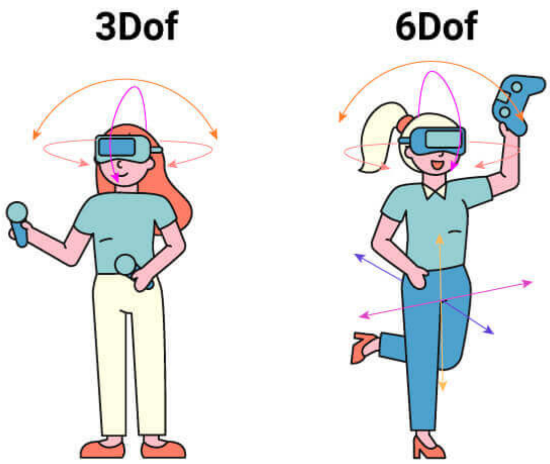


Figure 2.6. 3DoF vs 6DoF. Source: `https://www.mindport.co/blog-articles/3-dof-vs-6-dof-and-why-it-matters`. Accessed on 20 March 2024.

yond gaming, including professional training, architectural visualization, and scientific research. It represents one of the key evolutionary steps in VR technology, offering a more complete illusion of presence in a virtual environment.

A Future Yet Unwritten

Despite its advances, VR technology is still in its early stages. As media transmission technologies continue to evolve, facilitated by developments like 5G and edge computing, the scope for VR applications is expected to widen considerably. This is an exciting period of experimental growth, and it is likely that future generations will look back at our current VR technologies as rudimentary stepping stones to a more immersive future. The quest to capture and recreate the human experience has a long history, dating back to the Lascaux cave paintings. The development of media transmission technologies has been integral in this journey, culminating in the current era of virtual reality. While we have come a long way, it is crucial to recognize that VR is still in its formative years, with a future full of potential and challenges yet to be fully understood.

2.1.2 Brief history of VR technology

The concept of Virtual Reality (VR) dates back to the 1950s and 60s, when early computer scientists and researchers first began to experiment with the idea of creating a simulated environment that could be experienced by users in a computer-generated world (Bryson 2013).

In the 1980s and 90s, advances in computer technology allowed for the development of more sophisticated VR systems, which were initially used for military and scientific applications. During this time, the first commercial VR systems were introduced, including the Virtuality arcade system and the Virtual Boy by Nintendo (Bryson 2013).

Figure 2.7. Virtual Boy by Nintendo. Source: https://pl.wikipedia.org/wiki/Virtual_Boy#/media/Plik:Virtual-Boy-Set.png

In the 2000s and 2010s, further advancements in computer technology and the widespread adoption of the internet led to a new wave of VR development, including the release of consumer-oriented VR devices such as the Oculus Rift, HTC Vive, and PlayStation VR (Bakalova, Petkov, Cyril & Methodius 2020). In recent years, VR technology has become increasingly accessible and affordable, and is now being used for a range of applications, including gaming (Carroll, Osborne & Yildirim 2019), entertainment (Wehden, Reer, Janzik, Tang & Quandt 2021), education (Cicek, Bernik & Tomičić 2021), and research (Rach & Scott 2020). This study focuses on the application of VR in architectural design, specifically for evaluating window views in compliance with European Standard 17037, highlighting its potential to improve design accuracy and user engagement.

The development of VR technology continues to evolve, with ongoing advancements in fields such as computer graphics, human-computer interaction, and computer vision driving continued improvements in the quality and capability of VR systems (Yamaguchi, Hara, Okamoto, Inoue, Miyata, Fukuwa & Tobita 2020)(Shreenikesh 2023)(Zhao 2009). As VR technology continues to advance, new use cases are emerging, driving innovation and growth. VR is now being used across various industries and sectors, such as medicine, aviation, military, gaming, entertainment, and tourism (Vavenkov 2022)(Kaltenborn & Rienhoff 1993). In the entertainment industry, VR provides users with a unique and interactive way to consume media, and in education, it allows students to experience immersive learning environments that can enhance their understanding of complex concepts (Shreenikesh 2023)(Syed-Abdul, Upadhyay, Salcedo & Lin 2022). Additionally, in industries such as mining, VR is being used to provide staff with critical competencies required for the implementation of processes (Noghabaei, Heydarian, Balali & Han 2020), in medical contexts it offers potential for new medical treatments and rehabilitation medicine products (Riva, Wiederhold & Mantovani 2019), and in the real estate sector, VR technology is changing how it is being marketed and perceived (Ghobadi & Sepasgozar 2020).

As VR technology becomes more versatile and advanced, new technologies and tools are also emerging to make it easier to create and distribute VR content (Shreenikesh 2023). The rapid growth of the VR content creation market is driving the development of new tools and technologies (Yamaguchi et al. 2020)(Shreenikesh 2023). The future prospects of VR technology are significant as researchers and developers push the boundaries of this exciting technology (Kaltenborn & Rienhoff 1993). To realize its full potential, future research should focus on designing innovative and comprehensive VR systems that accurately capture real-world conditions and replicate them in VR environments (Kaltenborn & Rienhoff 1993)(Zhao 2009).

Overall, the history of VR technology is a story of ongoing innovation and growth, as researchers and developers continue to push the boundaries of what is possible with this exciting technology. As VR technology continues to evolve, it is likely to play an increasingly important role in many areas of our lives, from entertainment and education to healthcare and beyond.

Table 2.1: Milestones in the Development of Virtual Reality. Source: Author

Year	Milestone	Person /Organization	Description
1962	Sensorama	Morton Heilig	One of the earliest examples of multi-sensory, immersive technology, incorporating sight, sound, vibration, and smell.
1968	First HMD	Ivan Sutherland, Bob Sproull	Created the first head-mounted display, known as the "Sword of Damocles," displaying simple wireframe graphics.
1980s	DataGlove	VPL Research	Developed a glove that recognized hand movements and gestures for more natural interactions in virtual environments.
1990s	Virtuality Arcade	Virtuality Group	Launched arcade machines with stereoscopic 3D graphics and real-time multiplayer gaming.
Early 2000s	3DoF Systems	Various	Introduced 3DoF systems that allowed users to change the direction of their view but not move freely.
2014	Google Cardboard	Google	Launched a cardboard holder and app that made basic VR experiences accessible with just a smartphone.
2016	Consumer VR Headsets	Oculus, HTC, Sony	Introduced advanced 6DoF VR systems like the Oculus Rift, HTC Vive, and Sony's PlayStation VR.
2016-2018	6DoF Transition	Various	Shifted from 3DoF to 6DoF systems, allowing for more natural and immersive experiences.
2018	Wireless VR	Oculus	Introduced the Oculus Quest, a wireless VR headset that eliminated the need for external sensors or a tethered PC.
2019	Hand/Eye Tracking	Various	Implemented more advanced tracking features, eliminating the need for handheld controllers.
2020s	AI Integration	Various	Incorporated AI and machine learning for more interactive and responsive virtual environments.
2020s	XR Expansion	Various	Expanded into Extended Reality (XR), including Augmented Reality (AR) and Mixed Reality (MR).
2020s	Haptic Feedback	Various	Developed haptic suits and more advanced tactile feedback mechanisms for a more immersive experience.

2.1.3 VR as a Milestone in the Development of the Media Used in Education

The development in virtual reality started in the 1960s(Cipresso, Gigli-oli, Raya & Riva 2018), but it only took off after 2016 when high-end smartphones became famous and made VR more accessible to regular users.

As a result of the increased appearance of the low-cost VR technologies, it became a much broader present technology among researchers. Until 2018, over 20.000 papers were tagged with VR, available through the Web of Science Core Collection and in parallel, a little below 10.000 papers linked with Augmented Reality, which is closely related to VR(Cipresso et al. 2018).

Araiza-Alba has shown that using VR is more than 40% more efficient for problem-solving tasks than using tablets or board games when teaching children(Araiza-Alba, Keane, Chen & Kaufman 2021). The research confirmed that learned skills are easily transferable to the physical world.

VR growth seems to be closely connected to the ability to see the world directly from others perspectives. Another paper recently published in Computers and Education used it to boost empathy to the bullied peers by producing realistic emotional responses(Barreda-Ángeles, Serra-Blasco, Trepat, Pereda-Baños, Pàmias, Palao, Goldberg & Cardoner 2021).

In another article, Baceviciute confirms that VR technology has vast potential to enrich education, and based on the conducted experiment, students perform better on tests after learning using new technology. Furthermore, it states that we "remediate learning content from non-immersive to immersive media", which clarifies that the research in the field has just started(Barreda-Ángeles et al. 2021).

Accessibility of the technology allows it to be used on larger and larger groups. Araiza-Alba has tested 360° VR videos on a group of 182 children to learn about the dangers of drowning in coastal environments(Araiza-Alba, Keane, Matthews, Simpson, Strugnell, Chen & Kaufman 2021).

2.1.4 Accelerating Digital Transformation: The Role of VR and AR During the COVID-19 Pandemic

The COVID-19 pandemic has served as an accelerator for changes in various sectors, especially in the realms of work and education. Business interest in technologies like Virtual Reality (VR) and Augmented Reality

(AR) has surged since the onset of the pandemic. As lockdowns and social distancing measures were implemented globally, organizations specializing in VR technology saw an opportunity to deploy their products and services at an accelerated pace(Everett 2021). This unprecedented situation pushed companies to look for remote yet interactive ways of functioning, boosting VR's standing as a feasible tool for business continuity.

The acceptance of these new technologies was also significantly influenced by societal perspectives. As per the data presented by Mark McCrindle (2020), a broad spectrum of generations displayed a positive attitude toward increased online learning and new technologies like VR and AR (as seen in Table [table 2.2)]. Gen Z, Y, X, and even Boomers exhibited significant openness to adopting online methods for education and work. This reveals a shift in mindset that transcends generational barriers, making the integration of such technologies into daily life much smoother. The propensity of younger generations, who are already digital, mobile, and visual, to adapt to this new format is quite high.

Table 2.2: Understanding the impact of COVID-19 on the emerging generations. Source: McCrindle & Fell (2020)

How do you feel about an increased use of online learning in the following sectors (% who feel positive)

	Gen Z (18-25)	Gen Y (26-40)	Gen X (41-55)	Boomers (56-74)
School	81%	85%	87%	88%
Vocational Training	83%	90%	90%	93%
University	78%	86%	90%	95%
Workplace	82%	89%	91%	93%

The generational aptitude for digital learning technologies, as suggested by McCrindle's research (2020), meshes well with the technical possibilities that VR offers. Table [table 2.3] shows a fascinating trend of new job positions emerging in line with technological advancements, underscoring how the job market is adapting to the digital age. Notably, the position of Virtual Reality Engineer was created as early as 2016, marking a clear recognition of the technology's potential applications beyond gaming and entertainment.

VR's visual and interactive capabilities make it a particularly appealing option for newer generations like Gen Z and Gen Alpha. The technology goes beyond traditional learning or training formats by providing more visually complete and hands-on experiences. This aligns closely with the traits of these younger generations, who are accustomed to digital interactivity and prefer a visual and tactile approach to problem-solving.

Table 2.3: Gen Z and Gen Alpha Infographic. Source: McCrindle & Fell (2020)

Year	Word of the year	New Jobs
2003	Blog	Sustainability officers
2004	Texting	Blogger
2005	Emo	Data visualization designer
2006	Podcast	Big data analyst
2007	Peeps	App developer
2008	Bailout	Social media marketer
2009	Unfriend	Autonomous vehicle technician
2010	App	Medical nanotechnologist
2011	Cloud	UX manager
2012	Hashtag	Cyber security professional
2013	Selfie	Blockchain developer
2014	YOLO	Robotics technician
2015	<cry emote>	UAV operator
2016	Post-truth	Virtual Reality engineer
2017	Fake news	Workplace concierge
2018	Toxic	Professional manager
2019	Yeet	Wellbeing manager

In summary, the COVID-19 pandemic not only increased the speed of VR and AR technology adoption but also catalyzed a broader societal acceptance across various generations. The crisis underscored the practical applications of these technologies, from business to education, and highlighted how well-suited they are to meet the preferences and skills of newer generations. This confluence of factors suggests that VR and AR are more than mere technological novelties; they are becoming integral tools for the way we work, learn, and interact.

2.2 Conceptualizing and Defining Virtual Reality

Virtual Reality (VR) has been a part of public consciousness for decades, but its definition remains subject to ongoing refinement. Initially, VR was understood as creating a digital world separate from our physical reality. This often focused on the visual and auditory aspects of the experience due to the sensory limitations of early VR technologies.

The term "virtual reality" refers to a simulated experience that can be similar to or completely different from the real world. It typically involves a user wearing a head-mounted display (HMD) that tracks their head movements and may also include other peripherals such as motion controllers, haptic feedback devices, and sensors to provide a fully immersive experience. The user is then transported to a virtual environment that can be a 3D computer-generated world or a 360-degree video captured from the real world(Huygelier, Schraepen, Ee, Abeele & Gillebert 2019).

According to the widely used definition by the Virtual Reality Society, VR is "a three-dimensional, computer-generated environment that can be explored and interacted with by a person" (*Virtual Reality Society* n.d.)(Kardong-Edgren, Farra, Alinier & Young 2019). VR can create a sense of presence, where the user feels as if they are physically present in the virtual environment, and it can also offer interactivity, allowing users to manipulate objects, perform actions, and engage in experiences that may not be possible in the real world(Rosa, Morais, Gamito, Oliveira & Saraiva 2016).

As technology continues to evolve, so will our definitions and understanding of VR. Future sensory dimensions like smell and taste are being explored, and as AI becomes more integrated into VR, the boundary between user and environment may blur even further.

The definition of Virtual Reality is fluid, changing as technology advances and our understanding of human perception and interaction deepens. From initial definitions focusing on sight and sound to modern frameworks considering immersion and interactivity, VR remains a medium complex enough to defy easy categorization.

2.2.1 Milgram's Continuum of Reality

Milgram's Continuum of Reality is a theoretical framework that helps understand the relationship between different forms of reality, from completely real to completely virtual. The continuum encompasses Real Environment, Augmented Reality (AR), Augmented Virtuality (AV), and Virtual Environment (VE) (Milgram & Kishino 1994).

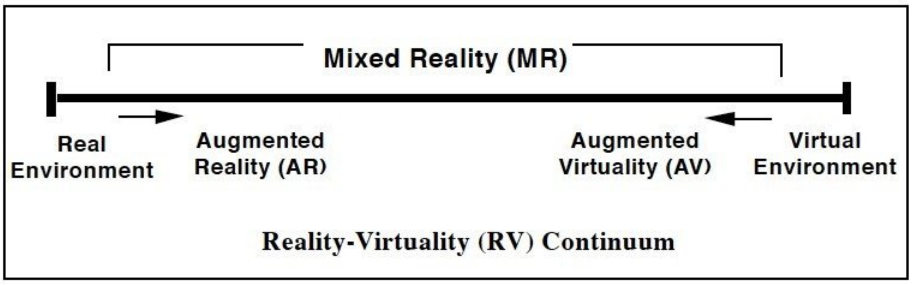


Figure 2.8. Milgram's et al. Reality-Virtuality Continuum. Source: Milgram & Kishino (1994)

This framework allows us to place a specific VR experience within the continuum, depending on the degree to which it incorporates elements of the real world and the virtual world.

2.2.2 Burdea's Triangle: Interaction, Immersion, and Imagination

Burdea's Triangle is a theoretical model for VR experiences that posits that they are defined by three components: interaction, immersion, and imagination (Burdea & Coiffet 2003).

Interaction refers to the extent to which users can interact with the VR environment. **Immersion** describes the degree to which the VR experience can engross the user's senses, giving the sensation of being physically present in the VR environment. **Imagination** encompasses the capacity of the VR system to stimulate and engage the user's creative and cognitive abilities.

2.2.3 VR Taxonomy Approach

By combining Milgram's Continuum of Reality and Burdea's Triangle, a comprehensive taxonomy for VR is proposed. This taxonomy accounts for both the type of reality (ranging from entirely real to entirely virtual)

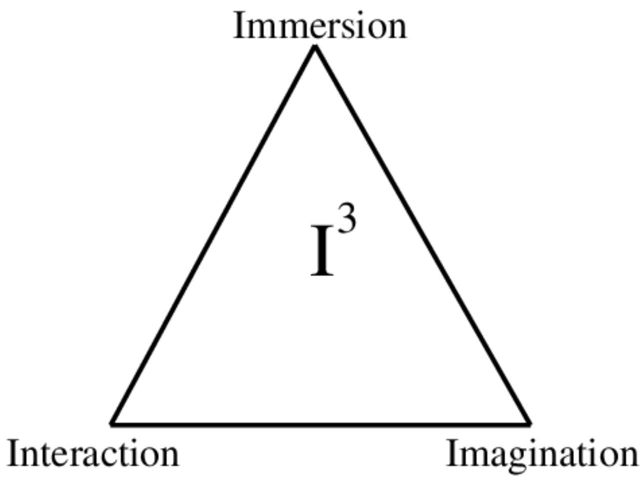


Figure 2.9. Burdea's et al. I^3 triangle. Source: Burdea & Coiffet (2003)

and the degree of interaction, immersion, and imagination facilitated by the VR experience.

The integration of these models allows for a nuanced understanding of VR experiences, considering both the technical aspects (reality-virtuality spectrum) and user experience aspects (interaction, immersion, imagination). Combining Milgram's Continuum of Reality and Burdea's Triangle, it encapsulates the essential elements of VR, fostering a comprehensive understanding of this complex and rapidly evolving field.

2.3 The Multifaceted Applications of Virtual Reality

Virtual Reality has a wide range of applications across various industries and sectors.

VR has revolutionized the entertainment and gaming industries, providing immersive and interactive experiences for users. VR gaming allows players to step into virtual worlds, interact with virtual objects and characters, and experience gameplay like never before. It offers a new level of immersion and realism, providing a sense of presence and interactivity that traditional gaming cannot replicate(Shelstad, Smith & Chaparro 2017).

One of the most popular VR gaming platforms is the Oculus, developed by Oculus VR, a subsidiary of Facebook. The Oculus offers a wide range of games and experiences, from action-packed adventures to creative simulations and social interactions, providing a diverse range of entertainment options for users (*Oculus* n.d.).

Studies have shown that VR can affect game user satisfaction (Shelstad et al. 2017), and that players of virtual reality exercise games want more physical activity (Farič, Potts, Hon, Yang, Newby, Steptoe & Fisher 2019). VR games based on a first-person perspective (1PP) have been found to be more enjoyable and immersive than those based on a third-person perspective (3PP) (Monteiro, Liang, Xu, Brucker, Nanjappan & Yue 2018). VR has also been used in ophthalmic image display and diagnosis (Zheng, He & Yu 2015), and for visualizing modules and dependencies of OSGi-based applications (Seider, Schreiber, Marquardt & Bruggemann 2016).

VR has shown promising applications in healthcare, including training, therapy, and rehabilitation. VR can provide realistic simulations for medical training, allowing healthcare professionals to practice procedures, surgeries, and emergency situations in a safe and controlled environment without any risk to patients. It can also be used for therapy and rehabilitation, such as treating phobias, PTSD, pain management, and motor skill rehabilitation (Slater 2016)(Freeman, Reeve, Robinson, Ehlers, Clark, Spanlang & Slater 2017).

For example, the Brave Mind program developed by the University of Southern California Institute for Creative Technologies uses VR to provide exposure therapy for veterans suffering from post-traumatic stress disorder (PTSD). It recreates realistic virtual environments that allow veterans to confront and process traumatic memories in a controlled and supportive setting (*Brave Mind* n.d.)(Rizzo & Shilling 2017)(Difede, Cukor, Patt, Giosan & Hoffman 2006).

Virtual reality (VR) is a valuable tool for therapeutic interventions that require adaptation to complex, multimodal environments (Bugnariu & Fung 2007).

The application of virtual reality (VR) technology in the healthcare industry has gained momentum in recent years and has the potential to revolutionize the way healthcare is delivered (Lian 2023). VR has recently been utilized as a therapeutic tool within the area of psychotherapy (Zhang, Ding & Zhang 2022). VR technology has been widely used in psychological therapy in many fields due to its characteristics of immersion, interaction, imagination, and so on (Xu & Wang 2023).

VR has the potential to revolutionize education by providing immersive and interactive learning experiences (Dede 2009). VR can transport students to virtual environments that are otherwise inaccessible or costly to visit, such as historical landmarks, outer space, or underwater ecosystems (Slater & Sanchez-Vives 2016). It can also facilitate collaborative learning, simulations, and interactive experiments, allowing students to actively engage with the subject matter (Huang, Cheng, Chan, Zheng, Hu, Sun, Lai & Yang 2022).

For example, Google Expeditions is a VR platform that provides virtual field trips to students, allowing them to explore different locations around the world without leaving the classroom. Students can visit ancient ruins, explore the Amazon rainforest, or dive into the Great Barrier Reef, all through a VR headset (Shreenikesh 2023)(*Google Expeditions* n.d.).

Educational systems can benefit from Virtual Reality's (VR) ability to support experiential learning, as demonstrated by the virtual reality role-playing serious game for experiential learning (Alrehaili & Osman 2019). VR has also been used to introduce complex concepts in chemistry education, such as atomic structure, through immersive experiences (Maksimenko, Okolzina, Vlasova, Tracey & Kurushkin 2021).

VR has been increasingly used in architecture and design to create virtual walkthroughs and simulations of buildings, interiors, and urban environments (Ashgan, Moubarki, Saif & El-Shorbagy 2023). VR allows architects, designers, and clients to visualize and experience the space before it is built, providing a more immersive and realistic representation of the final product (Ashgan et al. 2023). It can also be used for design review, collaboration, and client presentations (Fakahani, Aljehani, Baghdadi & El-Shorbagy 2022)(Gan, Liu & Li 2022). In this study, VR is applied to evaluate window views according to European Standard 17037, aiming to enhance the accuracy and effectiveness of view assessments in architectural design.

For example, the company Foster + Partners has been using VR to create virtual walkthroughs of their architectural designs. Clients can put on a VR headset and virtually explore the proposed building or space, providing valuable feedback and insights before construction begins (Pausch, Proffitt & Williams 1997)(*Foster + Partners* n.d.).

VR has also been used in architectural education, such as in the development of an educational application based on virtual reality technology for learning architectural details (Maghool, Moeini & Arefazar 2018). VR has also been used as a design tool to achieve abstract concepts of spatial experience in design studio teaching (Ibrahim & shakhs 2023).

VR has found applications in the automotive and aerospace industries for design, testing, and training purposes. VR can simulate driving and flying experiences, allowing engineers and pilots to test and optimize designs, evaluate safety protocols, and train in realistic environments. It can also be used for maintenance and repair simulations, reducing downtime and costs (Shamsuzzoha, Toshev, Tuan, Kankaanpaa & Helo 2019)(Guryeva 2023)(Wang, Song & Wang 2022).

For example, NASA has been using VR for astronaut training, allowing astronauts to simulate spacewalks and other tasks in a virtual environment that closely resembles the real conditions of space. VR helps astronauts to practice procedures, develop skills, and familiarize themselves with the space environment before their actual missions (*NASA* n.d.)(Eriksen & Grantcharov 2005).

VR is emerging as a new medium for artists and cultural institutions. Museums are beginning to offer virtual tours, and artists are exploring the unique possibilities for expression that the medium offers, from virtual sculptures to interactive narratives.

Social VR platforms allow for a form of interaction that is closer to real-life socializing than any other online medium. Users can meet in virtual environments, conduct business meetings, or even attend concerts and seminars, all within the VR space.

Businesses are exploring the use of VR for everything from virtual shopping experiences to product design. The technology allows consumers to try before they buy in a much more comprehensive manner, from test-driving cars to virtually trying on clothes.

As VR technology continues to advance, new applications are continuously being explored. The integration of AI, advancements in haptic feedback, and the incorporation of other sensory experiences promise to further expand the range of possible applications.

Challenges of Virtual Reality

Despite its many applications and potential benefits, VR also faces several challenges that need to be addressed for its widespread adoption and success. Some of the key challenges include:

One of the main challenges of VR is the cost and complexity of the hardware required for a high-quality VR experience. VR headsets, motion controllers, and other peripherals can be expensive, making it inaccessible for some users. The hardware also requires powerful computing systems to run the VR simulations smoothly, adding to the overall cost (Mahboob, Husung, Weber, Liebal & Krömker 2019)(Leal-Romo, Silva-Perales, Lopez-Limon & Rayas-Sanchez 2018)(Coburn, Freeman & Salmon 2017)(Yuan 2023).

It is also challenging to maintain a consistent user experience across different VR devices, as they often have fundamental differences in their hardware and software systems (Schlueter, Baiotto, Hoover, Kalivarapu, Evans & Winer 2017). A big challenge for the adoption of VR in education is the skills required for educators to design and develop VR-based instruction (Vert & Andone 2019). Technological defects such as friction and dizziness in current VR systems also need to be improved for a better user experience (Kim, Im, Lee & Choi 2019).

However, low-cost VR technology has the potential to enhance the design process and improve portions of the education system (Coburn et al. 2017)(Dinis, Guimarães, Carvalho & Martins 2017). Additionally, the use of EMG sensors for reducing latency in VR has been explored (Jung, Na, Lee, Lee & Kim 2016).

Motion sickness and discomfort are common issues in VR, as the sensory experiences in the virtual environment may not always align with the user's physical movements. This can result in motion sickness, nausea, and other health concerns. Long-term effects of prolonged VR use on physical and mental health are still being studied (Kiryu & So 2007)(Martirosov & Kopecek 2017)(Vehteva, Nazarova & Surkova 2021)(Wiederhold & Wiederhold 1998).

However, VR has also been explored as a tool for mental health interventions, such as virtual reality meditation for youth experiencing homelessness (Chavez, Kelleher, Slesnick, Holowacz, Luthy, Moore & Ford 2020) and virtual exposure therapy for anxiety disorders (Shiban 2018)(Wiederhold & Wiederhold 1998). Virtual reality-based approaches have also shown promise in addressing a range of mental health conditions, including anxiety, phobias, depression, and autism spectrum disorders (Peng, Menhas, Dai & Younas 2022).

Creating high-quality VR content requires specialized skills and tools, and there are currently no standardized formats or protocols for VR content creation. This can limit the availability and diversity of VR experiences for users. There are also concerns about the ethical implications of VR content, such as privacy, security, and potential for misuse (Serrano, Sitzmann, Ruiz-Borau, Wetzstein, Gutierrez & Masia 2017)(Kim, Baddar, Lim, Jeong & Ro 2017)(Bhattacharjee & Chaudhuri 2020)(Oyelude 2017)(Steele, Burleigh, Kroposki, Magabo & Bailey 2020).

VR experiences can vary widely in terms of user comfort, ease of use, and accessibility. Some users may find the VR technology cumbersome or uncomfortable to wear, and the learning curve for using VR interfaces may be steep for some. There is also a need for accessibility considerations for users with disabilities, such as visual or hearing impairments (Erra, Malandrino & Pepe 2018)(Zhang et al. 2022)(Alamäki, Dirin, Suomala & Rhee 2021).

2.4 Conclusions

Virtual reality is a rapidly evolving technology with significant potential for transforming various industries and domains. Its immersive and interactive nature offers new possibilities for entertainment, gaming, healthcare, education, architecture, automotive, aerospace, and more. However, it also faces challenges related to hardware, cost, motion sickness, content creation, standards, user experience, and accessibility (Abulrub, Attridge & Williams 2011)(Allcoat, Hatchard, Azmat, Stansfield, Watson & Mühlenen 2021)(Han & Kim 2017).

As VR technology continues to advance and become more accessible, it is crucial to address these challenges to ensure that VR can be used safely, responsibly, and inclusively. Standardization of content creation, development of more affordable hardware, addressing health concerns, and improving user experience are some of the areas that require further attention (Chandra, Jamiy & Reza 2022)(Chen & Wu 2023)(Reffat & Nofal 2013).

Despite the challenges, VR is expected to continue to grow and expand its applications in various industries, as more advancements are made in hardware, software, and content creation. As VR becomes more widespread, it has the potential to revolutionize how we interact with technology, engage with content, and experience the world around us (Abulrub et al. 2011)(Asad et al. 2021)(Lei & Shen 2018).

In conclusion, virtual reality is a rapidly evolving technology that offers exciting opportunities and challenges across multiple domains. From entertainment and gaming to healthcare, education, architecture, automotive, aerospace, and beyond, VR is transforming the way we perceive and interact with the digital world. As technology continues to advance and challenges are addressed, VR is poised to revolutionize industries, create new experiences, and shape the future of human-computer interaction.

Chapter 3

Key Aspects of EN 17037: Daylighting in Buildings

3.1 Introduction

Considering the author's educational background and the context of this thesis being developed at Politechnika Gdańska, it is essential to discuss and reference Polish regulations concerning natural lighting in buildings.

Polish technical and construction regulations only have one paragraph addressing sunlight exposure for residential rooms and those intended for the collective stay of children. Since January 1, 2018 (§ 60):

Rooms for children in nurseries, kindergartens, and schools (excluding labs) must have at least 3 hours of sunlight during equinox days from 8 AM to 4 PM, while residential rooms need sunlight from 7 AM to 5 PM.

In multi-room apartments, this requirement can be limited to at least one room. In urban infill, the required sunlight duration can be reduced to 1.5 hours, and for single-room apartments, there is no specific requirement.

Warunki techniczne (budynki) > Dział III. Budynki i pomieszczenia > Rozdział 2. Oświetlenie i nasłonecznienie

§ 60. [Minimalny czas nasłonecznienia pomieszczeń] (ENG: *Minimal sun exposure time for rooms*)

(a) Pomieszczenia przeznaczone do zbiorowego przebywania dzieci w żłobku, klubie dziecięcym, przedszkolu, innych formach opieki przedszkolnej oraz szkole, z wyjątkiem pracowni chemicznej, fizycznej i plastycznej, powinny mieć zapewniony czas nasłonecznienia wynoszący co najmniej 3 godziny w dniach równonocy w godzinach 8^{00}-16^{00}, natomiast pokoje mieszkalne - w godzinach 7^{00}-17^{00}.

ENG: *Rooms intended for collective stay of children in nurseries, children's clubs, kindergartens, other forms of preschool care, and schools, except for chemical, physical, and art studios, should have a minimum sun exposure time of 3 hours on equinox days between* 8^{00} *and* 16^{00}*, while living rooms should have sun exposure between* 7^{00} *and* 17^{00}*.*

(b) W mieszkaniach wielopokojowych wymagania ust. 1 powinny być spełnione przynajmniej dla jednego pokoju.

ENG: *In multi-room apartments, the requirements of paragraph 1 should be met for at least one room.*

(c) W przypadku budynków zlokalizowanych w zabudowie śródmiejskiej dopuszcza się ograniczenie wymaganego czasu nasłonecznienia, określonego w ust. 1, do 1,5 godziny, a w odniesieniu do mieszkania jednopokojowego w takiej zabudowie nie określa się wymaganego czasu nasłonecznienia.

ENG: *In the case of buildings located in urban areas, it is permissible to reduce the required sun exposure time specified in paragraph 1 to 1.5 hours, and for a one-room apartment in such a building, the required sun exposure time is not specified.*

These regulations are based on the method presented by Mieczysław Twarowski in his book *The Sun in Architecture* published in 1960. The Sun Ruler (orginal: *Linijka słońca*) is a tool used for measuring sunlight exposure time, utilizing a modified sundial. It allows for precise determination of the angle of sunlight incidence and the length of shadows cast by obstacles at different times of the day.

- **Diagram and Angle Measurement:** The Sun Ruler uses a special diagram that shows the angle of sunlight incidence in the horizontal plane. Thanks to this diagram, it is possible to determine the angle at which sunlight falls on the Earth's surface at different times of the day.
- **Shadow Length:** The diagram also allows for reading the length of shadows cast by obstacles of a certain height at different hours. This is crucial in planning the placement of buildings to ensure adequate sunlight exposure for rooms.
- **Precise Measurement of Sunlight Exposure Time:** The Sun Ruler enables precise determination of sunlight exposure time for a given latitude. This is particularly important in designing residential buildings, where sunlight exposure requirements are mandated by law.

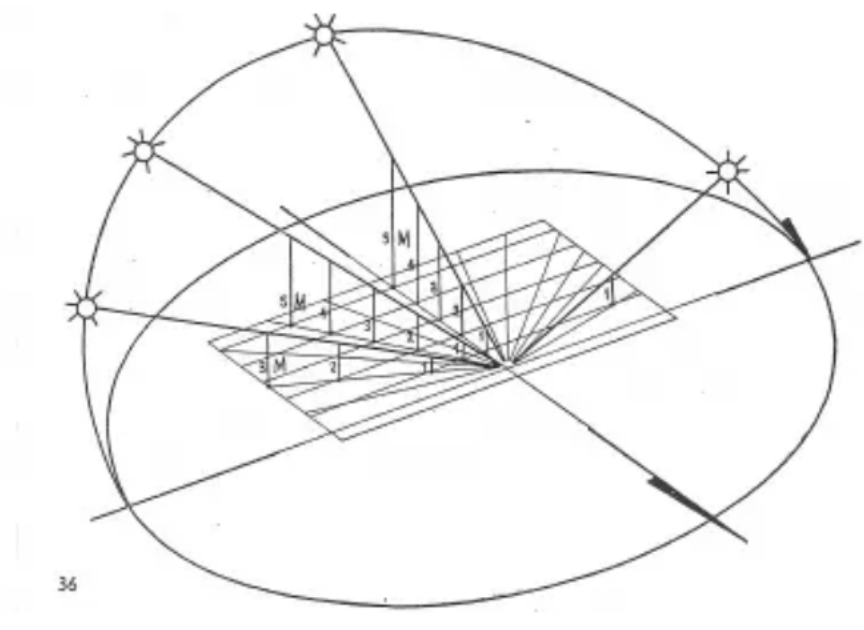


Figure 3.1. Sun ruler. Source: (Twarowski 1960)

The aforementioned method, despite being developed over 60 years ago, continues to serve as a reference point today. Notably, there are computer programs that utilize this method with a high degree of accuracy such as *Linijka słońca* plugin for Autodesk Autocad (*Linijka słońca* n.d.). However, it is important to acknowledge that current regulations concerning natural light primarily focus on its presence, overlooking other critical factors. This limitation has led researchers to refer to European standards, which provide more comprehensive solutions. These standards consider a wider range of variables, thereby offering a holistic approach to natural lighting in buildings.

3.2 EN 17037: Daylighting in Buildings

EN 17037 is a European standard titled "Daylight in Buildings." This standard, established in 2018, aims to ensure appropriately daylit spaces in buildings (Šprah & Košir 2019). It provides recommendations for daylight provision and specifies calculation methods for assessing daylight in buildings (Matusiak 2020). EN 17037 addresses factors such as daylight provision, view out, exposure to sunlight, and protection from glare, offering comprehensive methods for evaluating daylight properties in buildings (Dervishaj, Dervishaj, Gudmundsson & Björk 2022). The standard sets requirements for daylighting in spaces regularly occupied by people (Hraška & Čurpek 2024). Additionally, EN 17037 includes climate-based daylight simulations, contributing to energy-efficient building design (Solvang, Kristiansen, Bottheim & Kampel 2020). The standard's criteria for daylight provision consider achieving target illuminance levels across a fraction of the reference plane within a space for a specified duration of daylit hours (Foged 2024). EN 17037 has been implemented in various European countries, influencing urban planning, architectural design, and building energy efficiency (Arntsen & Hrynyszyn 2021). It plays a significant role in promoting sustainable urban planning by ensuring adequate daylighting in residential developments. Overall, EN 17037 serves as a crucial guideline for architects, designers, and planners to create well-lit, comfortable, and energy-efficient building environments.

3.2.1 Key Sections and Annexes of EN 17037

The EN 17037 standard is structured into several key sections. The **Scope** section outlines the purpose and applicability of the standard, specifying minimum recommendations for achieving adequate daylighting, ensuring an adequate view out, providing appropriate sunlight exposure, and minimizing glare. This section applies to all regularly occupied spaces except where daylighting is contrary to the nature of the work done.

The **Normative References** section lists the documents and standards referenced in EN 17037 that are essential for its application. Following this, the **Terms and Definitions** section provides specific definitions related to daylighting, including terms like daylight factor, target daylight factor, and daylight glare probability. This ensures clarity and uniform understanding of key concepts throughout the document.

Next, the **Symbols and Abbreviations** section defines the symbols and units used throughout the document, aiding in the precise interpretation of technical content. The **Assessment of Daylight** section is crucial, detailing methods for evaluating daylight provision in buildings. It includes criteria for minimum daylight provision, methods for calculating daylight factors and indoor illuminances, and guidelines for ensuring adequate daylighting throughout the year. This section also covers the importance of daylight availability, the impact of external obstructions, and the properties of interior spaces.

The **General Considerations** section discusses factors affecting the quantity and quality of daylight in building interiors, such as window placement, glazing types, external obstructions, and interior design elements. Finally, the **Verification** section describes methods for verifying compliance with the standard's criteria for daylight provision, view out, sunlight exposure, and glare protection. This includes on-site measurements, calculations, and the use of validated software.

The document includes several informative annexes that provide additional recommendations and detailed methods for assessing daylighting and view out. **Annex A** offers minimum recommendations for daylighting provision, view out, sunlight exposure, and glare protection. **Annex B** presents detailed procedures for calculating daylight availability and daylight factors. **Annex C** provides guidelines for assessing the quality of views from windows. **Annex D** outlines methods for evaluating exposure to sunlight, and **Annex E** describes procedures for assessing and mitigating glare.

The standard emphasizes the importance of natural daylight in enhancing the visual and psychological comfort of building occupants. It encourages building designers to assess and ensure well-daylit spaces and provides a framework for achieving high-quality daylighting in various building types and climates.

3.2.2 Detailed Section on View from the Window

General Requirements for View Out

The publication of the European Standard EN17037 has brought attention to the topic of the window view. Studies have shown that windows play a crucial role in buildings by providing natural lighting and a connection to the external environment (Besbas, Mezerdi & Belakehal 2022). The standard emphasizes the importance of the view outside and sets guidelines for evaluating the view out in building design (Waczynska, Sokol & Martyniuk-Peczek 2021). Research has indicated that the provision of a view out through windows is highly valued, as it allows occupants to stay connected to the external environment (Woo, MacNaughton, Lee, Tinianov, Satish & Boubekri 2021). Furthermore, the view from a window has been linked to various benefits such as job satisfaction, stress reduction, and improved well-being (Brzezicki, Regucki & Kasperski 2021).

The view out from windows is a critical aspect of indoor environmental quality, contributing to occupant well-being by providing a visual connection to the outside world. This part of EN 17037 was chosen for detailed analysis because it is most fitting to test with VR tools due to its visual aspects. The standard outlines several criteria to assess the quality of views from windows, emphasizing the need for clear, undistorted, and neutrally colored views through the glazing. A good view should include several layers: sky, landscape (urban or natural), and ground, providing information about the surrounding environment, weather changes, and time of day.

Key Criteria for View Quality:

- **Width of the View Window**: The horizontal sight angle from reference points within the room should be sufficiently wide to provide an expansive view. The standard defines minimum, medium, and high-quality views based on the horizontal sight angle.
- **Distance to Outside View**: The distance to the external view should be significant enough to offer depth and a sense of openness. The farther the view, the better the sense of spaciousness.
- **Number of Layers**: A good view should include multiple layers (sky, landscape, and ground). Higher quality views have more layers visible from the reference points.

Specific Criteria for View Out

The criteria for view out are designed to ensure that occupants have a refreshing and relaxing visual connection to the outside. The view should be assessed from selected reference points corresponding to where people are located within the utilized area.

Minimum Recommendations for View Out:

- **Minimum View Quality**: The view should include at least the landscape layer, providing basic information about the external environment, such as location, time, and weather conditions.
- **Medium View Quality**: The view should include at least two layers (e.g., landscape and sky) and a broader horizontal sight angle.
- **High View Quality**: The view should include all three layers (sky, landscape, and ground) with a wide horizontal sight angle and a significant distance to the outside view.

Table 3.1: Assessment of the View Outwards from a Given Position. Source: Author

Rating of View-Out	Minimum	Medium	High
Width of view window (Horizontal Sight Angle)	> 14°	> 28°	> 54°
Outside Distance of the View	> 6 m	> 20 m	> 50 m
Number of Layers Seen from 75% of Utilized Area	Min. the landscape layer	Min. 2 layers	All layers

Practical Applications and Examples

In practical applications, ensuring an adequate view out involves careful placement and sizing of windows and consideration of the surrounding environment. Designers must prioritize windows that offer views incorporating natural elements or distant cityscapes to enhance the quality of the view.

Example Scenarios:

- **Office Building**: Ensure that workstations have a clear view out with a wide horizontal sight angle and multiple layers visible, such as the sky and surrounding buildings or landscape.
- **Residential Building**: Design windows in living rooms and bedrooms to provide views that include natural elements and offer a sense of openness, meeting at least the medium view quality criteria.

By adhering to the guidelines in EN 17037, building designers can create environments that not only meet functional requirements but also enhance the overall quality of life for occupants. The emphasis on clear, multi-layered views helps in achieving visual comfort and psychological well-being, making spaces more enjoyable and beneficial for their users.

Quality of the View as a Subject of Study

Evaluating the quality of the view out of windows is crucial in environmental psychology and building design. The perception of external views can greatly affect the well-being, productivity, and satisfaction of building occupants. The assessment of view quality involves several key aspects (Kuhlenengel, Waters & Konstantzos 2019) (Curpek & Hraška 2021):

- **Presence of Natural Elements**: Views that include natural elements such as trees, plants, and water bodies are highly valued. Exposure to nature can reduce stress, improve mood, and enhance cognitive functioning.
- **Complexity and Interest**: Visual complexity and interest are important for maintaining attention and engagement. Dynamic views that change with seasons or time of day, like moving water or swaying trees, are particularly stimulating.
- **Visual Access and Connectivity**: The degree of visual access to the outside environment is fundamental. Views that provide a sense of space and freedom without obstructions contribute positively to well-being and satisfaction.
- **Clarity and Transparency**: The clarity and transparency of the view are affected by the number of glazing layers and window material quality. Minimizing reflections and obstructions ensures a clearer, more direct view.

- **Proximity to Natural Features**: The proximity of natural features is significant. Views that allow close-up details of nature, such as leaves and flowers, enhance the feeling of connection to the natural world.
- **Cultural and Contextual Relevance**: The cultural and contextual relevance of the view is also important. Views overlooking historical landmarks or community spaces can enhance a sense of place and identity.

In summary, the quality of the view out of windows involves aesthetic, psychological, and contextual factors. Natural elements, visual complexity, clarity, and cultural relevance all contribute to creating supportive and enriching indoor environments.

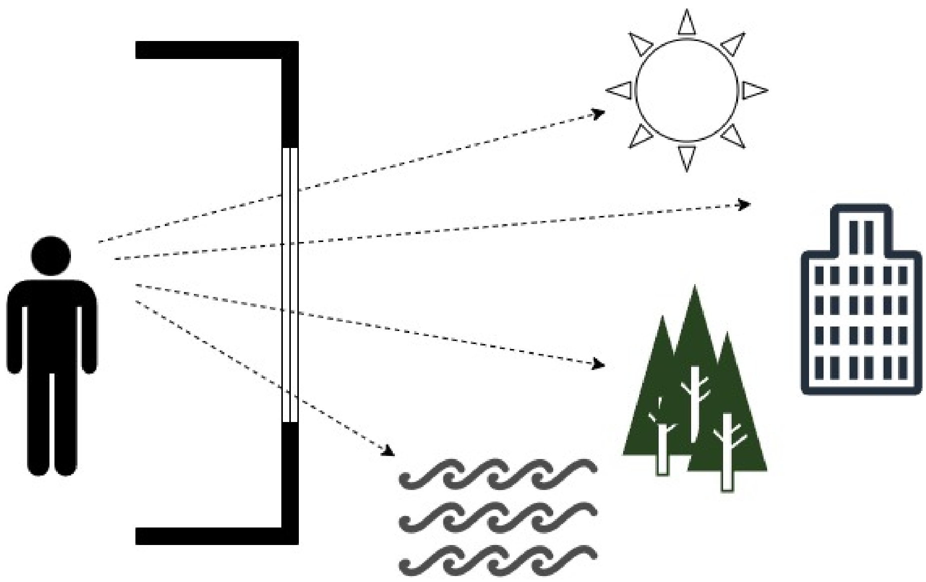


Figure 3.2. Quality of the View. Source: Author

Implications for Building Design

Incorporating these factors, EN 17037 aims to ensure that building designs not only facilitate the entry of natural light but also provide meaningful and enriching visual connections to the external environment. This approach contributes to creating more livable and sustainable building environments. By adhering to these guidelines, architects and designers can significantly improve the indoor environmental quality, thereby enhancing the overall user experience within buildings.

3.3 Categories of Measurements in Daylighting

In architectural and daylight design, various metrics and tools are employed to measure light. These measurements are crucial for creating spaces that are not only visually appealing but also functional, comfortable, and energy-efficient. This section delves into the categories of light measurements, each with its specific metrics and applications.

Daylighting involves various types of measurements that can be categorized based on different criteria such as the form of light, human reaction to light, and the application in different spaces. Here are some categories:

Form of Light This category focuses on the physical properties of light, such as its intensity, direction, and color (Phillips 2004).

Human Reaction to Light This category considers how humans perceive and react to light, including factors like comfort, mood, and health (Phillips 2004).

Application in Different Spaces This category looks at how light is applied in various types of buildings and spaces, such as residential, commercial, and public spaces (Phillips 2004).

Table 3.2: Categories of Light Measurements in Architectural and Daylight Design. Source: Author

Category	Metric	Tools	Applications
Source of Light	Daylight Factor (DF), Daylight Autonomy (DA)	Luxmeters, VELUX Daylight Visualizer	Green building certifications, architectural design
	Lumens, Wattage, Efficacy	Light meters, wattmeters	Interior design, stage design
Human Response to Light	Luminance, Glare Index	Luminance meters, HDR imaging	Office spaces, schools
	Color Rendering Index (CRI), Color Temperature	Spectroradiometers	Retail spaces, art galleries
	Melanopic Lux, Circadian Stimulus (CS)	Specialized sensors	Healthcare facilities, residential spaces
Quantitative Light Metrics	Lux (lm/m^2)	Luxmeters	Reading areas, workspaces
	Lumens (lm)	Integrating spheres	Product development, quality control
	Lumens per Watt (lm/W)	Light meters, wattmeters	Energy audits, green building certifications

Types of Daylight Calculations in Architecture Daylight calculations are crucial for optimizing the natural light in architectural designs. These calculations help in making informed decisions about the placement of windows, the type of glazing to use, and other architectural elements that influence daylighting. Here are three primary types of daylight calculations:

Illuminance Calculations Illuminance calculations measure the amount of light falling on a surface within the building, usually in lux. Factors like the sun's angle, obstructions, and surface reflectivity are considered (Phillips 2004).

Daylight Factor Calculations This method calculates the ratio of indoor to outdoor illuminance under overcast sky conditions. It is particularly useful in regions with frequent cloudy weather (Phillips 2004).

Climate-Based Daylight Modeling This comprehensive approach uses weather data to simulate daylight conditions throughout the year, providing a dynamic analysis of daylight availability (Phillips 2004).

3.4 Survey on the Usage of VR in Lighting Research and Lighting Design Practice Under IEA SHC Task 70

As part of the SHC IEA Task 70, a comprehensive survey was conducted to evaluate the use of Virtual Reality (VR) in lighting research. This section provides an executive summary of the survey findings, divided into specific subsections addressing the limitations, expectations, and key differences between professionals and researchers in the field [paper to be submitted].

3.5 Conclusions

EN 17037: Daylighting in Buildings sets comprehensive standards for natural lighting in architectural design, aiming to improve indoor environments through optimal daylight exposure. It applies to various building types, ensuring sufficient illuminance levels, access to direct sunlight, and protection from glare. By adhering to these guidelines, buildings can achieve better occupant well-being, energy efficiency, and sustainability.

This chapter has outlined the key aspects of EN 17037 and its importance in modern architectural practice. Implementing these standards helps designers and architects create spaces that not only meet regulatory requirements but also enhance the quality of life for occupants. The comprehensive approach of EN 17037 represents a significant step forward in the pursuit of optimized daylighting in buildings.

Part II

Research and Analysis: Utilizing VR Tools - An Overview of Practices and Technologies

Chapter 4

Utilizing VR in Lighting Research and in Practice

4.1 Introduction to VR in Research and in Practice

Virtual reality (VR) technology has been widely utilized in various fields of research and practice. In design research and practice, VR has proven to be a valuable tool (*Potential Usages of Virtual Reality in Design Research and Practice – A Review* 2022). It has also been used in education to improve career opportunities for women in technology (Onele 2022). In the field of sports psychology, VR has been applied to provide a more realistic and immersive experience for athletes (Liu, Li, Guo, Chai & Cao 2022). VR has also been explored in product design and evaluation systems, enabling decision assistance and data analysis (*Research on the Product Design and Evaluation System Based on Virtual Reality Technology* 2022). In the manufacturing industry, VR has been used for process simulation (Mujber, Szécsi & Hashmi 2004). In the realm of art and design, VR has been employed for virtual reality display design and expression (*The Application of Virtual Reality in Art Design: A New Approach* 2015). VR has also been studied in the context of competitive athletes, simulating real environments and invoking embodied simulations (Akbaş, Marszałek, Kamieniarz, Polechoński, Słomka & Juras 2019). In the medical field, VR has been investigated for its applications in medicine, therapy, and training (Riva 2003) (Jung, Eun, Cho, Kim & Park 2019).

Furthermore, VR has been used in psychology research to enhance experiential education and learning motivation (Hsiao 2021). In the context of festivals, VR has been examined for its potential in enhancing consumer experiences (Lee, Choi, Choi & Hong 2022). VR has also been applied in dance teaching, particularly in emotional guidance and knowledge understanding (Yuan 2023). Libraries have started incorporating VR and augmented reality (AR) technologies to enhance the user experience (Horban, Gaisynuik, Dolbenko, Karakoz, Kobyzhcha & Kulish 2023). VR has been used as a substitute for fieldwork in design education, providing contextual aspects in a virtual environment (Frydenberg & Nordby 2022). In the maritime industry, VR has been implemented for ship bridge simulation and training (Siswantoro, Haryanto, Hikmahwan & Pitana 2023). VR has also shown promise in design sessions when compared to traditional methods in architecture (Reddy, Venkatesh & Kumar 2022). In the realm of sports training, VR has the potential to facilitate scientific training and research (Zhang & Tsai 2021). In the field of education, VR has been explored for geometry classes and creative learning (Song & Lee 2002).

Additionally, VR has been applied to turn-milling centers, providing a realistic interactive environment (*Applications of Virtual Reality in Turn-Milling Centre* 2008). The future of VR and AR is expected to have significant impacts on various aspects of daily life (*International Workshop on Multimodal Virtual and Augmented Reality (Workshop Summary)* 2016). VR has been used to create virtual scenes of ancient architecture, allowing users to roam and explore (*Virtual Reality Scene Model of Ancient Architecture Based on 3D Technology* 2023). In the context of destination marketing, virtual tours of museums have been developed using VR and AR technologies (Yerden & Uydaci 2022). VR has been studied in the field of international business negotiation, integrating simulation, computer graphics, and sensing technology (Zhao 2022).

In context of VR in Urban Planning and Design Virtual reality technology has gained significant attention. It has been recognized as a valuable tool for enhancing public engagement, improving understanding of projects, and facilitating participatory processes (*Effectiveness of Virtual Reality in Participatory Urban Planning* 2018) (Meenar & Kitson 2020). VR allows users to experience immersive and interactive environments, providing a more vivid and engaging experience compared to traditional non-immersive displays (*Effectiveness of Virtual Reality in Participatory Urban Planning* 2018). By integrating 3D modeling and immersive VR technologies, citizens can be empowered to actively participate in the planning and design of their cities (*Effectiveness of Virtual Reality in Participatory Urban Planning* 2018).

One of the key advantages of VR in urban planning is its ability to enhance real-life perception through the implementation of urban digital twins (Dembski, Wössner, Letzgus, Ruddat & Yamu 2020). Urban digital twins are virtual representations of real-world cities that can be visualized and interacted with in VR and augmented reality (AR) environments (Dembski et al. 2020). These digital twins can seamlessly integrate various urban data from models, analysis, and simulations, providing a comprehensive and multi-layered view of the city (Dembski et al. 2020). This enables collaborative and participatory processes in urban planning and design, allowing stakeholders to make informed decisions based on a holistic understanding of the city (Dembski et al. 2020).

The use of VR in urban planning and design is not limited to visual aspects. It can also be applied to evaluate and enhance the soundscape of urban public spaces (sun, Coensel, Filipan, Aletta, Renterghem, Pessemier, Joseph & Botteldooren 2019). Immersive VR can provide a valuable tool for interactive participatory evaluation of the soundscape, allowing stakeholders to experience and assess the acoustic environment of urban spaces (sun et al. 2019). As VR reproduction systems become more affordable and widely available, the potential for using VR in soundscape evaluation and design becomes increasingly feasible (sun et al. 2019).

Furthermore, VR technology has been explored for its potential in improving the usability of online geographic VR for urban planning (Zhang & Moore 2013). With the availability of online VR tools, such as OpenSimulator, there is potential for using VR in 3D urban planning and design tasks (Zhang & Moore 2013). However, rigorous assessment is still needed to establish the effectiveness and usability of these tools (Zhang & Moore 2013).

In addition to its practical applications, VR has also been recognized as a valuable visualization tool in exploring user experience in urban planning and design (Negm, Elshater & Afifi 2023). It allows designers and planners to create immersive and interactive environments that simulate real-world scenarios, enabling them to assess the impact of design decisions on user experience (Negm et al. 2023). This can lead to more user-centered and inclusive urban design outcomes.

In the broader context of urban planning and design, VR has gained significant attention, especially in the domain of smart urban lighting design. By creating virtual environments, planners and designers can visualize and assess different design aspects, including lighting systems, from multiple perspectives (Jamei, Mortimer, Seyedmahmoudian, Horan & Stojcevski 2017). This allows for a comprehensive understanding of the potential impact of lighting design on the urban environment and its users (Scorpio, Laffi, Masullo, Ciampi, Rosato, Maffei & Sibilio 2020).

Furthermore, VR can support the integration of lighting design with other urban planning considerations, such as mobility and environmental sustainability. By combining VR with urban mobility simulations and air-flow simulations, designers can evaluate the impact of lighting systems on pedestrian and cyclist routes, as well as on air quality and energy consumption (Dembski et al. 2020). This integrated approach allows for a more holistic and sustainable design of smart urban lighting systems.

The combination of VR with other technological advancements, like Building Information Modeling (BIM), the Internet of Things (IoT), geographic information systems (GIS), and augmented reality (AR), further expands the opportunities for smart urban lighting design and daylighting analysis (Mazzucato, Dowsett & Walker 2017) (Mahdavi, Haase & Reinhart 2017) (Boulos, Lu, Guerrero, Jennett & Steed 2017) (Zhang et al. 2022).

Overall, VR technology has emerged as a powerful tool in urban planning and design, offering immersive and interactive experiences that enhance public engagement, improve understanding, and facilitate participatory processes. It enables the creation of urban digital twins, enhances the evaluation of soundscapes, improves the usability of online geographic VR, and contributes to user-centered and inclusive design outcomes. Furthermore, VR has the potential to support the modeling and visualization of smart cities, providing insights into sustainable and smart city development.

Table 4.1: Advancements and Challenges in Virtual Reality (VR) Technologies. Source: Author

Research Area	Current State	Gaps	Tools/Examples
Cloud-based Processing	Enables immersive VR without costly hardware for collaborative training and meetings.	Requires better real-world data integration.	LetsVR: Cloud VR collaboration.
Volumetric VR	Provides realistic 3D scenes for enhanced interactivity.	Needs AI/ML advancements for efficiency.	Iconic Engine: Immersive content solutions.
High-Fidelity Display & Audio	Boosts VR realism with superior visual and audio quality.	Innovation needed in displays and audio for realism.	Hypervision: Wide-view devices; Treble Technologies: Spatial audio.
Eye & Gesture Tracking	Offers intuitive VR interactions, enhancing engagement.	Needs more accurate, non-intrusive technologies.	
Haptics and Interactive VR	Delivers dynamic experiences with tactile feedback.	Requires advanced systems for varied textures.	
Full-Body Capture	Transfers user movement to VR avatars for presence.	Seeks better accuracy and lower latency.	
Daylight Analysis in VR	Uses VR for architectural daylighting simulations.	Gaps in lighting models and physical validation.	Inferred from VR advancements in visualization.

4.2 Focus on VR in Daylight Research

Daylighting research, a crucial aspect of architectural and urban design, significantly benefits from the application of VR. VR's ability to provide an immersive and interactive setting for assessing daylighting conditions has enhanced both the methodology and the outcomes of daylight studies.

Ensuring human health and well-being is a primary concern in architectural design, particularly in how daylighting affects human comfort and physiological responses. The application of VR in daylighting research, though relatively nascent, has seen a surge in studies exploring its potential benefits and applications. A cornerstone in this emerging field is the PhD thesis by Kynthia Chamilothori (2019). Her work employs immersive VR as an experimental tool and combines it with physiological data collection. This multi-faceted approach has led to significant findings, such as the influence of façade and daylight patterns on both subjective and physiological human responses. These findings substantiate the utility of VR in daylighting studies, offering a robust methodology for understanding human perception in architectural settings.

A primary advantage of employing VR in daylighting research is its capability to offer an immersive and interactive setting for assessing daylighting conditions. This immersive nature can facilitate a more intuitive and captivating experience for users, as opposed to conventional 2D visualizations and numerical data. Evidence suggests that VR can be effectively utilized to model and forecast daylighting conditions in structures, yielding more precise and exhaustive outcomes than traditional daylighting analysis techniques (Chowdhury, Kim & Lee 2017) (Kim, Lee & Chowdhury 2017) (Kim, Lee, Cho, Hwang, Yoo & Chae 2019).

Despite the myriad benefits, the adoption of VR in these domains comes with challenges, including the need for accurate data for creating realistic virtual environments and the integration of advanced lighting simulation models (Dembski et al. 2020) (Krupiński 2020). However, as VR technology continues to evolve, it is poised to play an increasingly pivotal role in these fields, fostering more informed and sustainable decision-making processes (Allam, Sharifi, Bibri, Jones & Krogstie 2022).

VR holds immense promise in reshaping the future of daylighting research, urban planning, and smart urban lighting design. Its potential to revolutionize traditional methodologies and offer immersive, real-world simulations makes it an indispensable tool for future research and applications.

Virtual Reality (VR) technology presents multiple merits for daylight analysis in architectural design. Some of these advantages encompass:

- **Realistic Simulation:** VR furnishes an intensely immersive and lifelike emulation of the physical milieu, empowering designers to visualize and experience the influence of daylight in a space prior to its construction. This is particularly beneficial for intricate architectural designs where conventional daylight analysis might fall short in detailing (Kim, Lee & Chowdhury 2017).
- **Ease of Use:** VR platforms are user-centric and instinctive, enabling designers to promptly comprehend the outcomes of their daylight simulations. This efficiency trumps traditional methods that demand intricate computations and manual interventions (Chowdhury et al. 2017).
- **Interactive Exploration:** VR grants designers the liberty to engage with the virtual realm and modify it instantaneously. This adaptability allows designers to swiftly modify and hone their concepts, eliminating the necessity for tangible prototypes or mock-ups (Kim, Lee, Cho, Hwang, Yoo & Chae 2019).
- **Enhanced Communication:** VR facilitates a collective visual journey for all stakeholders, simplifying the process for designers to relay their design visions and propositions to clients, engineers, and the broader design ensemble. This augmented communication can catalyze more proficient and informed decision-making (Sabater, Martínez, Puertas, Lumbreras & Adánez 2019).

Notwithstanding its plethora of benefits, the incorporation of VR in daylight analysis is not devoid of limitations. Some of the challenges are:

- **Expense:** Procuring VR technology can be a costly affair, necessitating substantial investments in hardware, software, and training. This might restrict its adoption in smaller entities or budget-constrained projects (Kim, Lee & Chowdhury 2017).
- **Complexity:** Setting up VR simulations, especially for expansive and multifaceted structures, can be intricate. Such setups might demand specialized acumen, which could be scarce, particularly in smaller locales (Chowdhury et al. 2017).

- **Limited Accuracy:** The precision of VR simulations hinges on the accuracy of the input data and the models employed. Inaccurate inputs or non-representative models can skew the simulation results (Mahdavi et al. 2017).
- **Lack of Standardization:** The infusion of VR in daylight analysis is still in its infancy, leading to an absence of standardized protocols and best practices. This void can result in inconsistent outcomes and challenges in juxtaposing data across different simulations (Liang, Chen & Tai 2019).

On the whole, while VR technology brings a host of advantages to daylight analysis, it's imperative to weigh both its strengths and weaknesses when contemplating its adoption for a specific project.

Despite the increasing interest, certain gaps in the existing literature hint at the immense potential for future research in the use of VR technology for daylight analysis. This section highlights the major gaps and suggests avenues for future research to refine and improve the use of VR for daylight analysis.

4.2.1 Comparison Between VR and Traditional Daylighting Analysis Methods

Virtual Reality (VR) and traditional daylighting analysis methods are two approaches for evaluating and predicting the amount of daylight in a building. While both methods have their own advantages and limitations, there are several key differences between VR and traditional daylighting analysis methods.

One of the main differences is the level of immersion and interactivity. VR technology provides a highly immersive and interactive environment that allows users to experience and analyze daylight in a more realistic and intuitive way. In contrast, traditional daylighting analysis methods typically rely on 2D representations and numerical data, which can be less engaging and less accessible to non-specialists.

Another difference is the level of accuracy and precision. Traditional daylighting analysis methods are based on complex mathematical models and simulations that can provide highly accurate and precise results. However, these results may not always be easily understandable or intuitive. On the other hand, VR technology provides a more realistic and intuitive representation of daylighting, but may not always provide the same level of accuracy and precision as traditional methods.

Finally, the speed and efficiency of the analysis process is also a difference between VR and traditional methods. Traditional daylighting analysis methods can be time-consuming and require specialized knowledge and software to complete. VR technology, on the other hand, provides a more streamlined and accessible process that can be completed more quickly and efficiently, without the need for specialized knowledge or software.

Despite the increasing interest in the use of Virtual Reality (VR) technology for daylight analysis, there are still several gaps in the existing literature. Some of these gaps include:

One of the major gaps in the current research is the lack of validation and verification of VR simulations. While VR provides a highly immersive and realistic simulation of the physical environment, it is important to determine how accurate these simulations are, and to compare them to actual physical measurements. Further research is needed to develop and validate methods for verifying the accuracy of VR simulations, and to compare them to traditional daylight analysis methods (Mahdavi et al. 2017).

Another gap in the current research is the lack of integration between VR and other design tools, such as Building Information Modeling (BIM) and computer-aided design (CAD) tools. Integration would allow designers to easily import and export data between these tools, and to more efficiently and effectively use VR for daylight analysis. Further research is needed to explore the possibilities for integrating VR with other design tools, and to develop methods for doing so (Liang et al. 2019).

While VR simulations can provide a highly realistic representation of the physical environment, they may not accurately reflect human perception and comfort. For example, VR simulations may not take into account the effects of glare or other factors that can affect human comfort. Further research is needed to better understand the relationship between VR simulations and human perception and comfort, and to develop methods for accurately representing these factors in VR simulations (Sabater et al. 2019).

Overall, there are many opportunities for future research in the use of VR technology for daylight analysis. Further studies are needed to address the gaps in the existing literature, and to continue to refine and improve the use of VR for this purpose.

4.2.2 Overview of the SHC IEA Task 70 Survey

The SHC IEA Task 70 survey aimed to gather insights from both academics and professionals regarding the integration of VR technology in lighting research. The survey explored various aspects such as the current limitations, expectations, and practical challenges faced by both groups.

Academic Limitations

Academic respondents highlighted that while VR cannot fully simulate climatic behaviors, it can visually represent daylight and its qualities in space. VR was identified as a promising tool to address the shortcomings of traditional daylight experiments, providing immersive and accurate visual representations of light. Additionally, academics emphasized novel methods for creating fully immersive scenes from photometrically accurate renderings, encouraging the use of VR technologies as empirical tools in lighting research.

Professional Expectations

Professionals see VR as a powerful tool for rapid prototyping and testing lighting designs in controlled virtual environments, accelerating the design process without the need for physical prototypes. In educational contexts, VR provides immersive experiences that are difficult to replicate in traditional classroom settings, making it valuable for training lighting designers, photographers, and cinematographers. Furthermore, for consumer-facing industries like retail and interior design, VR offers customers a virtual preview of how lighting will appear in their spaces, aiding decision-making and providing personalized design solutions.

Key Differences Between Professionals and Researchers

The survey revealed that professionals prioritize ease of use and highlight the importance of user-friendly interfaces and straightforward integration into their workflows. Professionals and researchers both emphasized the importance of accuracy and realism in lighting simulations, but this was a more prominent concern for researchers. Real-time rendering capabilities were more significant for researchers, highlighting the research community's need for immediate feedback and adjustments during experimental studies.

Shared Challenges

The effectiveness of VR simulations is heavily dependent on the underlying technology, including the accuracy of color reproduction and light behavior in the VR environment. Both groups acknowledged that hardware limitations could affect the fidelity of lighting simulations. While VR technology is becoming more accessible, the cost of high-quality VR setups remains a barrier, especially for small businesses and individuals. Issues such as motion sickness, eye strain, and the ergonomics of VR headsets limit the usability of VR for prolonged periods, affecting the practicality of using VR for extended design sessions or training. Integrating VR into existing design and workflow systems can be complex and require significant adjustments, including training staff to use VR tools effectively and ensuring VR outputs are compatible with other software systems.

Conclusion

The SHC IEA Task 70 survey highlights both the promising potential and the significant challenges associated with the use of VR in lighting research. While professionals emphasize ease of use and practical applications, researchers focus on technical accuracy and realism. Both groups recognize the need for advancements in hardware, better integration with existing systems, and overcoming user experience issues to fully harness the benefits of VR technology in lighting research.

4.3 Conclusions

This comprehensive exploration into the utilization of Virtual Reality (VR) across various domains, particularly within the realms of lighting research, urban planning, and design, underscores the transformative potential of VR technology. An extensive review delineates VR's multifaceted applications, from enhancing immersive educational experiences to revolutionizing urban planning processes and facilitating advanced daylighting analysis. The versatility of VR, as highlighted through its application in diverse fields, signifies a paradigm shift towards more interactive, user-centered design and research methodologies.

The examination of VR's benefits reveals its capacity to render complex architectural and urban concepts into immersive simulations, thereby offering stakeholders a more intuitive understanding of spatial dynamics and lighting aesthetics. VR's unique ability to simulate realistic environments contributes significantly to participatory design processes, enabling a deeper engagement with end-users and fostering a collaborative decision-making environment.

However, the adoption of VR is not without challenges. Issues such as high costs, complexity in simulation setup, and the need for accurate data for realistic environments are notable barriers. Moreover, the precision of VR simulations, dependent on the veracity of input data and the fidelity of models used, poses a question to its reliability for detailed analysis. These challenges necessitate a balanced consideration of VR's potential against its limitations.

This review also identifies critical gaps in the current body of research, notably the need for validation and verification of VR simulations against real-world measurements and the integration of VR with other architectural and design tools. Addressing these gaps through future research will be crucial in harnessing VR's full potential.

In conclusion, VR technology emerges as a powerful tool in the landscape of urban planning, design, and lighting research, offering unprecedented opportunities for immersive visualization and participatory engagement. Its ability to combine detailed architectural simulations with user-centric experiences positions VR as a catalyst for innovative design and research methodologies. As the technology continues to evolve, and as solutions to its current challenges are developed, VR's role in shaping the future of urban environments and architectural practices is poised for significant expansion. The journey towards fully realizing VR's capabilities is ongoing, with promising avenues for future research and application that could redefine traditional methodologies and foster more informed, sustainable, and inclusive design outcomes.

Chapter 5

Hardware and software for VR in Research

5.1 Wider Analysis of VR Devices and its Development

The development of Virtual Reality (VR) devices has seen significant advancements, resulting in headsets that are more powerful, smaller, and offer higher resolutions. The variety of VR headsets available today includes options for different needs and budgets, from high-end, feature-rich systems to more affordable, specialized solutions. This includes PC-connected VR (PCVR) headsets, standalone VR headsets, and smartphone-based VR solutions, each with its own advantages and limitations.

PCVR headsets are known for their superior graphics and extensive features, making them suitable for complex applications but requiring powerful computers and often being more expensive. Standalone VR headsets offer a balance between performance and convenience, providing a wireless experience without the need for a PC, but typically with slightly lower performance compared to PCVR. Smartphone-based VR solutions are the most cost-effective, utilizing the phone's display and processing power, but they lack the immersive quality and advanced features of more expensive options.

Choosing the right VR device is crucial and depends on the specific needs and constraints of the project. High-end VR systems are ideal for applications requiring high fidelity and complex interactions, whereas more affordable and simpler devices can be sufficient for targeted use cases, such as basic simulations or educational tools. This chapter provides a comprehensive analysis of VR devices, evaluating their capabilities, limitations, and suitable applications to aid in selecting the most appropriate technology for various project requirements.

5.1.1 Evolution of VR Devices

The journey of VR headsets from tethered devices reliant on powerful PCs to standalone units has significantly expanded the scope and accessibility of virtual reality. Major players in the market have continually evolved their offerings, improving aspects like resolution, field of view, tracking accuracy, and overall user experience. This evolution has largely been driven by advancements in computing power, miniaturization of sensors, and the development of better display technologies.

5.1.2 Meta Quest 2

The Meta Quest 2 stands out for its standalone capabilities, eliminating the need for external hardware. Its high-resolution display ensures crisp visuals, making it suitable for detailed simulations in research. The device's intuitive interface and user-friendly design make it a preferred choice for researchers who prioritize ease of use. Moreover, its compatibility with a wide range of VR applications broadens its utility in various research domains.

Applications in Research

The Meta Quest 2's versatility has been leveraged in fields like medical training, where students can practice surgeries in a risk-free environment. In architectural research, the device allows for immersive walkthroughs of 3D building models, facilitating better design evaluations.

5.1.3 PlayStation VR2

Sony's PlayStation VR2 is not just a gaming accessory; it's a powerful research tool. Its high refresh rate ensures smooth visuals, crucial for maintaining immersion in research simulations. The device's compatibility with the PlayStation 5 console means it can tap into a robust hardware ecosystem, ensuring high-performance VR experiences.

Applications in Research

The PlayStation VR2 has found applications in psychological research, where researchers study human responses to various stimuli in a controlled VR environment. Its gaming-centric design also makes it suitable for gamified research experiments, where participant engagement is paramount.

5.1.4 HTC Vive Cosmos

The HTC Vive Cosmos is renowned for its precision tracking and high-resolution display. Its modular design allows for hardware upgrades, ensuring it remains relevant even as VR technology advances. The device's expansive field of view ensures a more natural and immersive experience, which can be crucial in research settings where realism is essential.

Applications in Research

The HTC Vive Cosmos is popular in behavioral research, where the device's precise tracking can monitor minute participant movements. Its high-resolution display is beneficial in visual experiments, where detail and clarity are essential.

Table 5.1: Comparison of mainstream HMDs. Source: Author

	Oculus Quest 2	**PlayStation VR**	**HTC Vive Cosmos**
Price	$299	$299	$699
Resolution (pixels per Eye)	1832 x 1920	960 x 1080	1440 x 1700
Refresh Rate	90 Hz	120 Hz	90 Hz
Field of View	Approx. 100°	Approx. 100°	Approx. 110°
Tracking	6DOF	6DOF	6DOF

5.1.5 Emerging VR Devices

Meta Quest 3

Meta Quest 3, released in October 2023, is a standalone VR headset with a per-eye resolution of 2064x2208 pixels. Its mixed reality features offer a diverse category of VR games and experiences, enhancing the exploration of the metaverse. Priced $500 shows a significant improvement over its predecessor, Quest 2, by packing more power and features without adding to the headset's weight.

Apple Vision Pro

The Apple Vision Pro [fig. 5.1], available from early 2024, is a standalone mixed-reality headset. Its resolution is 3660×3200 pixels per eye. This headset, featuring a dual-chip system with Apple's M2 and a new R1 chip, doesn't require a PC or external base stations for use. Its design includes a unique headband, a light seal, and an array of advanced cameras and sensors for a seamless VR/AR experience.

The Apple Vision Pro boasts an intuitive user experience, where users select options by looking at them and confirm their choices by pinching their fingers. However, being as personal device as iPhone, it presents challenges for group use when only one device is available. Its advanced technology and user-friendly interface make it a powerful tool for individual users, offering an unparalleled mixed-reality experience.

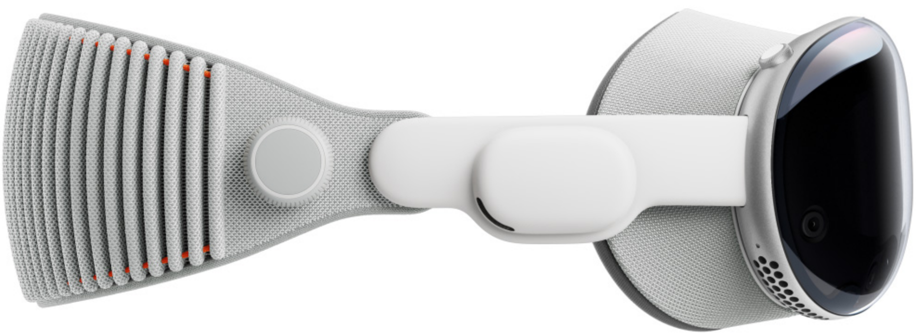


Figure 5.1. Apple Vision Pro. Source: `https://www.apple.com/v/apple-vision-pro/c/images/overview/intro/intro_spin_endframe__dy927flmi3au_large.jpg`

Table 5.2: Comparison of Emerging HMDs. Source: Author

	Meta Quest 3	Apple Vision Pro
Price	$500	$3499
Resolution (pixels per Eye)	2064 x 2208	3391 x 3391
Tracking	6DOF	6DOF

5.2 VR Software and Examples

5.2.1 Development Platforms

When it comes to developing Virtual Reality (VR) applications, Unity and Unreal Engine stand out as the most prominent game engines, each bringing distinct advantages to the table. Unity is known for its user-friendly interface and gentle learning curve, making it accessible to beginners and seasoned developers alike. Its extensive documentation and active community further enhance the development experience. Unity supports a wide range of VR platforms, including Oculus, HTC Vive, and PlayStation VR, providing developers with flexibility in targeting multiple devices. Additionally, Unity offers robust performance optimization capabilities, allowing developers to fine-tune their applications for smooth performance even on less powerful hardware.

On the other hand, Unreal Engine excels in delivering exceptional graphics quality, making it the preferred choice for projects that require high-end visuals and advanced rendering capabilities. Although it has a steeper learning curve, Unreal Engine provides detailed documentation and a strong community to support developers. Its native and mature Blueprint system for visual scripting is particularly advantageous for creating complex interactions without extensive coding. Unreal Engine also boasts comprehensive support for major VR platforms and offers powerful performance tuning tools. Despite its initial complexity, Unreal Engine's superior graphics, advanced animation tools, and seamless integration with VR SDKs make it a powerful engine for developing immersive and visually stunning VR experiences.

Both engines offer extensive asset marketplaces, regular updates, and abundant learning resources, ensuring developers have access to the tools and support needed for VR development. While Unity is praised for its straightforward setup and ease of use with popular VR devices like Oculus Quest and HTC Vive, Unreal Engine offers unparalleled performance and visual fidelity for high-end VR projects. The choice between Unity and Unreal Engine ultimately depends on the specific needs of the project and the developer's priorities in terms of ease of use, graphical requirements, and platform support [table 5.3].

5.2.2 VR Software Examples

Software like ENGAGE VR and ClassVR provide interactive learning environments, enabling immersive educational experiences.

Touch Surgery and Osso VR offer realistic surgical simulations, aiding in medical training and procedure planning.

Tools like Twinmotion and Enscape allow for real-time architectural visualization, facilitating better design evaluations and client presentations.

5.3 Uncanny Valley in VR

The concept of the uncanny valley [fig. 5.2] in virtual reality (VR) has been a topic of interest in various fields, including computer science, psychology, and perception (MacDorman, Green, Ho & Koch 2009). The uncanny valley refers to the phenomenon where human-like virtual characters or objects that are almost, but not quite, realistic can evoke feelings of unease or discomfort in viewers (Seyama & Nagayama 2007). This concept has implications for the design and development of VR experiences, as it highlights the importance of creating virtual characters and environments that strike a balance between realism and familiarity.

Research has shown that the degree of realism in virtual human faces can influence the perception and impression of these characters (MacDorman et al. 2009). When virtual faces are too realistic, they can elicit negative responses from viewers, leading to a dip in affinity known as the uncanny valley (MacDorman et al. 2009). Design principles have been proposed to bridge this uncanny valley and create more comfortable and engaging virtual experiences (MacDorman et al. 2009).

The uncanny valley has also been studied in the context of social interaction in VR (Pan & Hamilton 2018). Challenges such as embodiment, simulation sickness, and presence can impact the perception of virtual

Table 5.3: Comparison of Unity and Unreal Engine Features for VR Development. Source: Author

Feature	Unity	Unreal Engine
Ease of Use	User-friendly with a gentle learning curve; extensive documentation and community support	Steeper learning curve; detailed documentation; strong community
Platform Support	Supports a wide range of VR platforms (Oculus, HTC Vive, PlayStation VR, etc.)	Comprehensive support for major VR platforms (Oculus, HTC Vive, PlayStation VR, etc.)
Performance Optimization	High level of optimization control; lightweight engine	Highly optimized for high-end graphics; powerful performance tuning tools
Graphics Quality	Good graphics quality; suitable for many VR applications	Exceptional graphics quality with advanced rendering capabilities
Blueprints /Visual Scripting	Bolt for visual scripting; less mature than Unreal's system	Native and robust Blueprint system for visual scripting
Asset Store /Marketplace	Extensive Asset Store with a variety of VR-ready assets	Unreal Marketplace with high-quality assets, including many VR-specific resources
VR SDK Integration	Easily integrates with VR SDKs (OpenVR, Oculus SDK, etc.)	Seamless integration with VR SDKs (OpenVR, Oculus SDK, etc.)
Cross-Platform Development	Strong support for cross-platform development, including VR	Equally strong support for cross-platform VR development
Animation System	Powerful and flexible animation system	Advanced animation tools; superior for complex animations
Cost	Free tier available; subscription plans for advanced features	Free with royalty-based model on commercial products
Community and Support	Large, active community with numerous tutorials and forums	Active community with extensive tutorials and forums
Updates and Improvements	Regular updates with new features and improvements	Regularly updated with cutting-edge features and enhancements
Native VR Support	Built-in VR support; easy to set up and deploy VR projects	Comprehensive native VR support; highly configurable for VR projects
Learning Resources	Abundant learning resources, including official tutorials and third-party courses	Extensive learning resources, including detailed official documentation and third-party tutorials
Ease of Use with Top VR Devices	Very straightforward setup and development with Oculus Quest, HTC Vive, and other popular VR headsets	Slightly more complex setup but excellent support and performance with top VR headsets like Oculus Rift, HTC Vive, and PlayStation VR

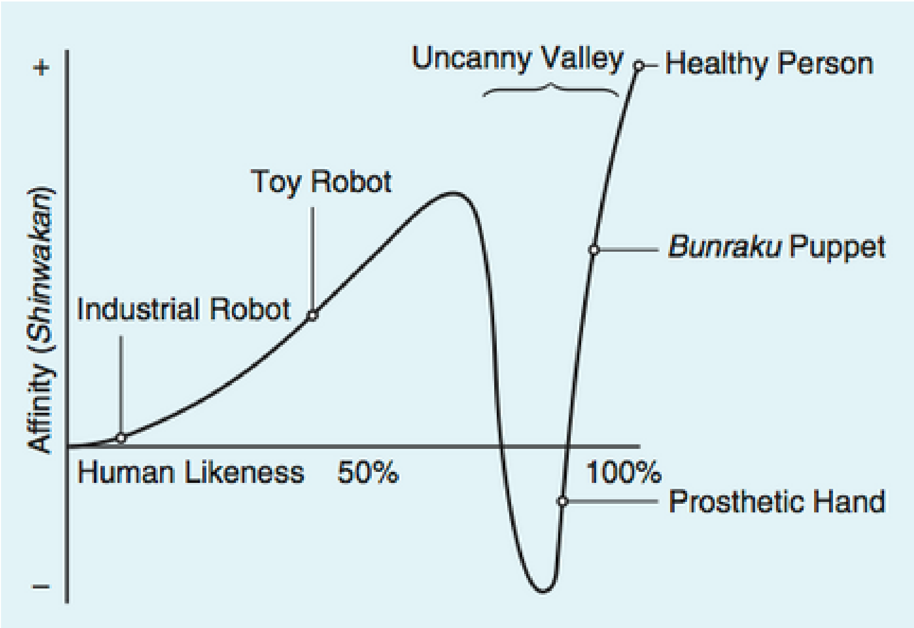


Figure 5.2. Uncanny Valley. Source: Masahiro Mori, "The Uncanny Valley." IEEE Robotics & Automation Magazine

characters and contribute to the uncanny valley effect (Pan & Hamilton 2018). Understanding and addressing these challenges is crucial for creating more realistic and immersive social interactions in VR (Pan & Hamilton 2018).

Research has explored the development of the uncanny valley effect in infants (Lewkowicz & Ghazanfar 2011). It is suggested that this phenomenon may be evolutionary in origin, tapping into modules for disgust or attractiveness that detect violations of normal expectations regarding social signals (Lewkowicz & Ghazanfar 2011). This research highlights the potential role of innate responses in the perception of the uncanny valley.

The uncanny valley effect has also been investigated in the context of non-human virtual characters, such as animals (Rátiva, Postma & Zaanen 2022). The findings contribute to our understanding of the uncanny valley hypothesis and provide a basis for further studies on animal-likeness in virtual characters (Rátiva et al. 2022).

Furthermore, the uncanny valley has been examined in relation to the perception of artificial agents and robots (Diel & Lewis 2022). Studies have shown that familiarity, orientation, and realism can increase the perception of uncanniness in faces and nonverbal behavior of artificial agents (Diel & Lewis 2022). Overcoming the uncanny valley is a topic of interest in the field of robotics and human-robot interaction (Thepsoonthorn, Ogawa & Miyake 2021).

In summary, the concept of the uncanny valley in VR has been explored in various research fields, including computer science, psychology, and perception. The degree of realism, familiarity, and embodiment in virtual characters and environments can influence the perception and response of viewers, leading to the uncanny valley effect. Understanding and addressing the challenges associated with the uncanny valley is crucial for creating more comfortable and engaging VR experiences.

5.4 Conclusions

This chapter provides an in-depth overview of the essential tools and technologies that facilitate virtual reality applications in various research domains. The rapid evolution of VR hardware, from early devices to advanced systems has significantly enhanced the capability to conduct immersive and interactive research. The development of these devices has focused on improving user experience, increasing accessibility, and expanding the potential for realistic simulations.

On the software front, platforms such as Unity, Unreal Engine and various VR-specific development tools have emerged as powerful solutions for creating and implementing VR environments. These software solutions enable researchers to design complex simulations and conduct detailed analyses, contributing to advancements in fields like architecture, education, and health. By leveraging these advanced hardware and software tools, researchers can achieve more accurate and impactful outcomes, demonstrating the transformative potential of VR in the research landscape.

Part III

Building and Testing the Author's VR Tools for Daylighting and Architectural Research

Chapter 6

Pilot tools - from the most common to perfect scenario

6.1 Introduction

This chapter delves into the development of two significant Virtual Reality (VR) tools created by the author, highlighting the diverse approaches to leveraging VR technology within the domains of architecture and urbanism. The first tool emerged from the author's extensive experience and observations within architectural practices. Although these insights were not derived from hard data, it became evident that VR walkthrough applications were the most prevalently utilized tools in the architectural field. These allow users to navigate through meticulously crafted virtual models of buildings or urban spaces, providing an immersive and interactive experience that significantly aids in design visualization, client presentations, and decision-making processes.

Recognizing the value of VR walkthroughs in architectural design, the author embarked on developing a second, more specialized application named ALTO VR - the Architectural Lighting Tool. This tool was conceived to address the specific need for evaluating daylighting in architectural designs. ALTO VR introduced a pioneering feature that allowed users to create and manipulate the environment from within the VR experience itself, akin to the building mechanics found in popular simulation games like The Sims. This interactive capability enabled architects and designers to experiment with various design elements and observe the impact of natural light in real-time. Additionally, ALTO VR supported the importation of pre-existing 3D models, allowing users to modify parameters and conditions to explore different lighting scenarios and their effects on architectural spaces.

The insights collected from the development and deployment of these two applications were crucial for the subsequent experiment involving a larger number of participants. It became clear that for such experiments to be effective, the applications needed to feature a flat learning curve, enabling participants to quickly learn and navigate through the experiment. Moreover, the features incorporated had to deliver the highest value to the experiment, facilitating meaningful and productive interactions within the VR environment. The VR walkthrough application demonstrated the importance of creating intuitive navigation and realistic spatial representations to enhance user engagement and comprehension. In contrast, ALTO VR highlighted the potential of interactive and dynamic tools in architectural design, particularly in understanding and optimizing natural lighting conditions.

These experiences were instrumental in informing the design of the final application presented in this project. This application integrates the practical usability of VR walkthroughs with the innovative capabilities exemplified by ALTO VR, ensuring that it is both easy to learn and highly valuable for experimental purposes. The following sections of this chapter will provide an in-depth exploration of the design, development, and implementation processes of these applications. By examining the challenges encountered and the solutions devised, this chapter aims to offer valuable insights into the creation of VR tools that effectively support architectural and urban design. Through this detailed analysis, the author seeks to contribute to the broader understanding of how VR technology can be harnessed to enhance architectural practice and improve the quality of design outcomes, especially in experimental settings.

6.2 Walkthrough Tool - Most Common Scenario

6.2.1 Background

The walkthrough tool was developed using the Unity Game Engine, leveraging its robust features and ease of use for VR development. To create an immersive and realistic environment, a suburban model of an American neighborhood was purchased from the Unity Marketplace. This model served as the foundation of the tool and was meticulously adjusted to support various VR interactions.

The Meta Quest VR headset was chosen as the primary hardware platform for testing and deploying the VR tool. This standalone headset provided a high-quality immersive experience without the need for external hardware, making it an excellent choice for both development testing and end-user deployment. The Meta Quest's comprehensive developer support and ease of use enabled the team to rapidly prototype and iterate on the VR experience. For the admin part of the tool the Samsung smartphones were picked and all testing were done on those devices.

The primary VR tool allowed users to explore the virtual neighborhood, providing a range of interactive features to enhance the user experience. Key functionalities included the ability to walk around the environment, interact with objects, teleport to different locations, and change materials of various objects. These features were designed to make the virtual experience as engaging and dynamic as possible, offering users a high degree of freedom and interactivity.

In addition to the main VR tool, a companion app was developed to facilitate a moderated experience. This companion app allowed a moderator, referred to as the admin, to observe and interact with the VR user in real-time from a mobile device. The admin could communicate with the VR user, teleport them to different locations within the virtual environment, and perform any actions that the VR user could execute. This dual setup was particularly useful for scenarios where the VR experience needed to be guided or controlled by a second party.

One practical scenario for this setup could be a real estate market simulation. In this context, the VR user would take on the role of a potential home buyer, exploring the virtual neighborhood and interacting with the environment to get a sense of the property. Meanwhile, the mobile device user would act as the real estate agent or designer, guiding the client through the experience, answering questions, and showcasing different features of the homes.

The development of this walkthrough tool provided several valuable insights into creating effective VR experiences. The use of Unity Game Engine proved advantageous due to its user-friendly interface, extensive asset store, and strong community support. The adjustment of the suburban model to accommodate various VR interactions highlighted the importance of customizing pre-built assets to meet specific project requirements. Additionally, the integration of a companion app demonstrated the potential of multi-device interactions in VR tools, offering new ways to enhance user engagement and control.

Overall, this walkthrough tool exemplified the capabilities of VR technology in creating immersive and interactive environments, laying the groundwork for more complex and feature-rich VR tools. The insights gained from this project were instrumental in shaping the development of subsequent VR tools, ensuring they were both user-friendly and highly functional for various experimental and practical purposes.

6.2.2 Features

The development process of the walkthrough tool began with the initial idea of creating a typical immersive and interactive VR experience tailored to architectural and real estate contexts. This idea evolved into three main components: an immersive environment, interactive elements, and the ability to administer the experience from a mobile device. The following part detail the features planned and implemented to achieve these goals.

Immersive Environment

Creating a highly realistic and engaging virtual environment was crucial to the success of the walkthrough tool. The following features were designed to enhance the visual fidelity and immersion:

- **Navigation:** Allows users to walk around the virtual environment using VR controllers, providing a realistic sense of movement and presence.
- **Teleportation:** Enables users to quickly move between different locations within the VR environment, enhancing mobility and reducing disorientation.
- **Realistic Environment:** Provides a highly detailed and realistic suburban neighborhood model, enhancing the visual fidelity and immersion of the VR tool.
- **Proximity Animations:** Includes animations triggered by user proximity to certain objects or areas, adding dynamic and responsive elements to the environment.

Interactive Elements

To make the VR experience more engaging and useful, various interactive elements were integrated into the tool. These features enable users to interact with and customize the environment:

- **Object Interaction:** Users can pick up, manipulate items, and interact with household appliances, adding to the interactivity and immersion of the VR experience.
- **Material Change:** Allows users to change the materials and textures of objects in the environment, enabling real-time experimentation with different design options.
- **Changing Wall Colors/Textures:** Allows users to change the colors and textures of walls within the environment, offering additional customization options for architectural visualization.
- **Adding Props:** Users can add new props to the environment to customize the space, enhancing creativity and personalization.
- **Changing Props:** Allows users to modify existing props in the environment, providing flexibility in adjusting the virtual space to meet specific needs.
- **Environment Customization:** Allows users to create and adjust the environment directly within VR, similar to the building mechanics in simulation games.

Admin Capabilities

A unique aspect of the walkthrough VR tool was the integration of a companion mobile app, enabling a moderator to administer and enhance the VR experience. The following features were developed to support this functionality:

- **User Observation:** Admin can observe the VR user's actions and view the virtual environment from the user's perspective, facilitating guidance and support.
- **Real-time Communication:** Enables voice communication between the VR user and the admin, ensuring seamless interaction and feedback.
- **Remote Control by Admin:** Admin can remotely control various aspects of the VR environment, including user navigation and object manipulation, enhancing the moderated experience.

Table 6.1: Features of the Walkthrough VR Tool. Source: Author

Feature	Description	VR App	Mobile
Navigation	Allows users to walk around the virtual environment using VR controllers or by tracking	Yes	No
Teleportation	Enables users to quickly move between different locations within the VR environment	Yes	Yes
Realistic Environment	Provides a highly detailed and realistic suburban neighborhood model	Yes	No
Proximity Animations	Includes animations triggered by user proximity to certain objects or areas	Yes	No
Object Interaction	Users can pick up, manipulate items, and interact with household appliances	Yes	Yes
Material Change	Allows users to change the materials and textures of objects in the environment	Yes	Yes
Changing Wall Colors /Textures	Allows users to change the colors and textures of walls within the environment	Yes	Yes
Adding Props	Users can add new props to the environment to customize the space	Yes	Yes
Changing Props	Allows users to modify existing props in the environment	Yes	Yes
Environment Customization	Allows users to create and adjust the environment within VR	Yes	No
User Observation	Admin can observe the VR user's actions and view from the user's perspective	No	Yes
Real-time Communication	Enables voice communication between the VR user and the admin	No	Yes
Remote Control by Admin	Admin can remotely control various aspects of the VR environment, including user navigation and object manipulation	No	Yes

6.2.3 Methodology

The project was systematically approached through four main stages: Conceptualization, Brainstorming, Structuring, and Development, each contributing distinctively to the project's objectives and outcomes.

(a) **Conceptualization**:

- This initial stage involved defining the project's goals, scope, and requirements. Key stakeholders were consulted to ensure a comprehensive understanding of the desired features and functionalities. The primary focus was to outline the high-level vision and key deliverables.

(b) **Brainstorming**:

- In this stage, various ideas and solutions were generated through collaborative sessions with the project team (the author and one developer). Different approaches were discussed, and potential challenges were identified. This process was crucial for fostering creativity and ensuring that all possible solutions were considered.

(c) **Structuring**:

- During structuring, the ideas and solutions from the brainstorming sessions were organized into a coherent plan. Detailed project plans, timelines, and resource allocations were developed. This stage also involved creating wireframes and mockups for initial visualization of the project's components.

(d) **Development**:

- The development stage was executed using an agile methodology, segmented into five iterations, each focusing on different aspects of the project. This iterative approach allowed for continuous feedback and improvement, ensuring that the project stayed aligned with its goals and could adapt to any changes or new insights.

Development Process

The agile development process was segmented into five iterations, each focusing on different aspects of the project:

- **Iteration 1**: Basic scene creation using Unity with Oculus integration for initial testing.

To manage the project effectively and ensure timely delivery within the agile development framework, several project management tools were utilized:

  - *Google Cloud Tools* provided a suite of cloud-based services that supported various aspects of the project, including storage, computing, and networking. These tools facilitated collaboration among team members, version control, and the deployment of testing environments.
  - *Trello*, a web-based Kanban-style list-making application, was employed to manage the agile development process. Trello boards were used to track progress, manage sprints, and organize tasks into to-do lists, allowing for a transparent and flexible management of the development workflow.

- **Iteration 2**: Enhancement with a detailed neighborhood model and additional minor details.

  The next step after initial setup in creating the walkthrough tool was obtaining the 3D model from the asset store. A suitable model that matched the requirements was searched and purchased. It included various houses, streets, and environmental elements. After downloading the model, it was imported into the Unity game engine.

  Integrating the model into Unity involved several steps. The model's assets were organized, such as textures and meshes, in a structured manner within the Unity project. It was ensured that the model's materials were correctly imported and applied to the corresponding objects. This allowed us to achieve a visually appealing representation of the realistic environment in the virtual reality space.

- **Iteration 3**: Introduction of proximity-based animations.

  Implementing proximity-based animations allowed users to experience a more interactive and realistic virtual environment. These animations, triggered by the user's proximity to certain objects or areas, created a dynamic and responsive experience. For instance, when users approached a virtual door, it opened automatically. This immediate feedback made the environment feel more alive and responsive, enhancing the overall immersion.

- **Iteration 4**: Development of interactive elements and cross-platform functionality.

  To provide user assistance and interactivity within the virtual reality walkthrough, it was decided to connect the tool with a mobile phone. By leveraging the capabilities of a mobile device, users could receive additional information, guidance, or instructions while exploring the 3D model in VR.

- **Iteration 5**: Implementation of a communication layer for user-admin interaction.

  There was established connection between the Unity tool running on the VR headset and the mobile phone using a network communication protocol. This connection enabled real-time communication between the VR tool and the mobile device. Through a dedicated mobile app, users could receive notifications, view relevant information about the environment, or request assistance.

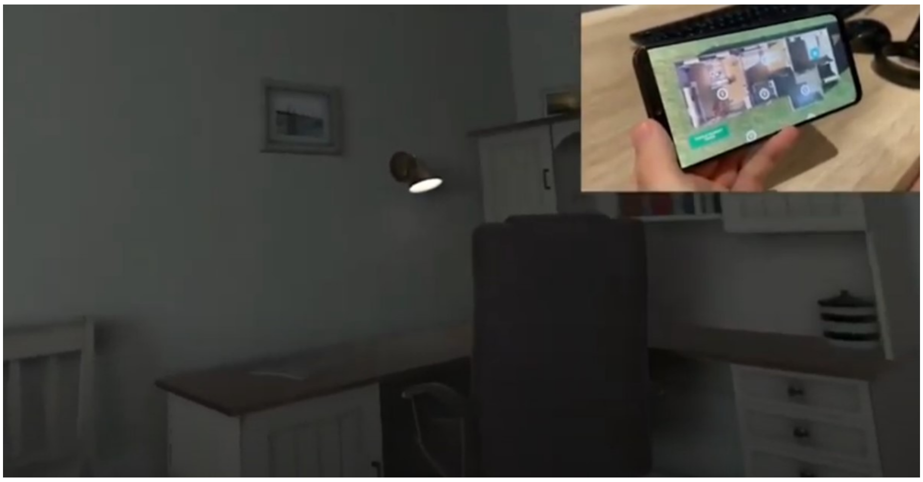


Figure 6.1. Walkthrough tool. Source: Author

6.2.4 Conclusions

After developing the walkthrough tool, it was crucial to evaluate each feature based on its value for experimental purposes and its learning curve. This evaluation helps in understanding the effectiveness and usability of the features when deployed in user studies or practical applications. The table below provides a comprehensive assessment of each feature, categorized by its importance for experiments and the ease with which users can learn to use it.

Evaluation Criteria

- **Value for Experiments (1-6):** This column rates the significance of each feature for maximizing the use of the VR tool's potential and experimental results, where 1 indicates the lowest value and 6 indicates the highest value. A higher value signifies that the feature is more beneficial for the experimental objectives.

  - **1 - Low Importance:** The feature is not essential for maximizing the use of the VR tool's potential and experimental results. It offers minimal benefits and can be easily omitted without affecting the outcomes.
  - **2 - Somewhat Low Importance:** The feature has limited usefulness for the VR tool and experiments. It can provide some benefits but is not crucial.
  - **3 - Moderate Importance:** The feature has a moderate impact on maximizing the use of the VR tool's potential and experimental results. It is useful but not indispensable.
  - **4 - High Importance:** The feature is quite important for maximizing the VR tool's potential and experiment results. Its absence would likely hinder the effectiveness of the VR tool and experiments.
  - **5 - Very High Importance:** The feature is critical for the VR tool and experiments. It significantly enhances the potential and outcomes.
  - **6 - Essential:** The feature is indispensable for maximizing the use of the VR tool's potential and experimental results. Most applications rely heavily on this feature, and its absence would severely impair functionality.

- **Learning Curve (1-6):** This column assesses how easy it is for users to learn and use each feature, where 1 indicates a low learning curve (easy to learn) and 6 indicates a high learning curve (difficult to learn). A lower value suggests that the feature is more user-friendly and can be quickly mastered.
  - **1 - Intuitive:** No training is required. Users can intuitively understand and use the feature without any guidance. It is highly user-friendly.
  - **2 - Easy:** Minimal training is needed. Users can quickly learn how to use the feature with very little effort.
  - **3 - Moderate:** The feature requires a moderate amount of training. Users need some time and effort to become proficient in using it.
  - **4 - Challenging:** The feature is somewhat challenging to learn.

Table 6.2: Evaluation of Walkthrough Tool Features. Source: Author

Feature	Value (1-6)	Learning Curve (1-6)	VR App	Mobile
Navigation	6	1	Yes	No
Teleportation	5	3	Yes	Yes
Realistic Environment	5	N/A	Yes	No
Proximity Animations	4	1	Yes	No
Object Interaction	5	5	Yes	Yes
Material Change	4	3	Yes	Yes
Changing Wall Colors /Textures	4	3	Yes	Yes
Adding Props	4	5	Yes	Yes
Changing Props	4	6	Yes	Yes
User Observation	5	2	No	Yes
Real-time Communication	6	2	No	Yes
Remote Control by Admin	6	5	No	Yes

Users require a considerable amount of training and practice to use it effectively.

  – **5 - Difficult:** The feature is difficult to learn. Significant time and effort are needed for users to master it, and it may require extensive training sessions.
  – **6 - Very Difficult:** The feature has a steep learning curve. It is the most challenging to learn, and users will need substantial training and ongoing practice to use it properly.

- Included in VR App: Indicates whether the feature is included in the main VR tool.
- Included in Mobile App: Indicates whether the feature is included in the companion mobile application.

The table [table 6.2] presents the evaluation of each feature.

6.3 ALTO VR - Perfect Scenario

6.3.1 Background

Daylight plays a crucial role in architectural design as it greatly influences the occupants' visual comfort, well-being, and energy consumption within buildings. The availability of natural light can enhance the aesthetics of indoor spaces, improve occupant productivity, and reduce the need for artificial lighting during daytime hours. Additionally, daylighting strategies can contribute to energy efficiency and sustainability in buildings by reducing the reliance on artificial lighting and minimizing the heat gain associated with excessive solar radiation.

However, assessing daylight in buildings poses significant challenges due to the complex interplay of various factors, such as building geometry, orientation, fenestration design, shading devices, and the dynamic nature of the surrounding environment. Traditional methods of daylight analysis, which often rely on physical scale models or static simulations, are time-consuming, expensive, and limit the exploration of design alternatives.

The purpose of the ALTO VR tool is to address the challenges in assessing daylight in buildings by providing architects, designers, and researchers with a powerful PCVR-based tool for daylight analysis and visualization. This tool enables users to immerse themselves in a virtual environment, allowing for intuitive and interactive exploration of different building setups and their corresponding daylight conditions.

Figure 6.2. ALTO VR. Source: Author

6.3.2 Features

The features of ALTO VR were derived from a comprehensive brainstorming session, resulting in three main categories: changing light properties, changing building context, and adjusting shading and occlusion conditions.

Change Light Properties These features allow users to manipulate various lighting conditions within the VR environment:

- **Adjustable Time of Day and Date:** Users can change the time of day and date to observe how natural light interacts with the building throughout the year.
- **Adjustable Latitude and Longitude:** Allows users to set the geographic location of the building, affecting the angle and intensity of sunlight.
- **Adjustable Artificial Lighting Settings:** Users can modify the intensity, color, and placement of artificial lights within the environment.
- **15 CIE Sky Types:** Provides different sky conditions based on the International Commission on Illumination (CIE) standards, allowing users to test lighting under various weather conditions.

Change Building Context These features provide tools for adjusting and importing building models within the VR environment:

- **Creating Setup within VR Mode:** Users can create and customize their environment directly in VR, enhancing the immersive design experience.
- **Loading Custom 3D Models:** Allows users to import and integrate their own 3D models into the VR environment for testing and visualization.

Adjust Shading and Occlusion Conditions These features enable users to control and adjust elements that affect shading and light occlusion:

- **Adjustable Weather Conditions:** Users can change weather settings to see how different weather conditions affect daylighting.
- **Adjustable Urban Context:** Users can modify the surrounding urban environment to study its impact on the building's lighting conditions.

- **Virtual Assistant:** Provides guidance and support within the VR environment, helping users navigate and utilize the various features effectively.

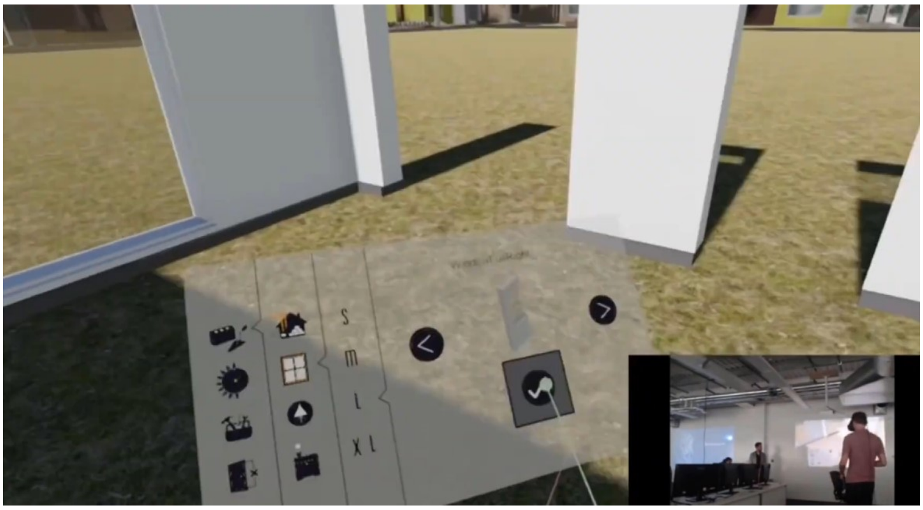


Figure 6.3. ALTO tool during session. Source: Author

Description of the Unity Tool's Interface The Unity tool features interface that allows architects, designers, and researchers to efficiently interact with the daylight testing environment. The interface provides easy access to various functionalities and controls, facilitating seamless navigation and experimentation.

The interface consists of interactive menus, panels, and toolbars that enable users to manipulate and customize building setups. Users can easily create walls, windows, and furniture elements, adjust their dimensions and positions, and assign different materials and textures. Additionally, the interface provides controls to modify environmental parameters such as time of day, weather conditions, and urban density. Visual feedback and analysis tools are also incorporated to assist users in understanding and evaluating the daylighting performance of different setups.

Key Components and Tools Utilized in the Tool The tool utilizes several key components and tools to support accurate daylight testing and analysis:

Compatibility and System Requirements The tool is designed to be compatible with standard PCVR (PC Virtual Reality) platforms, ensuring a seamless immersive experience for users. The tool supports popular PCVR headsets, such as Oculus Rift, HTC Vive, and Windows Mixed

Reality devices. It is essential to have a compatible PC with adequate processing power, memory, and a dedicated graphics card to ensure smooth operation of the tool.

Overall, the tool is designed to provide a seamless and immersive daylight testing experience, offering a user-friendly interface, utilizing key components and tools, and being compatible with standard PCVR platforms while meeting the necessary system requirements.

6.3.3 Methodology

The project was systematically approached through four main stages: Conceptualization, Brainstorming, Structuring, and Development, each contributing distinctively to the project's objectives and outcomes.The project was systematically approached through four main stages: **Conceptualization**, **Brainstorming**, **Structuring**, and **Development**, each contributing distinctively to the project's objectives and outcomes. The stage of the ALTO VR project were defined in the similar way to Walkthrough project with that difference that it included four instead of five iterations.

Agile Development Iterations

The agile development process was segmented into five iterations, each emphasizing specific project components:

(a) **First Iteration: Building Environments, Changing Time of Day**

- The focus was on creating various virtual environments and implementing the feature to change the time of day dynamically. This iteration laid the foundation for the immersive aspects of the project.

(b) **Second Iteration: Changing Materials, Changing Location, UI/UX Solutions**

- This phase involved adding functionality for changing materials within the environments, enabling location changes, and developing UI/UX solutions to ensure a user-friendly interface. The goal was to enhance the interactive and aesthetic qualities of the project.

(c) **Third Iteration: Changing Urban Context, Types of CIE Skies, Weather Conditions**

- The third iteration introduced the ability to alter the urban context, select different types of CIE skies, and modify weather conditions. These features were critical for creating realistic and varied scenarios within the virtual environments.

(d) **Fourth Iteration: Virtual Assistant, Loading .fbx Models, Artificial Lighting**

- This iteration focused on integrating a virtual assistant to aid users, enabling the loading of .fbx models for custom 3D objects, and implementing adjustable artificial lighting settings. These additions aimed to enhance usability and customization options.

Development Environment and Programming Language

The core development of the VR tool was carried out in *Unity*, a powerful and versatile game development platform known for its robust support for VR content creation. Unity's comprehensive suite of tools and its ability to compile for multiple platforms made it the ideal choice for developing the immersive and interactive elements of the tool. The programming language used for scripting within Unity was *C#*, known for its object-oriented capabilities, which facilitated the implementation of complex interactive and immersive features. C# enabled the development team to efficiently handle the tool's logic, user interface, and interaction with VR hardware.

Project Management Tools

To manage the project effectively and ensure timely delivery within the agile development framework, several project management tools were utilized:

- *Google Cloud Tools* provided a suite of cloud-based services that supported various aspects of the project, including storage, computing, and networking. These tools facilitated collaboration among team members (students of Virtual Reality Innovation Academy), version control, and the deployment of testing environments.
- A physical *Scrum Board* was employed to manage the agile development process. The Scrum Board was used to track progress, manage sprints, and organize tasks into to-do lists, allowing for a transparent and flexible management of the development workflow.

Hardware

The *HTC Vive* VR headset was chosen as the primary hardware platform for testing and deploying the VR tool. This standalone headset provided a high-quality immersive experience without the need for external hardware, making it an excellent choice for both development testing and end-user deployment. The Vive's comprehensive developer support and ease of use enabled the team to rapidly prototype and iterate on the VR experience. For the admin part of the tool, Samsung smartphones were picked and all testing was done on those devices.

Development Workflow Integration

Integrating these tools and technologies into the development workflow was critical for the project's success. Unity's versatility in creating immersive environments, combined with C#'s programming efficiency, allowed for the rapid development of complex features. Google Cloud Tools facilitated seamless collaboration and version control, while Trello's project management capabilities ensured that the development process remained agile and responsive to changes. The HTC Vive headset provided a reliable and accessible platform for testing and user experience evaluation, ensuring that the final VR tool met the project's high standards for immersion and interactivity.

6.3.4 Conclusion

After developing ALTO VR, it was crucial to evaluate each feature based on its value for experimental purposes and its learning curve. This evaluation provides insights into the effectiveness and usability of the features when deployed in user studies or practical applications. Understanding these aspects helps in determining which features are most beneficial for users and how easily they can be adopted.

Evaluation Criteria

- **Value for Experiments (1-6):** This column rates the significance of each feature for maximizing the use of the VR tool's potential and experimental results, where 1 indicates the lowest value and 6 indicates the highest value. A higher value signifies that the feature is more beneficial for the experimental objectives.
  - **1 - Low Importance:** The feature is not essential for maximizing the use of the VR tool's potential and experimental results. It offers minimal benefits and can be easily omitted without affecting the outcomes.

  - **2 - Somewhat Low Importance:** The feature has limited usefulness for the VR tool and experiments. It can provide some benefits but is not crucial.
  - **3 - Moderate Importance:** The feature has a moderate impact on maximizing the use of the VR tool's potential and experimental results. It is useful but not indispensable.
  - **4 - High Importance:** The feature is quite important for maximizing the VR tool's potential and experiment results. Its absence would likely hinder the effectiveness of the VR tool and experiments.
  - **5 - Very High Importance:** The feature is critical for the VR tool and experiments. It significantly enhances the potential and outcomes.
  - **6 - Essential:** The feature is indispensable for maximizing the use of the VR tool's potential and experimental results. Most applications rely heavily on this feature, and its absence would severely impair functionality.

- **Learning Curve (1-6):** This column assesses how easy it is for users to learn and use each feature, where 1 indicates a low learning curve (easy to learn) and 6 indicates a high learning curve (difficult to learn). A lower value suggests that the feature is more user-friendly and can be quickly mastered.
  - **1 - Intuitive:** No training is required. Users can intuitively understand and use the feature without any guidance. It is highly user-friendly.
  - **2 - Easy:** Minimal training is needed. Users can quickly learn how to use the feature with very little effort.
  - **3 - Moderate:** The feature requires a moderate amount of training. Users need some time and effort to become proficient in using it.
  - **4 - Challenging:** The feature is somewhat challenging to learn. Users require a considerable amount of training and practice to use it effectively.
  - **5 - Difficult:** The feature is difficult to learn. Significant time and effort are needed for users to master it, and it may require extensive training sessions.
  - **6 - Very Difficult:** The feature has a steep learning curve. It is the most challenging to learn, and users will need substantial training and ongoing practice to use it properly.

The table 6.3 presents the detailed evaluation of each feature.

Table 6.3: Evaluation of key ALTO VR Features. Source: Author

Feature	Value (1-6)	Learning Curve (1-6)
Adjustable Time of Day and Date	6	3
Adjustable Latitude and Longitude	6	3
Adjustable Artificial Lighting Settings	5	3
15 CIE Sky Types	5	3
Creating Setup within VR Mode	4	6
Loading Custom 3D Models	5	2
Adjustable Urban Context	4	3
Adjustable Weather Conditions	5	3
Virtual Assistant	4	1

Chapter 7

Arch ViewR

7.1 Introduction

The development of the Walkthrough Tool and ALTO VR significantly influenced the direction and objectives of the Arch ViewR, which is the focus of this thesis. The insights gained from these preliminary tools underscored the necessity for the Arch ViewR to be highly modular, supporting multiple input configurations and adaptable output generation. This modularity ensures that the tool can cater to a variety of experimental setups and research needs. Moreover, it emphasizes the importance of creating a framework that enables other researchers to test their hypotheses and conduct experiments within a virtual reality (VR) environment, without requiring extensive technical expertise in VR technology.

The comprehensive development process of the Walkthrough Tool and ALTO VR, as detailed in the previous chapter, was succeeded by a meticulous evaluation of their features. This evaluation was conducted from three distinct perspectives to ensure a thorough understanding of their efficacy and applicability. These perspectives include:

(a) **Value**: This perspective focuses on whether the tools enhance the user experience by making it more realistic, immersive, and reliable. The goal is to determine if the tools significantly contribute to a more engaging and authentic experience for users, thereby adding substantial value to the experimental process. The tables detailing the evaluation of features in terms of value are provided in the previous chapter.

(b) **Learning Curve**: This assessment centers on the ease with which users can learn to use the tools proficiently. A steep learning curve can hinder productivity, making it crucial that users quickly grasp the tools' functionalities. The objective is to ensure that users spend minimal time learning and maximum time effectively utilizing the tools to achieve the experimental aims. The tables evaluating features based on the learning curve are available in the previous chapter.

(c) **European Standard EN 17037 Compliance**: This standard pertains to the quality of the view from windows. The evaluation examines whether the tools comply with or challenge this standard. The table below [table 7.1] presents various elements important for EN 17037 compliance and evaluates their testability, with a score of 6 indicating the easiest to test.

Table 7.1: Criteria for Quality of View According to Standard PN-EN 17037. Source: Author

Criterion	Description	Testable (1-6)
Sky visibility	A fragment of the sky should be visible from inside the building. The view of the sky provides daylight and affects the users' circadian rhythm.	6
Landscape and nature elements visibility	The view should include natural elements such as trees, parks, rivers, and mountains. A view of natural elements positively impacts the users' well-being.	5
Limitation of obstacles in the field of view	The view from the window should be as unobstructed as possible, minimizing obstacles such as buildings, walls, or other structures.	5
Minimum viewing distance	A view of distant objects is preferred as it gives a sense of space and positively impacts the users' psyche.	4
Proportions and size of windows	Windows should be adequately large and positioned to provide a wide viewing angle, covering at least 30% of the glazing area providing the view outside.	6
View from various positions within the room	The quality of the view should be assessed from different positions within the room, both seated and standing.	5
Diversity of view	The external view should be varied, including different landscape and nature elements.	5
Privacy protection	The external view should be provided without compromising the privacy of the users, considering visibility from inside and to the inside of the building.	3

The comprehensive evaluation of these perspectives allowed for the identification and selection of the best features that meet the specified requirements. Consequently, this informed the development of a VR tool that optimally integrates these features, ensuring it is both effective and user-friendly.

7.2 Features

7.2.1 Fully Implemented Features

Several features tested in the Walkthrough tool and ALTO VR demonstrated high value, a minimal learning curve, and substantial utility in testing European Standard EN 17037. These features were seamlessly integrated into the Arch ViewR with minimal modifications. The fully implemented features include:

- **Navigation**: It is essential that users can navigate the virtual environment with full six degrees of freedom, allowing for a comprehensive and immersive experience.
- **Teleportation**: In scenarios where the physical testing area is limited, teleportation enables users to move efficiently. To minimize the learning curve, lessons learned from the Walkthrough tool were applied, and teleportation is fully controlled by the administrator.
- **User Observation**: Administrators can freely observe users within the VR environment while also being able to move around the physical experimental area, enhancing the monitoring and supervision capabilities.
- **Loading Custom 3D Models**: The tool supports the loading of custom 3D models for use in experiments. Unlike the ALTO VR, there is no specialized interface; instead, administrators add 3D models during the preparation phase of experiment sessions.

7.2.2 Partially Implemented Features

Certain features required adjustments prior to their integration into the Arch ViewR. These modifications aimed to enhance the efficiency and value of the experimental process:

- **Realistic Environment**: While the tool allows for realistic environments, it is constrained by hardware capacity and design considerations. Not all experiments necessitate a fully detailed environment, and sometimes a simplified setting may yield better results.

– **Environment Customization**: The Arch ViewR offers environment customization capabilities, albeit in a more limited manner compared to the Walkthrough tool, allowing administrators to tailor the environment to specific experimental needs.
– **Real-time Communication**: Unlike the Walkthrough tool, which enabled remote connections, the Arch ViewR is designed for scenarios where administrators and users are in the same physical space, facilitating direct communication.
– **Remote Control by Admin**: The Arch ViewR allows administrators to exercise control over the environment and user experience remotely within the same space.
– **Adjustable Time of Day and Date**: The tool permits adjustments to the time of day and date, aiding in experiments that require specific lighting conditions.
– **Adjustable Latitude and Longitude**: The Arch ViewR supports modifications to latitude and longitude settings, accommodating experiments that necessitate geographical specificity.
– **Adjustable Urban Context**: Administrators can alter the urban context within the tool, allowing for a variety of experimental scenarios.

7.2.3 Not Implemented Features

Some features were deemed either insufficiently valuable or too resource-intensive to integrate into the Arch ViewR. These features include:

– **Proximity Animations**
– **Object Interaction**
– **Material Change**
– **Changing Wall Colors/Textures**
– **Adding Props**
– **Changing Props**
– **Adjustable Artificial Lighting Settings**
– **15 CIE Sky Types**
– **Creating Setup within VR Mode**
– **Adjustable Weather Conditions**

– **Virtual Assistant**

These features were not implemented either because they did not add sufficient value to justify the effort or due to their high implementation costs.

7.3 System Design and Modularity of the Main VR Tool

The Arch ViewR system is designed with a modular architecture that facilitates flexibility and adaptability, allowing researchers to configure and customize the tool according to their specific experimental needs without requiring extensive technical expertise in VR technology. The modularity of the system is illustrated in Figure 7.1, which outlines the core components and their interactions.

7.3.1 Key Components of the Main VR System

- **Modules**:
  - **Location Module**: This module handles inputs related to geographical locations. It allows the integration of different location variables from a predefined bank of location data. This enables the simulation of various real-world settings within the VR environment.
  - **Urban Module**: This module is responsible for managing urban models. It can load and utilize urban variables from an urban models bank, facilitating the creation of diverse urban scenarios for experimentation.
  - **Architectural Module**: This module deals with architectural models, enabling the inclusion of various architectural elements from an architectural models bank. This supports the creation of detailed and context-specific architectural environments.
- **Bank Variables**:
  - **Location Bank Variable**: A repository of different geographical locations that can be used to configure the Location Module.
  - **Urban Models Bank Variable**: A repository of various urban models that can be utilized by the Urban Module to create urban environments.

* **Architectural Models Bank Variable**: A collection of architectural models that the Architectural Module can incorporate into the VR environment.

– **Outputs**: The combined outputs from the Location, Urban, and Architectural Modules are processed and rendered by the Arch ViewR, providing a cohesive and integrated VR environment that can be used for various research purposes.

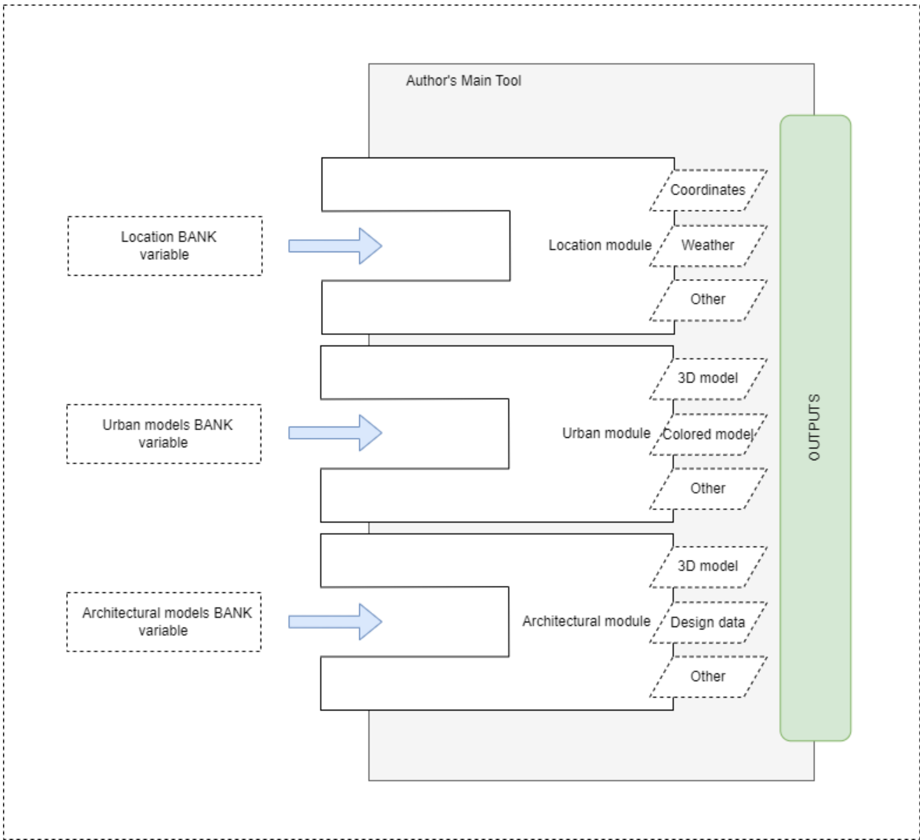


Figure 7.1. Diagram illustrating the modular architecture of the Arch ViewR System. Source: Author

Table 7.2: Features in Main VR Tool. Source: Author

Feature	Original Tool	Included
Navigation	Walkthrough VR	Yes
Teleportation	Walkthrough VR	By admin
Realistic Environment	Walkthrough VR	Partially
Proximity Animations	Walkthrough VR	No
Object Interaction	Walkthrough VR	No
Material Change	Walkthrough VR	No
Changing Wall Colors /Textures	Walkthrough VR	No
Adding Props	Walkthrough VR	No
Changing Props	Walkthrough VR	No
Environment Customization	Walkthrough VR	By admin
User Observation	Walkthrough VR	Yes
Real-time Communication	Walkthrough VR	Partially
Remote Control by Admin	Walkthrough VR	Partially
Adjustable Time of Day and Date	ALTO VR	By admin
Adjustable Latitude and Longitude	ALTO VR	By admin
Adjustable Artificial Lighting Settings	ALTO VR	No
15 CIE Sky Types	ALTO VR	No
Creating Setup within VR Mode	ALTO VR	No
Loading Custom 3D Models	ALTO VR	Yes
Adjustable Urban Context	ALTO VR	Partially
Adjustable Weather Conditions	ALTO VR	By admin
Virtual Assistant	ALTO VR	No

7.3.2 System Workflow

(a) **Input Integration**: Each module receives inputs from its respective BANK variables. For instance, the Location Module fetches location data from the Location BANK Variable, the Urban Module retrieves urban models from the Urban Models BANK Variable, and the Architectural Module accesses architectural models from the Architectural Models BANK Variable.

(b) **Module Processing**: Each module processes the input data to create a segment of the VR environment. The Location Module generates the geographical context, the Urban Module constructs the urban landscape, and the Architectural Module builds the architectural features.

(c) **Output Generation**: The outputs from all three modules are integrated to form a complete VR environment. This modular approach ensures that different aspects of the VR environment can be customized and adjusted independently, providing flexibility for various experimental setups.

7.3.3 Benefits of a Modular VR System

- **Flexibility**: Researchers can easily modify individual components (e.g., changing the location without altering the urban or architectural context), making it possible to test various scenarios and hypotheses with minimal effort.
- **Scalability**: New modules can be added to the system as needed, allowing for the expansion of the tool's capabilities without requiring a complete overhaul.
- **User-Friendly**: The system's design ensures that researchers without deep technical knowledge in VR can still configure and use the tool effectively, focusing on their experimental objectives rather than the technical complexities.
- **Efficiency**: By separating different aspects of the VR environment into distinct modules, the system allows for more efficient processing and quicker adjustments, enhancing the overall experimental workflow.

In summary, the Arch ViewR System's modular architecture, as depicted in Figure 7.1, provides a robust framework that supports diverse and customizable VR environments. This design not only enhances the tool's adaptability and usability but also ensures that it can meet the varied needs of researchers conducting VR-based experiments, facilitating the collection and analysis of critical data such as user position, head orientation, and other dynamic metrics.

7.4 Banks as a Data Repository

The Arch ViewR System employs a modular architecture that includes several banks, each serving as a repository for different types of models and data. These banks are designed to store and organize various input elements that can be utilized by the modules within the tool to create customizable and adaptable VR environments. The use of banks enables efficient data management and retrieval, facilitating the creation of diverse and detailed experimental setups.

The provided diagram illustrates the structure and interaction of three primary banks:

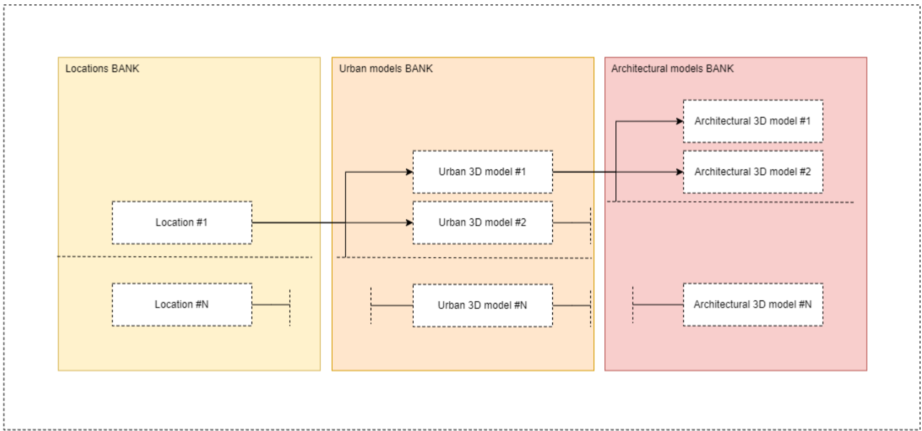


Figure 7.2. Tree system of banks concept. Source: Author

- **Locations bank**: This bank contains various geographical locations that can be integrated into the VR environment. Each location is represented as a node within the bank, allowing for easy access and selection during the configuration process.
- **Urban Models bank**: This bank stores a collection of urban 3D models. These models can be combined with location data to create comprehensive urban scenarios. The modular nature of this BANK allows for the seamless inclusion of different urban elements as required by the experimental setup.

– **Architectural Models bank**: This bank includes a variety of architectural 3D models. These models can be used to construct detailed architectural environments within the VR system. The architectural models can be combined with urban models and location data to create a fully immersive and context-specific VR environment.

7.5 Overall Development Process Overview

The tool was designed and built solely by the author without the assistance of additional developers or artists, necessitating a straightforward development process. While agile methodologies are highly effective for teams, their application in solo development can be limited; certain elements may be helpful, but overall, they are not entirely applicable.

The development process was structured into distinct phases. Initially, the objective was planned, focusing on the possibility of evaluating the actual view in VR in contrast to traditional view evaluation methods. The next phase involved implementing various sky features into the model. Subsequently, VR functionalities were developed to allow for walking around the virtual environment. A simplified 3D was blocked out for testing VR environment.

In addition to these developments, a mechanism was devised for collecting data, which included coloring the layers of the 3D model and calculating the percentage amounts in the snapshot. The tool underwent rigorous testing to ensure its functionality and stability. The final phase involved optimizing the tool for performance and user experience.

The entire development process spanned approximately four months.

7.5.1 Design Overview

2D Art

User Interface and Interactions

In the VR simulation, no 2D UI elements were incorporated for users. The design emphasized simplicity, aiming to minimize complex functionalities and steep learning curves. The primary objective was to create an intuitive and immersive environment for the users.

Table 7.3: Example how banks could be placed for the Arch ViewR System. Source: Author

Locations bank	Urban Models bank	Architectural Models bank
New York	1 km^2 around Times Square	12th floor living skyscraper near Times Square
		20th floor office building near Times Square
	1 km^2 around Central Park	5th floor apartment overlooking Central Park
		8th floor condo near Central Park
Paris	1 km^2 around Eiffel Tower	7th floor apartment near Eiffel Tower
		10th floor penthouse near Eiffel Tower
	1 km^2 around Louvre Museum	3rd floor studio overlooking Louvre Museum
		5th floor flat near Louvre Museum
London	1 km^2 around Big Ben	10th floor office near Big Ben
		15th floor corporate suite near Big Ben
	1 km^2 around Buckingham Palace	8th floor flat overlooking Buckingham Palace
		12th floor residence near Buckingham Palace
Tokyo	1 km^2 around Shibuya Crossing	15th floor apartment near Shibuya Crossing
		18th floor office near Shibuya Crossing
	1 km^2 around Tokyo Tower	12th floor living skyscraper north of Tokyo Tower
		20th floor office building north of Tokyo Tower

Conversely, the administrative interface was equipped with a 2D UI to facilitate interaction and control over the VR experience. Administrators could take snapshots during communication with the user, relocate users to otherwise inaccessible areas if necessary, and reset the simulation for subsequent users.

The output from the system included graphical representations indicating the percentage distribution of various elements within the city, as well as the user's position on the map. Additionally, all this data was made available in CSV format for further analysis and record-keeping.

3D Art

At this stage of development, the 3D art was at the minimal viable product (MVP) level. A simple, generic mockup of an urban area was created. The interior of the observation point, designed as a flat, was also blocked out. Furthermore, an underlying 3D model divided into colored layers was developed to thoroughly test the concept.

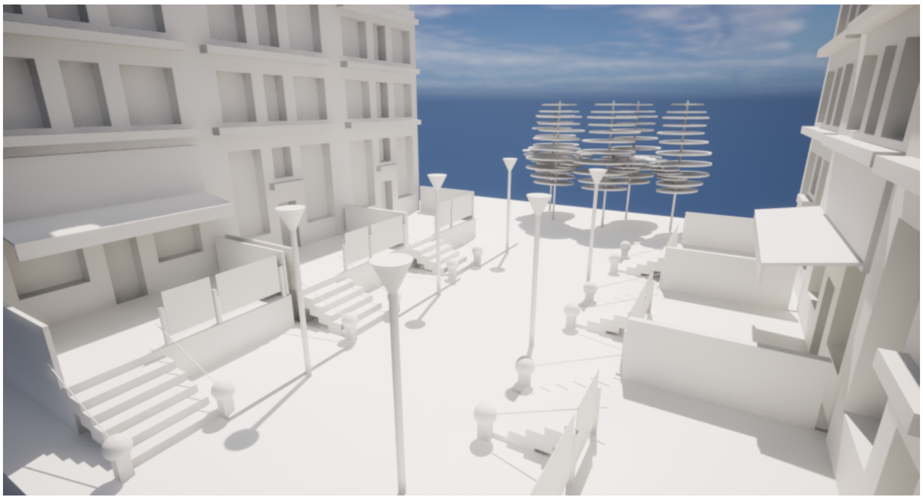


Figure 7.3. Example of the blockout in game engine. Source: Author

7.5.2 Code Overview

Average camera position

The Approximation Method This coroutine approximates the position of the camera over a given duration. It adds up the camera's position and rotation frame by frame, then divides by the count to find an average.

```
IEnumerator Approximation(float duration)
{
  float timeStamp = Time.time;
  Vector3 appPos = Vector3.zero;
  Quaternion appQua = camTransform.rotation;
  int counter = 0;

  while (Time.time - timeStamp < duration)
  {
    appPos += camTransform.position;
    appQua *= transform.rotation;
    Debug.LogWarning($"{appQua}::{camTransform.
rotation}");
    counter++;
    yield return new WaitForEndOfFrame();
  }
  camColor.position = appPos / counter;
  camColor.rotation = appQua;
  yield return new WaitForSeconds(1f);

  //save as csv
  colorCount._StartSampling();
  yield return new WaitForSeconds(10f);
  saveRes._AddNewData(camColor.position,
camColor.rotation.eulerAngles);
  timerText.enabled = true;
  timerText.text = "DONE";
}
```

Get color values bib script

This Unity3D script, *GetColorValuesBib*, performs a color analysis on a given RenderTexture. This can be useful for tracking what colors the user is looking at on-screen. The script uses various concepts such as Coroutine, Asynchronous programming, and Unity3D specific functions.

Class Fields

```
public RenderTexture sample;
private Texture2D converted;
```

```
private List<Vector3> listOfColors = new List<
  Vector3>();
private Dictionary<Vector3, int> colourCount;
private Vector3 c = Vector3.zero;
public float samplesCount = 3f;
public UnityEvent<float> progresUpdated;
int calculations = 0;
public int calculationsLimit = 1000;
public CreateGraph createGraph;
private int notUsedPixels = 0;
```

This part of the script declares the class variables. Here, ‘sample‘ is the input RenderTexture to be analyzed. ‘converted‘ is the 2D version of the input RenderTexture. ‘listOfColors‘ is a list that stores all the colors in the RenderTexture as Vector3, with each element in the vector representing Red, Green, and Blue color components. ‘colourCount‘ is a dictionary that stores the frequency of each color in the texture. ‘samplesCount‘ is the number of samples per pixel. ‘progresUpdated‘ is a UnityEvent that gets triggered when the progress is updated. ‘calculations‘ and ‘calculationsLimit‘ are used to control the yield points in the coroutine, ‘createGraph‘ is an instance of ‘CreateGraph‘ class that handles the creation and saving of graphs, and ‘notUsedPixels‘ counts the number of pixels that are not used.

Method: ConvertTo2DTex

```
void ConvertTo2DTex()
{
   RenderTexture.active = sample;
   converted = new Texture2D(sample.width,
  sample.height);
   converted.ReadPixels(new Rect(0, 0, sample.
  width, sample.height), 0, 0);
   converted.Apply();
}
```

The ‘ConvertTo2DTex‘ method converts the RenderTexture ‘sample‘ to a 2D texture ‘converted‘. This is done by first setting the active RenderTexture to ‘sample‘, then creating a new Texture2D with the dimensions of ‘sample‘. The pixels from ‘sample‘ are then read and applied to ‘converted‘.

Method: ReadColorValue

```
async void ReadColorValue(int x, int y)
{
  //... method body omitted for brevity
}
```

The ‘ReadColorValue‘ method is a coroutine that reads the color value of each pixel in the converted texture and stores them in the ‘colourCount‘ dictionary. It takes two arguments, ‘x‘ and ‘y‘, which represent the dimensions of the texture. The method uses asynchronous programming to allow the Unity engine to continue running while the color values are being read.

Method: GetOccurance

```
async void GetOccurance(float x, float y)
{
  //... method body omitted for brevity
}
```

The ‘GetOccurance‘ method calculates the frequency of each color in the texture and logs the results. It also calls the ‘PassToGraphs‘ method, which is used to create and save graphs.

Method: PerformAsyncAction and StartSampling

```
public async void PerformAsyncAction()
{
  ConvertTo2DTex();
  int x = sample.width;
  int y = sample.height;

  ReadColorValue(x, y);
}

public void _StartSampling()
{
  PerformAsyncAction();
}
```

The ‘PerformAsyncAction‘ method calls the ‘ConvertTo2DTex‘ method to convert the RenderTexture to a 2D texture, and then calls ‘ReadColorValue‘ method to start the color reading process. The ‘StartSampling‘ method is the public interface that starts the color sampling process.

Method: PassToGraphs

```
void PassToGraphs(Color col, float perc)
{
  createGraph.CreateGraphNow(perc, col);
  createGraph.SaveGraphNow(perc, col);
}
```

The 'PassToGraphs' method takes a color and a percentage as input and calls 'CreateGraphNow' and 'SaveGraphNow' methods on the 'createGraph' object to create and save a graph with these values.

CreateGraph script

This Unity3D script, *CreateGraph*, generates a bar graph to visualize the color data acquired from the *GetColorValuesBib* script. The graph bars represent colors, and their height indicates the percentage of each color in the examined image. It demonstrates the usage of Unity's UI system to dynamically instantiate and adjust Image components.

Class Fields

```
[SerializeField]
GetColorValuesBib bib;
public Image baseImage;
public Canvas myCanvas;
private int counter = 0;
public List<Color> cols = new List<Color>();
public List<float> perc = new List<float>();
```

In this section, the 'bib' field represents the *GetColorValuesBib* script instance. 'baseImage' is a UI Image used as a template for the graph bars, and 'myCanvas' is the canvas on which the graphs are drawn. 'counter' keeps track of the number of bars already created to correctly position the new ones. 'cols' and 'perc' are lists storing the color and percentage values for each graph bar, respectively.

Method: CreateGraphNow

```
public void CreateGraphNow(float percentage,
  Color col)
{
  //... method body omitted for brevity
}
```

The ‘CreateGraphNow‘ method creates a new bar in the graph. It takes a ‘percentage‘ value and a ‘Color‘ instance as input, then creates an ‘Image‘ instance using the ‘baseImage‘ as a template. The newly created ‘Image‘ is placed as a child of the ‘myCanvas‘ and its position and color are set according to the inputs. It also adjusts the bar’s height relative to the ‘percentage‘ value and displays this percentage as text within the bar.

Method: SaveGraphNow

```
public void SaveGraphNow(float percentage,
  Color col)
{
   cols.Add(col);
   perc.Add(percentage);
}
```

The ‘SaveGraphNow‘ method stores the color and percentage values of a bar to the ‘cols‘ and ‘perc‘ lists, respectively, for future reference.

SavingResults script

The Unity3D script, *SavingResults*, saves session data including head position, rotation, and color percentages into a CSV file. It makes use of ES3Spreadsheet, an Easy Save 3 API for working with spreadsheets, to create, load, manipulate, and save the data.

Class Fields

```
string path;
[SerializeField]
CreateGraph graphInfo;
ES3Spreadsheet sheet = new ES3Spreadsheet();
```

In this segment, ‘path‘ stores the path to the CSV file. The serialized field ‘graphInfo‘ is an instance of the ‘CreateGraph‘ class, which contains information about the graph to be saved. ‘sheet‘ is an instance of ES3Spreadsheet used for creating and manipulating the spreadsheet data.

Method: Start

```
private void Start()
{
   //... method body omitted for brevity
```

```
}
```

The ‘Start‘ method is a Unity callback method which runs at the start of the script. This method initializes the ‘path‘ and tries to load a CSV file from the ‘path‘. If the file does not exist, a new spreadsheet is created.

Method: CreateNewSpreadsheet

```
void CreateNewSpreadsheet()
{
  //... method body omitted for brevity
}
```

The ‘CreateNewSpreadsheet‘ method sets up the column headers for the new CSV file and saves it to the given path. The column headers include ID, time, position coordinates (Px, Py, Pz), rotation coordinates (Rx, Ry, Rz), and color percentages (Color1, Percentage, Color2, etc.).

Method: _AddNewData

```
public void _AddNewData(Vector3 position,
  Vector3 orientation)
{
  //... method body omitted for brevity
}
```

The ‘$_{A}ddNewData$‘ method takes head position and rotation as parameters and adds them to the CSV file. If the color percentages are available from ‘graphInfo‘, they are also added. If not, zeros are filled instead. The updated data is then saved back to the file at the specified path.

Visualizing User Results with Unity3D

This script is responsible for generating a report page that visualizes user results obtained from the Unity3D engine. It is capable of retrieving data from a previously stored CSV file, and uses this data to construct a color-coded version of a scene from a user's perspective, based on the user's head position and orientation.

Initialization and loading the spreadsheet

```
void Start()
{
```

```
    path = Application.persistentDataPath + "/myData.csv";
    Debug.Log(path);

    try
    {
      sheet.Load(path);
      exists = true;
      Debug.Log("File loaded");
    }
    catch
    {
      Debug.Log("File doesn't exist!!");
    }
    if(exists)
    {
      LoadPage(currentPage);
    }
  }
```

The ‘Start()‘ method is called when the script instance is being loaded. Here, the path of the CSV file is constructed and stored in ‘path‘. Next, an attempt is made to load the spreadsheet data from the file. If the file is successfully loaded, ‘exists‘ is set to ‘true‘ and the current page is loaded using the ‘LoadPage‘ method.

Page loading and data visualization

```
  public void LoadPage(int pageNumber)
  {
    int posStart = 2;
    Vector3 position = new Vector3( sheet.GetCell<float>(posStart, pageNumber),
    sheet.GetCell<float>(posStart+1, pageNumber),
    sheet.GetCell<float>(posStart+2, pageNumber));

    Vector3 rotation = new Vector3( sheet.GetCell<float>(posStart + 3, pageNumber),
    sheet.GetCell<float>(posStart + 4, pageNumber),
    sheet.GetCell<float>(posStart + 5, pageNumber
```

```
        ));

        Quaternion rotConverted = Quaternion.Euler(rotation);

        id.text = "ID of test: #" + sheet.GetCell<int>(0, pageNumber).ToString();
        timeOfTest.text = "Date and time: " + sheet.GetCell<string>(1, pageNumber).ToString();

        head.position = position;
        head.rotation = rotConverted;
        colorCamera.position = position;
        colorCamera.rotation = rotConverted;
        realCamera.position = position;
        realCamera.rotation = rotConverted;

        pageText.text = $"{currentPage} / {sheet.RowCount - 1}";

        graph.counter = 0;

        foreach (Transform child in graph.graphContainer)
        {
            GameObject.Destroy(child.gameObject);
        }

        for (int i = posStart + 6; i < sheet.ColumnCount; i += 2)
        {
            graph.CreateGraphNow(sheet.GetCell<float>(i + 1,pageNumber), sheet.GetCell<Color>(i, pageNumber));
        }
    }
```

The ‘LoadPage‘ method visualizes the data for a given page number. It retrieves the position and orientation information for the user’s head from the spreadsheet, and uses this to adjust the position and orientation of various objects within the scene. Additionally, it updates the display text for the ID and time of the test, as well as the current page number.

The method then resets the graph counter and destroys any existing child objects within the graph's container. After that, it iterates through the remaining data in the spreadsheet, using it to construct a graph via calls to the 'CreateGraphNow' method.

Script for Manual User Movement

The LABCamera script is responsible for providing the functionality of manually moving the user's point of view in a virtual environment when the normal mode of navigation (through VR technology) is not in use. This can be useful during development and debugging or for testing purposes.

The code snippet below shows a simplified version of the LABCamera script:

```
[SerializeField]
private float velocity = 20f;
[SerializeField]
private float angularVelocity = 10f;

// Update is called once per frame
void Update()
{
  transform.parent.Translate(Vector3.forward * Input.GetAxis("Vertical") * Time.deltaTime * velocity);
  transform.parent.Translate(Vector3.right * Input.GetAxis("Horizontal") * Time.deltaTime * velocity);
  transform.parent.Translate(Vector3.up * Input.GetAxis("Mouse ScrollWheel") * Time.deltaTime * velocity * 50f);

  if (Input.GetMouseButton(1))
  {
    transform.parent.Rotate(Vector3.up, Input.GetAxis("Mouse X") * angularVelocity);
```

```
        transform.Rotate(Vector3.left, Input.
    GetAxis("Mouse Y") * angularVelocity);
    }
}
```

Listing 7.1: Snippet from the LABCamera script

In this script, the user's movement is governed by the `Update` function, which is called once per frame.

The three `Translate` function calls in the `Update` method provide the ability to move forward/backward, left/right, and up/down. They take into account the user's input through keyboard and mouse, as well as the frame time to ensure smooth movement. The movement speed is controlled by the `velocity` parameter.

Furthermore, to allow for rotation of the camera, the script checks if the right mouse button is held down. If it is, the script adjusts the rotation of the camera according to the mouse's movements along the X and Y axes. This rotation speed is controlled by the `angularVelocity` parameter.

This script thus provides an alternative means for user navigation in the virtual environment, useful for a variety of testing and development scenarios.

7.6 Conclusions

The tool, though currently in its minimum viable product (MVP) stage, has been meticulously designed with scalability and modularity as core principles. This foundational approach ensures that the tool can be easily adapted for broader applications and diverse research inquiries within the fields of architectural design and urban planning. To fully evaluate the effectiveness and reliability of the tool, it is imperative to conduct rigorous testing under experimental conditions. Such testing will provide crucial insights into its functionality and potential for broader application.

Part IV

Arch ViewR - Capabilities, Evaluation and Conclusions

Chapter 8

Results and Pilot Testing of the Arch ViewR

8.1 Introduction

The development of the Arch ViewR emerged from the integration and evaluation of features from two earlier tools, resulting in the Arch ViewR presented in this thesis. Although the previous tools were thoroughly tested and their evaluated features included, it is necessary to subject the Arch ViewR to a comprehensive usage phase and design an experiment to assess its performance.

This chapter will outline how the Arch ViewR can be used and describe the types of results it can produce. By demonstrating its application, the chapter aims to show the tool's versatility and effectiveness in solving problems within architectural design and urban planning. The outcomes of this experimental phase will provide important insights into the tool's practical utility and potential for future improvements and broader applications.

8.2 Tool as a Main Result

The development of the tool presented in this thesis is the culmination of an extensive and methodical process, as illustrated in the accompanying flowchart. The process can be delineated into four distinct phases: Definition, Creation, Evaluation, and Final Tool Features, each contributing critically to the final product.

Definition Phase

The initial phase involved defining various scenarios through brainstorming sessions. Two primary scenarios were identified: the Most Common Scenario, derived from market observations, and the Perfect Scenario, conceptualized through specialist consultations. This dual approach ensured that the tool would be relevant both in typical use cases and in ideal conditions, providing a comprehensive framework for its development.

Creation Phase

During the creation phase, technological constraints were acknowledged, guiding the development of two prototype tools: the Walkthrough Tool and ALTO VR. Each prototype was equipped with distinct features aimed at addressing specific needs within architectural design and urban planning. These prototypes served as the foundational elements from which the final tool would evolve.

Evaluation Phase

The features from both prototypes were aggregated into a Feature Collective Bucket, a critical step in the evaluation phase. Here, a rigorous testing and filtering process was applied, encompassing value filtering to assess usefulness, learning curve filtering to evaluate usability, and EN 17037 filtering to ensure compliance with industry standards. Features that did not meet these stringent criteria were systematically filtered out, ensuring only the most effective and relevant features remained.

Final Tool Features Phase

The features that passed the evaluation phase were then selected for inclusion in the final tool. This selection process was guided by a commitment to incorporate functionalities that would enhance user experience and meet professional standards. The final tool was subjected to further testing to verify its effectiveness and reliability.

Outputs

The final outputs of this comprehensive process included several key metrics:

- **Pre and Post VR Questionnaires Comparison**: This metric provided insights into user satisfaction and the tool's impact on user experience.
- **User Positions and View Directions**: Tracking these metrics helped in understanding how users interact with the tool and

navigate within the VR environment. Available as comma separated value files.

- **Layer Frequencies**: This analysis offered valuable data on the usage patterns of different features within the tool.
- **Other Outputs**: Additional data collected during testing provided further evidence of the tool's utility and areas for potential enhancement.

8.3 Need to Test the Tool

The necessity to test the developed tool arose from the need to validate its functionality, usability, and effectiveness in real-world scenarios. While the tool had undergone initial testing during the development phase, comprehensive testing in a specific use case was deemed essential to ensure its reliability and performance in practical applications.

The testing involved simulating a particular scenario within the fields of architectural design and urban planning. This focused approach provided detailed insights into the tool's practical utility and identified areas for improvement. This phase of testing not only highlighted the strengths and weaknesses of the tool but also informed future enhancements and refinements.

The subsequent sections detail the methodology and results of this test, concentrating on the selected scenario. The tests included user interactions, performance metrics, and feedback analysis, which collectively contributed to a deeper understanding of the tool's capabilities and its potential impact on professional practice.

Through this rigorous testing process, the tool was established as a reliable and valuable asset for architects and urban planners, capable of addressing complex design challenges and improving overall project outcomes.

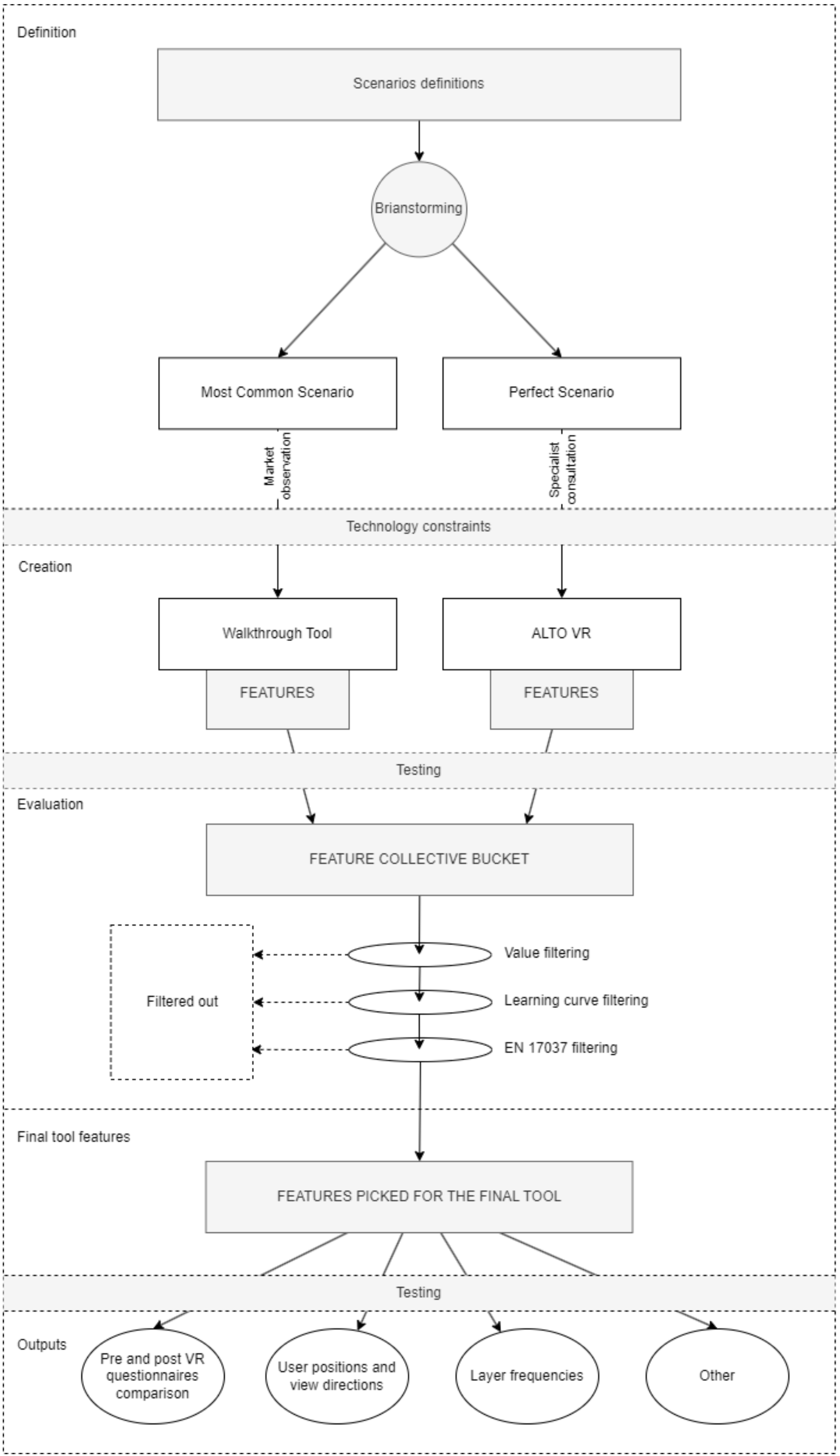


Figure 8.1. Arch ViewR development phases. Source: Author

8.4 Gdańsk as a Case Study for the Arch ViewR Bank System

Given the author's extensive connection to the city of Gdańsk—having pursued both engineering and master's degrees there—and the current affiliation with the Gdańsk University of Technology, it is evident that Gdańsk serves as an optimal starting point for this study. The author's prolonged engagement with the city has provided a substantial foundation for the initiation of this research.

The geographical location of Gdańsk has been utilized as the initial input for the tool bank system. The first experiment was meticulously planned and executed using variables derived from this locale.

Gdańsk is a coastal city situated on the southern edge of the Baltic Sea, in northern Poland. It is the capital of the Pomeranian Voivodeship and serves as a significant economic and cultural hub in the region. The city is renowned for its well-preserved medieval architecture, including the iconic St. Mary's Church and the historic Long Market, flanked by the Neptune Fountain and the Gdańsk Town Hall. The Gdańsk University of Technology, one of the oldest universities of technology in Poland, is a prominent institution contributing to the city's academic and research landscape.

In addition to its historical and cultural significance, Gdańsk is also a modern center for science, education, and industry. The city's port and shipyards make it a vital economic zone. This blend of historical richness and contemporary advancement positions Gdańsk as an exemplary site for initiating and conducting scientific experiments, such as the tool bank system in this research.

By utilizing Gdańsk as the first input for the Arch ViewR bank system, the research draws upon the city's multifaceted profile, thereby enriching the study with a robust and contextually relevant dataset. This strategic choice not only underscores the author's personal and academic ties to Gdańsk but also capitalizes on the city's intrinsic value as a vibrant and dynamic urban center.

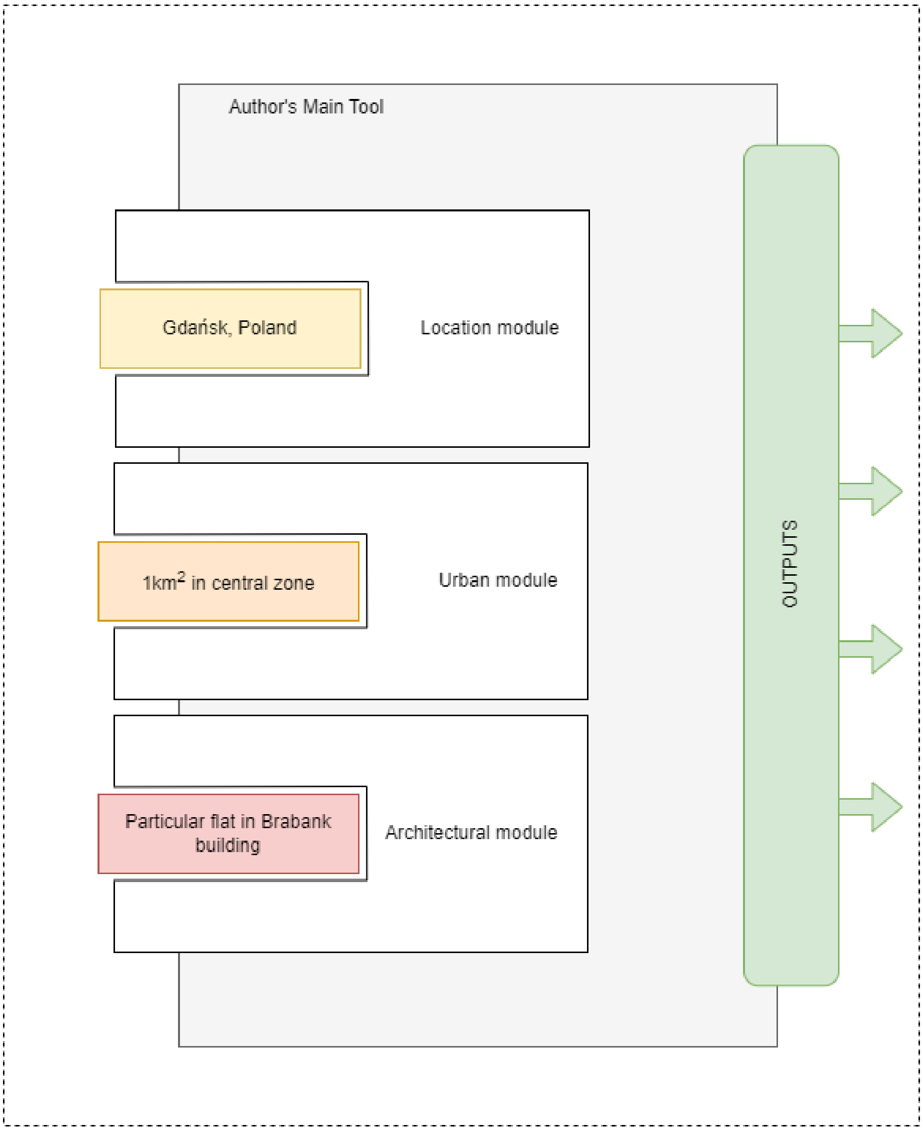


Figure 8.2. Diagram illustrating variables chosen from the bank system to be used in pilot experiment. Source: Author

8.4.1 Location Bank

Gdańsk, located on the northern coast of Poland, is positioned at coordinates 54°22′N latitude and 18°38′E longitude. This coastal city is part of the Pomeranian Voivodeship and lies along the southern edge of the Baltic Sea, contributing to its moderate maritime climate.

The weather in Gdańsk is characterized by relatively mild conditions compared to the inland regions of Poland. The city experiences four distinct seasons. Summers are generally warm, with average temperatures ranging from 15°C to 20°C in July and August, the warmest months. Winters are cold but not severe, with average temperatures hovering around 0°C to -2°C in January and February, the coldest months (*Gdańsk Climate: Average Temperature, Weather by Month, Gdańsk Weather Averages* n.d.) (*Gdańsk, Poland — Sunrise, Sunset, and Daylength* n.d.) (*Gdańsk Monthly Climate Averages* n.d.).

Precipitation in Gdańsk is fairly evenly distributed throughout the year, though the summer months of July and August typically see slightly higher rainfall. The city receives an average annual precipitation of about 600-700 millimeters. On average, there are about 160-170 rainy days per year. Snowfall is common in winter, with an average of 50-60 snowing days annually, although it is usually light(*Gdańsk Climate: Average Temperature, Weather by Month, Gdańsk Weather Averages* n.d.) (*Gdańsk, Poland — Sunrise, Sunset, and Daylength* n.d.) (*Gdańsk Monthly Climate Averages* n.d.).

During the summer solstice in late June, the city enjoys long daylight hours, with the sun rising around 4:00 AM and setting around 9:30 PM, resulting in approximately 17.5 hours of daylight. Conversely, during the winter solstice in late December, daylight is much shorter, with the sun rising around 8:00 AM and setting around 3:30 PM, providing only about 7.5 hours of daylight (*Gdańsk Climate: Average Temperature, Weather by Month, Gdańsk Weather Averages* n.d.) (*Gdańsk, Poland — Sunrise, Sunset, and Daylength* n.d.) (*Gdańsk Monthly Climate Averages* n.d.).

These biogeographical characteristics of Gdańsk are vital for understanding the local environment and planning experiments related to the tool bank system. The city's climate and geographical location offer a unique set of variables that are beneficial for comprehensive and contextually relevant research.

This information, although very general, provides essential back-

Table 8.1: Annual Weather and Daylight Data for Gdańsk (2019-2023). Source: Author

Year	Avg Temp (°C)	Precipitation (mm)	Rainy Days	Snowy Days	Sunny Days
2019	8.5	650	165	55	145
2020	8.2	670	170	60	135
2021	8.3	640	160	50	155
2022	8.6	660	168	58	139
2023	8.4	655	162	52	151

ground and context for understanding the geographical and climatic characteristics of Gdańsk. Such knowledge is crucial for preparing the mindset necessary for the subsequent development and application of the tool bank system. By situating the research within the specific environmental conditions of Gdańsk, we can ensure that the variables and outcomes are both relevant and contextually grounded. This foundational understanding facilitates a more informed and effective approach to the work on the following banks, enabling a nuanced appreciation of the interplay between local conditions and experimental design.

8.4.2 Urban Bank

The second variable to be developed was the element of Urban Bank, which is intrinsically linked to the Location Bank, inheriting all its foundational details. For the pilot experiment, a flat with an exceptional view was sought. After a comprehensive search, the area around the Brabank complex, located in the central part of Gdańsk, was selected.

Extensive urbanistic analyses were conducted, leading to the selection of the subject area. A 3D model of this part of Gdańsk was acquired from the Gdańsk City Development Office. This raw model was converted to the FBX format to ensure compatibility with Blender and Unity.

Following the conversion, the model underwent a rigorous optimization process, which included enhancements to both the mesh and the textures. Mesh optimization focused on reducing the polygon count to improve performance without sacrificing visual fidelity.

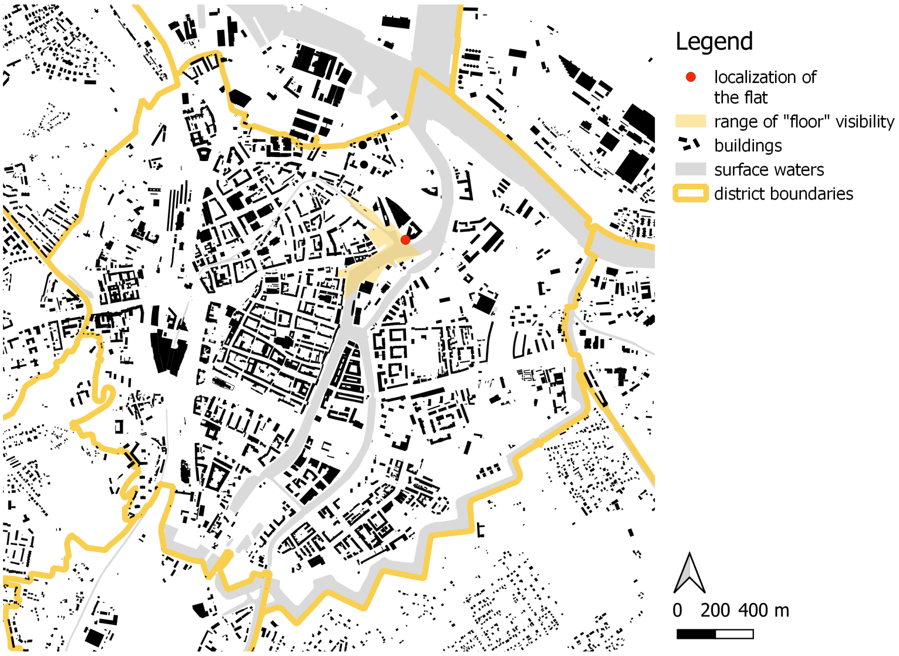


Figure 8.3. Urban analysis of chosen area with marked selected flat. Source: A. Zackiewicz

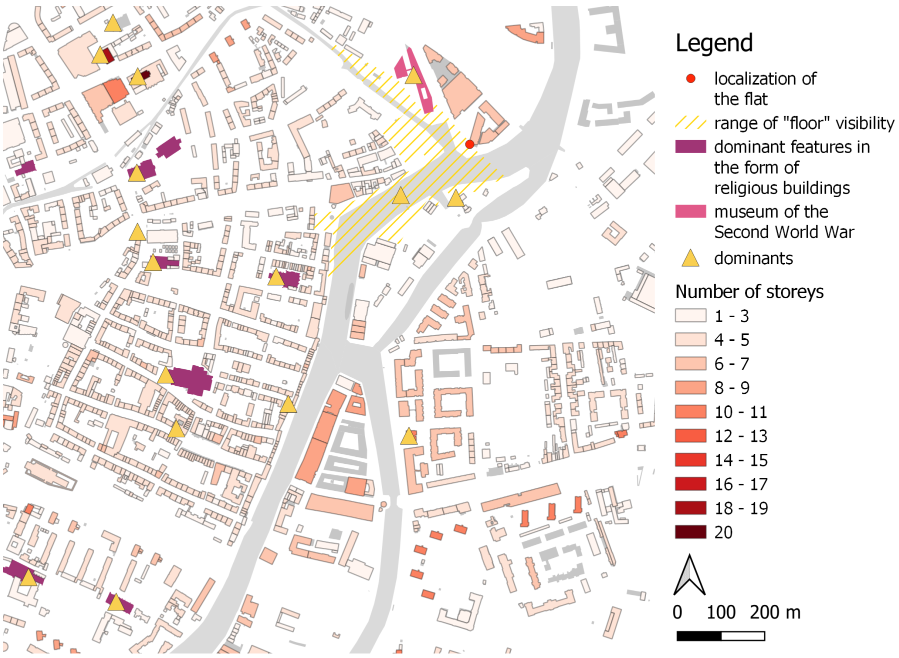


Figure 8.4. Urban analysis of chosen area with marked selected flat. Source: A. Zackiewicz

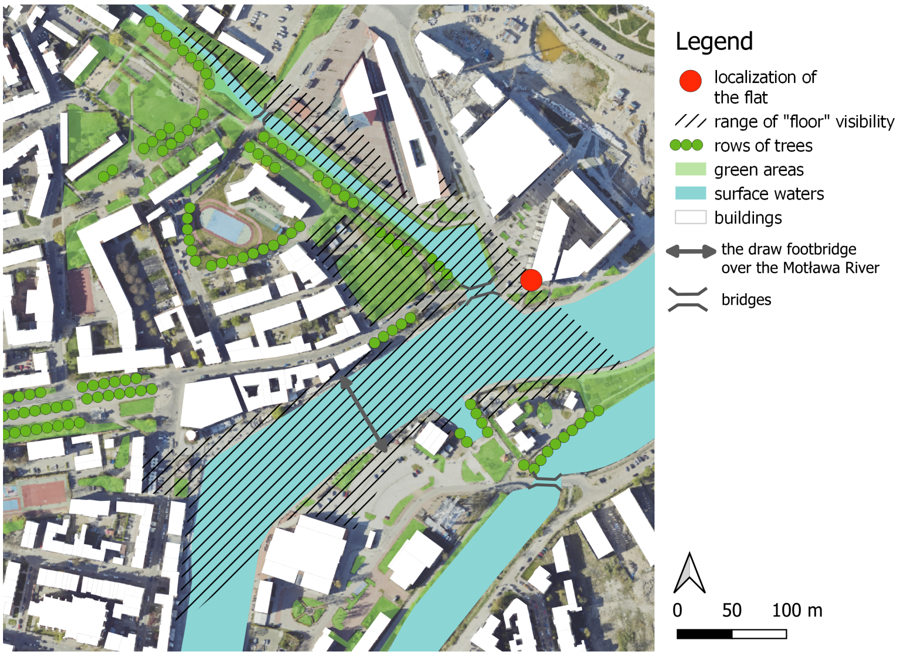


Figure 8.5. Urban analysis of chosen area with marked selected flat. Source: A. Zackiewicz

Concurrently, texture optimization aimed to enhance visual quality while minimizing memory usage.

A significant aspect of the model preparation involved the enhancement of the river flowing through Gdańsk. A specialized river shader was integrated to simulate water movement and reflections, thereby adding a layer of realism to the overall model. The model was also paired with appropriate lighting to ensure a realistic representation of the urban environment.

To support urban consistency calculations, a colored 3D model overlay was created atop the original Gdańsk model. This facilitated various analyses, such as assessing the visual coherence of urban elements, thus contributing to a comprehensive understanding of the urban landscape.

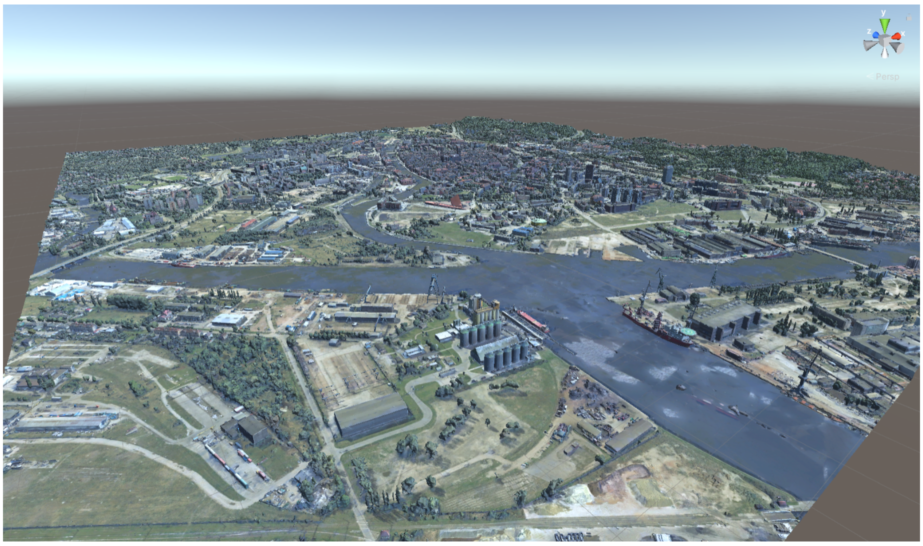


Figure 8.6. 3D model of Gdańsk acquired from the Gdańsk City Development Office implemented in the Unity 3D. Source: Author

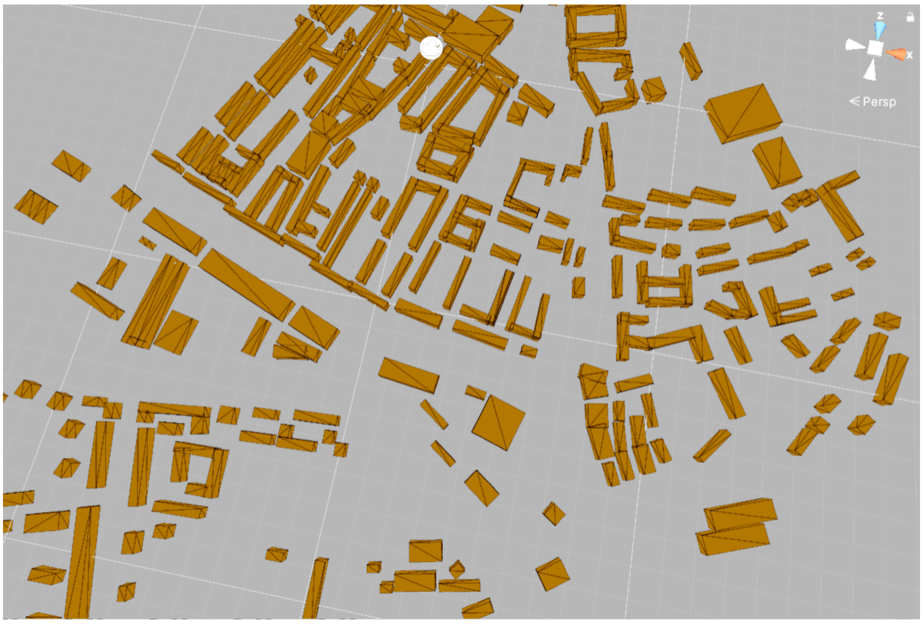


Figure 8.7. Example of the colored urban layer in the Unity 3D. Source: Author

8.4.3 Architectural Bank

The third variable to be developed belongs to the Architectural Bank. Building upon the parent variable from the Urban Bank, the flat in the Brabank complex was selected. This flat offered a prominent view from the living room, featuring a river in the foreground and various landmarks of Gdańsk's old city in the background.

Figure 8.8. Living room and view from the chosen flat. Source: J. Martyniuk-Pęczek

A decision was made to prepare a simplified 3D model of the flat, rendered entirely in white, including the largest elements such as wardrobes and couches, to provide accurate proportions for users. Only a few essential pieces of furniture were included in the apartment model, represented as simplified blockouts to give context without overwhelming detail.

Realistic glass materials were applied to the windows, enhancing the overall realism of the apartment model and accurately portraying the interaction with natural light. This approach ensured that the model was both functional for the study's purposes and visually representative of the actual living space.

Figure 8.9. View from the chosen flat. Source: J. Martyniuk-Pęczek

Figure 8.10. Building that the flat is situated in. Source: J. Martyniuk-Pęczek

The variable was incorporated into the Architectural Bank in two distinct versions. The only difference between these versions was their location within the building: one version was situated on the 1st floor, while the other was located on the 4th floor. This distinction allowed for comparative analysis of different perspectives and their impacts on the experiment's outcomes.

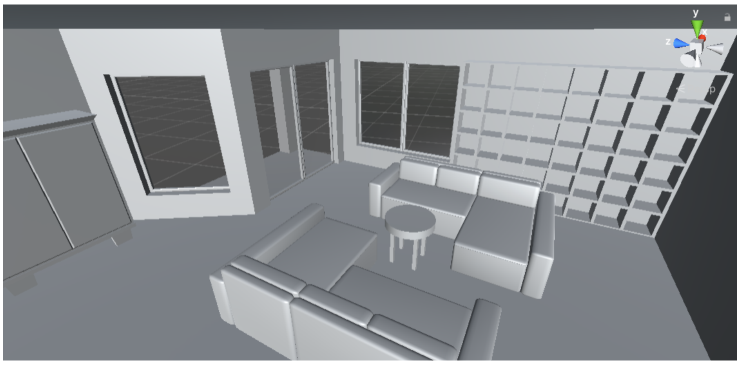


Figure 8.11. 3D model of the flat, simplified and reproduced in white. Source: Author

8.5 Pilot Experiment Design Overview of the Arch ViewR

8.5.1 Methodology

The study employed a pre-post design format to evaluate the impact of virtual reality (VR) simulations on participants' perspectives regarding window placement and viewpoints. The methodology was structured as follows:

(a) Participants were initially given a questionnaire to assess their baseline perspectives on window placement and viewpoints.

(b) Subsequently, participants were immersed in a VR simulation that presented various scenarios related to window positioning and viewpoints.

(c) After the VR experience, participants completed a follow-up questionnaire to measure any changes in their perspectives or decisions influenced by the VR simulation.

The study involved a cohort of 43 students who were meticulously chosen to ensure a diverse representation of perspectives. The primary criterion for selection was their academic background. While the participants were not directly involved in architectural studies, they were closely associated with related disciplines. This strategic choice was made to ensure that the participants, while not being architects, still had a foundational understanding of the subject matter, thereby providing a balanced viewpoint.

Figure 8.12. Author during Arch ViewR setup for the experiment. Source: J. Martyniuk-Pęczek

The study was conducted over a span of eleven months, with multiple cohorts of participants undergoing the testing process during this period. The primary variables under observation were the position of the window in the simulated environment and the preferred point of view or perspective deemed optimal by the participants.

It was hypothesized that VR simulations could play a pivotal role in architectural design, particularly in decisions related to window placement. The immersive nature of VR was anticipated to provide participants with a clearer understanding and visualization of different design scenarios, thereby influencing their design choices.

Figure 8.13. Ongoing experiment. Source: J. Martyniuk-Pęczek

8.5.2 Survey Design and Implementation

The survey's design was crucial for obtaining data to address the research question concerning the influence of Virtual Reality (VR) technology on decision-making for window placement in an apartment's living room. The survey was structured in two main parts: pre-VR and post-VR.

In the first part, participants were acquainted with the apartment and its surroundings. They were provided with a detailed description, supplemented with drawings of the apartment. To better understand the location, participants were encouraged to conduct their own research. Subsequently, they were tasked with deciding on a window placement on the living room's layout. This segment gathered baseline data on participants' initial preferences and decisions.

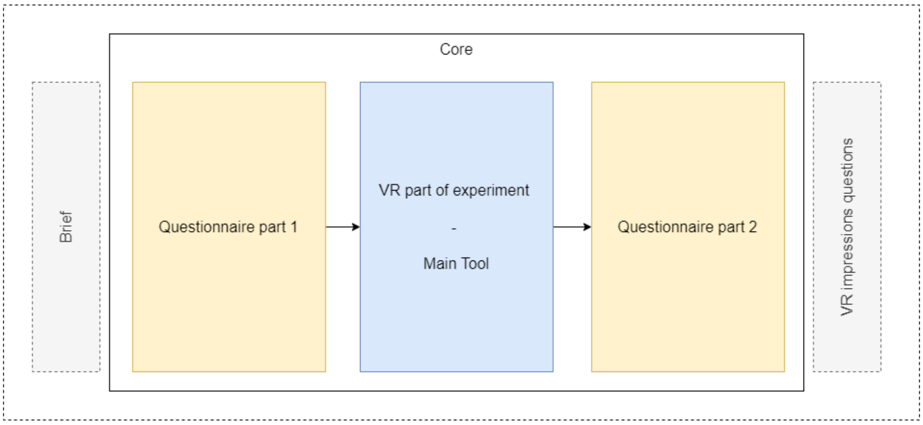


Figure 8.14. Structure of the pilot experiment. Source: Author

Participants were then introduced to a VR simulation, aiming to capture their decision-making process in a more immersive environment. Participants navigated the VR simulation at their own pace, selecting their preferred view and focusing on it for a duration of 5 seconds. The simulation recorded the user's head position and viewing direction.

The second part of the survey took place post-VR. After the VR experience, participants revisited the living room layout, deciding on the window placement once more. They were then asked whether the VR experience influenced their initial decision. For ease of comparison, the core questions regarding window placement were consistent between the pre-VR and post-VR surveys. Additionally, the post-VR survey included specific questions about the VR experience and its impact on their decision-making process.

This structured approach ensured a comprehensive analysis of the data, enabling a direct comparison of participant choices before and after the VR intervention and providing insights into the effectiveness of VR as a tool in architectural design.

8.6 Pilot Testing Results of the Arch ViewR

Within the Arch ViewR, mechanisms have been designed to obtain specific types of data that serve as foundational elements for further investigation. This section demonstrates how this data can be utilized and visualized. The types of raw data to be collected include:

(a) Comparison of pre- and post-experiment questionnaire responses.

(b) Comparison between questionnaire answers and experiment results.

(c) Position and direction of the user's head during the VR simulation.

(d) Percentage composition of view components based on the Urban Bank design.

These datasets provide a comprehensive basis for analyzing the impact of VR on architectural decision-making. By examining the pre- and post-experiment questionnaire responses, we can assess changes in participants' perspectives. Comparing questionnaire answers with experiment results allows us to validate the effectiveness of the VR simulations. Analyzing the position and direction of the user's head offers insights into their focus and preferences during the VR experience. Lastly, evaluating the percentage composition of view components based on the Urban Bank design helps in understanding the visual preferences influenced by the urban environment.

This structured approach not only facilitates the collection of essential data but also ensures that it can be effectively visualized and interpreted to draw meaningful conclusions for future research in architectural design.

8.6.1 Pre- and Post-experiment Questionnaire Comparison

The comparison between users' pre- and post-experiment responses is the most straightforward result to analyze. This comparison reveals whether and where decisions were influenced by the VR experience. During the completion of the post-experiment questionnaire, users still have access to their initial answers. Consequently, any changes in their responses are likely to be well-considered decisions, reflecting the impact of the immersive VR environment on their perspectives.

Graphical Dissection of Preferences The visual data, as encapsulated in Figures 8.15 and 8.16, provides an intriguing narrative. The juxtaposition in the bar chart (8.15) not only emphasizes the shifts in choices after the VR immersion but also underscores the potential of VR as a persuasive tool. On the other hand, the discrete distribution chart (8.16 provide a more holistic understanding, situating individual factors within a broader context and highlighting the relative importance of each influencing parameter.

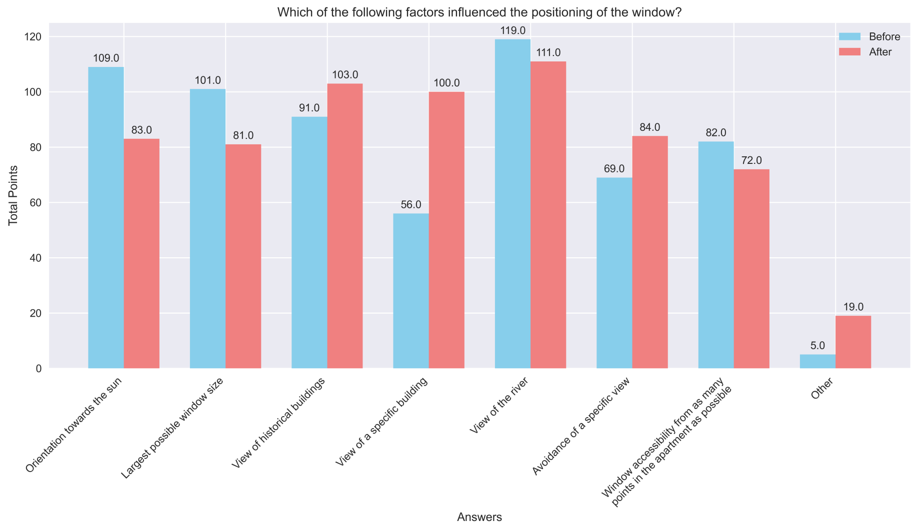


Figure 8.15. Factors that influenced the positioning of the window. Source: Author

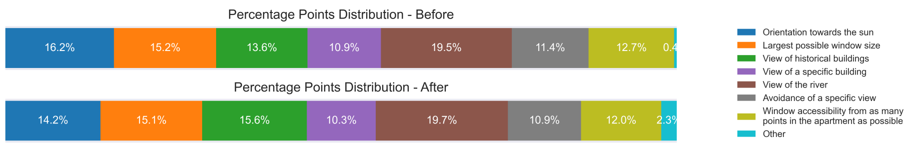


Figure 8.16. Factors that influenced the positioning of the window. Source: Author

Evolution of View Preferences

Pre-VR Experience: With the living room delineated into specific sectors (visualized in 8.17), a clear pre-VR inclination emerged. Participants predominantly gravitated towards section B3(10), showcasing a collective affinity towards the Southwest direction, potentially indicative of a universal appreciation for certain natural vistas or light conditions.

Post-VR Experience: Post immersion, while the allure of section B3(6) persisted, there was a pronounced drift towards C2(7) and B4(8) sectors. This shift could allude to the profound impact of the VR simulation in enhancing spatial awareness or augmenting the perceived aesthetics of particular views. Despite these shifts, the Southwest direction's unwavering popularity deserves further ex-

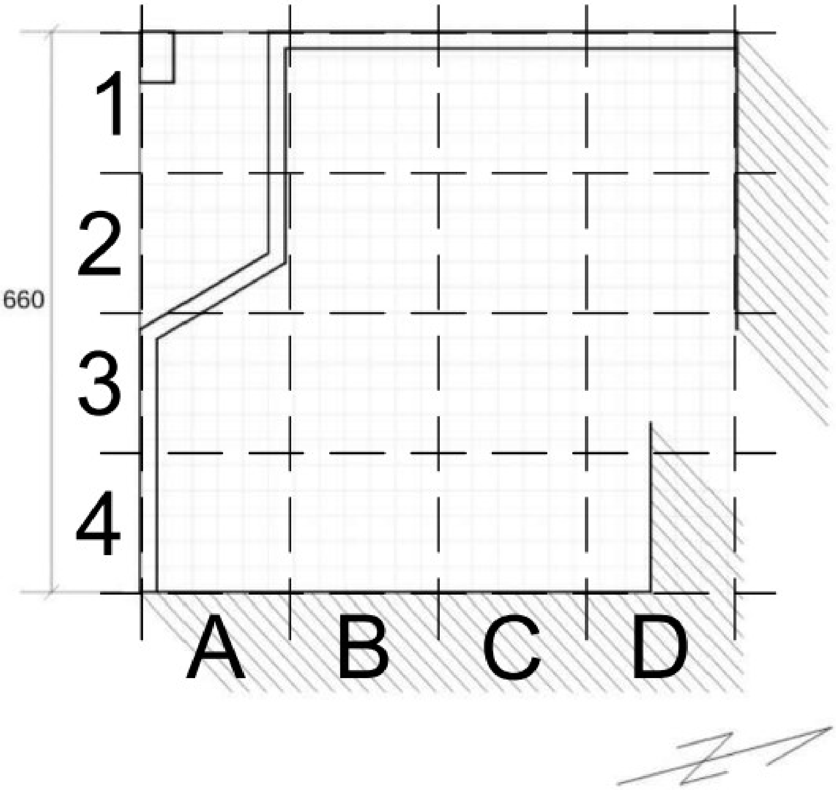


Figure 8.17. Sections of the flat. Source: Author

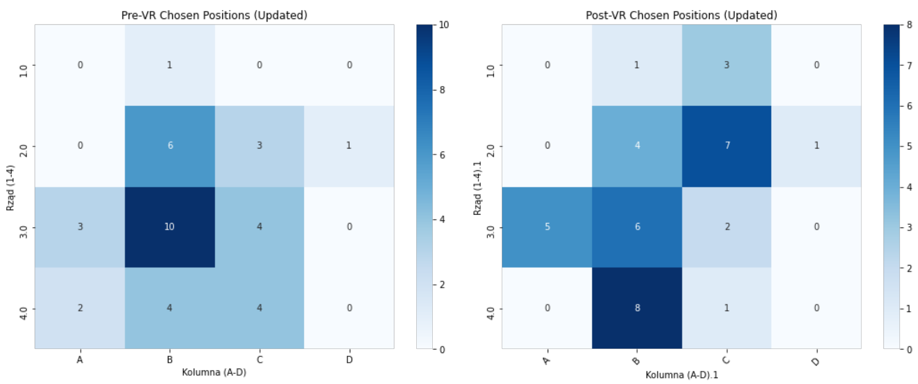


Figure 8.18. Heatmap showing the results of the questionnaire. Source: Author

ploration.

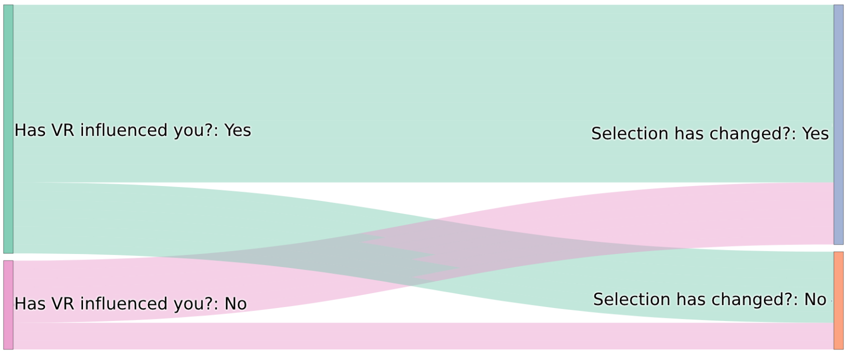


Figure 8.19. Declaration of influence vs actual choice. Source: Author

Determinants of Architectural Preferences

Before stepping into the VR realm, participants showcased a clear hierarchy of preferences: the serene "river view" topped the list, followed by the allure of "natural light", and the architectural appeal of the "potential for the largest window". Post-VR, while the "river view" retained its prime position, there was a newfound appreciation for "historical buildings", suggesting that the VR experience might have elevated the aesthetic or emotional value of such vistas. Interestingly, there was also a conscious inclination to "omit specific views", hinting at the power of VR to possibly highlight less desirable visual aspects of the environment.

8.6.2 Landmarks: The Lures of the Landscape

Primary Attraction – St. Mary's Church and Motława River: The direction of view chart (8.20) underscores a significant proclivity towards the iconic St. Mary's Church in Gdańsk and the serene stretch of the Motława River punctuated by the bridge. These landmarks, with their historical and aesthetic allure, seemed to magnetize the majority of participants, suggesting their potent influence in shaping the desirability of a viewpoint. The inclusion of these landmarks in one's view could be equated with anchoring the living space within the city's cultural and natural tapestry, offering residents a sense of belonging and connection.

Secondary Magnetism – Basilica of St. Nikola: While St. Mary's Church and the Motława River held undisputed primacy, the Basil-

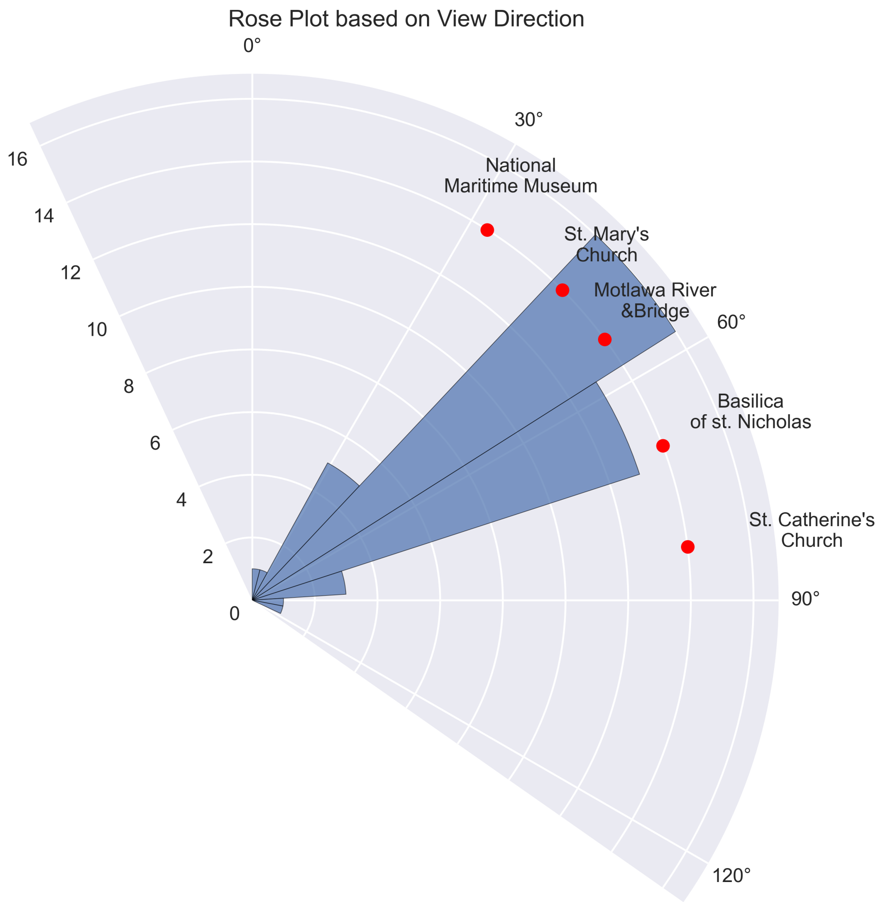


Figure 8.20. Direction of view with marked directions for landmarks. Source: Author

ica of St. Nikola also emerged as a favorable visual entity, albeit to a lesser degree. This preference illuminates the multifaceted nature of visual attraction, where different historical or architectural elements resonate with varied segments of participants.

Tertiary Preference – National Maritime Museum: Further down the preference spectrum lay the National Maritime Museum. Though it held a diminished appeal compared to the other landmarks, its selection by a subset of participants showcases the diverse tapestry of architectural attractions Gdańsk offers. This nuanced hierarchy of visual preferences could be pivotal for architects and designers, emphasizing the importance of framing not just any view, but the 'right' view, imbued with cultural and historical significance.

The findings from both the heatmap and direction of view chart culminate in a compelling argument for architects: the external environment, particularly landmarks, plays an indelible role in shaping interior design preferences. As the boundaries between digital and physical realms blur, understanding these preferences could revolutionize architectural decision-making in an increasingly virtual age.

8.6.3 Questionnaire Answers and Experiment Results Comparison

After comparing the questionnaires with each other, it is also possible to compare them with the data from the VR simulation and the decisions made by users within the Arch ViewR. This comparison allows for a comprehensive analysis of how the VR simulation influenced users' decisions and whether their initial questionnaire responses align with their actions in the virtual environment.

One of the interesting analyses is to compare how users choose positions in a questionnaire with the actual positions they select in a VR environment using the Arch ViewR. Observations indicate changes between these choices, showing that the positions chosen in VR often differ from those predicted by the post-VR questionnaire. This suggests that spatial perception in a virtual environment is not always congruent with spatial perception on paper.

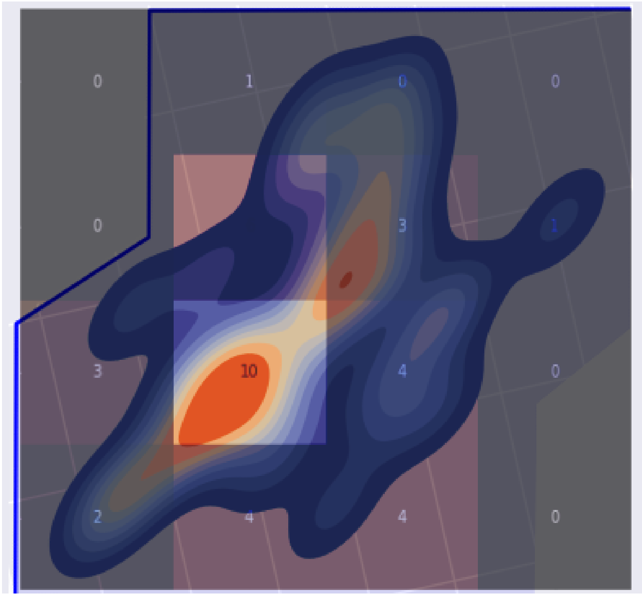


Figure 8.21. Comparison of Questionnaire Pre-VR choice and in-VR choice. The squares and numbers indicates answers in Questionnaire. Source: Author

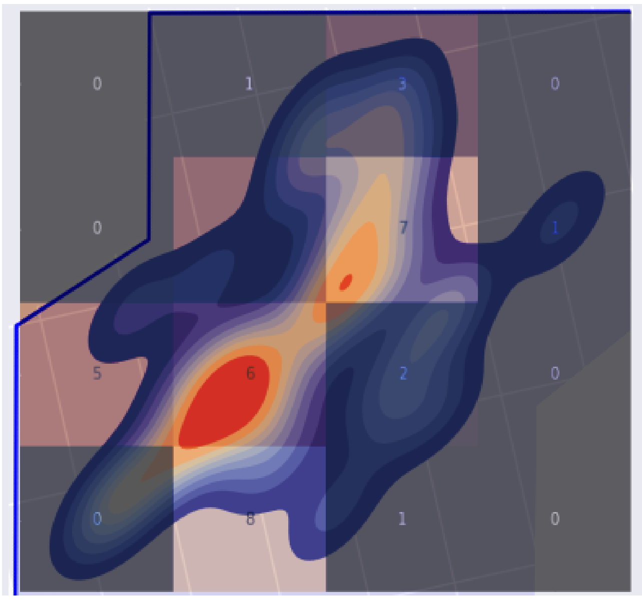


Figure 8.22. Comparison of Questionnaire Post-VR choice and in-VR choice. The squares and numbers indicates answers in Questionnaire. Source: Author

8.6.4 Analysis of the Numerical Data Obtained During the Experiment

The most complex analysis arises from the numerical data. Several insights can be derived from the position and orientation of the user's head, as well as from the composition data of the view. This data enables a detailed examination of user behavior and preferences, providing a deeper understanding of how users interact with the VR environment and the specific elements that capture their attention.

Users' position and head orientation

The heatmap visualization (8.23) offers a powerful testament to participants' behavioral tendencies within the VR environment. The chart illuminates the density of participants' chosen positions, creating a visual narrative of predominant preferences.

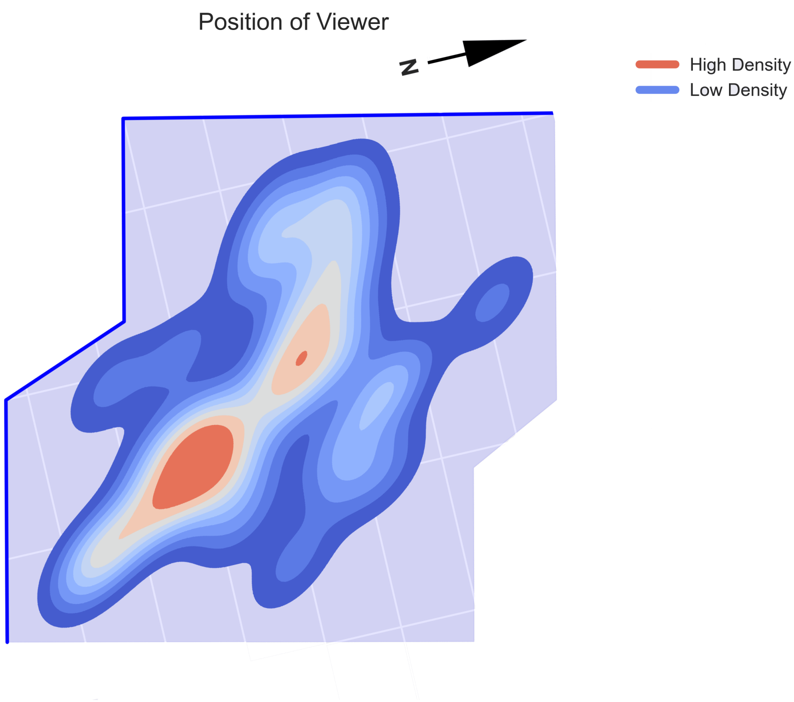


Figure 8.23. Heatmap for VR experience. Source: Author

Intriguingly, there emerged distinct hotspots within the virtual living room, with participants being drawn to specific vantage points. The rationale behind such preferences could stem from a combination of the room's layout, the positioning of windows, and the external vistas they frame.

Data Collection: The process of data collection was meticulously designed to capture the intricacies of participants' decision-making both before and after the VR experience. A blend of quantitative and qualitative methods ensured a comprehensive understanding of the factors influencing window placement and view direction choices.

Survey Instrument: A Google Form served as the primary tool for data collection. This platform was chosen for its ease of use, flexibility, and capability to handle a variety of question types. The form was structured to guide participants through the decision-making process in a logical sequence, starting with window placement based on the flat plan, transitioning through the VR experience, and culminating in post-VR decisions and reflections.

Spatial Decisions: Participants were presented with top plan representation of the apartment. They were tasked with selecting single window placement, ensuring that the chosen location aligned with the apartment's structural constraints. Additionally, they indicated their preferred direction of view, providing insights into their aesthetic and functional preferences.

Factors Influencing Decisions: Beyond the spatial choices, the survey delved deeper into the reasons behind participants' decisions. A set of predefined factors was presented, and participants ranked them in order of importance. This ranking process offered a hierarchical understanding of the considerations driving window placement and view direction choices. An open-ended option was also provided, allowing participants to specify any other influencing factors not listed.

Post-VR Reflection: After the VR experience, participants revisited their initial decisions, offering an opportunity to compare and contrast choices made in different contexts. The same set of questions was presented, ensuring consistency in the data collection process and facilitating direct comparisons.

Data Cleaning and Validation: Given the importance of data integrity, any incomplete or inconsistent responses were removed from the dataset. This cleaning process ensured that the subsequent analysis was based on a robust and reliable data set. Additionally, data validation techniques were employed during the survey design phase,

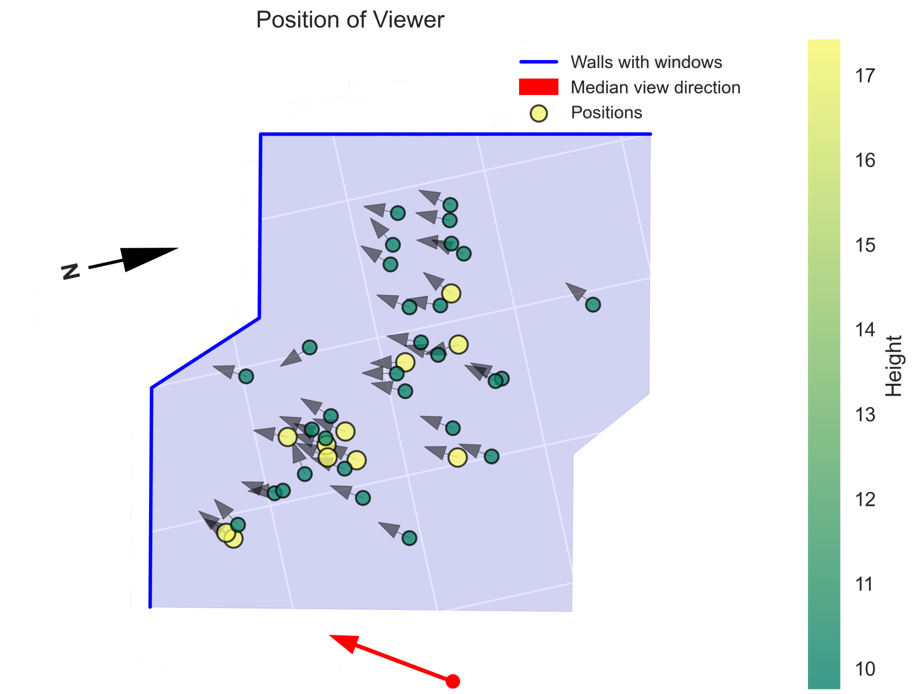


Figure 8.24. Chosen position of viewer in flat in VR. Source: Author

minimizing the chances of erroneous entries.

Data Processing: The data processing phase is pivotal in transforming raw survey responses into actionable insights. This phase involved a series of steps to ensure the data's integrity, consistency, and readiness for analysis.

Data Cleaning: The initial step in data processing was to cleanse the dataset of any anomalies or inconsistencies. Incomplete responses, where participants might have left certain sections of the survey unanswered, were excluded to maintain the dataset's robustness. This step ensured that the subsequent analysis was based on comprehensive and consistent data.

Categorization and Encoding: Given the nature of the survey, responses spanned both categorical and numerical data. For instance, the direction of view, represented using cardinal and intercardinal directions, was categorical. Such responses were encoded to facilitate quantitative analysis. This encoding process transformed qualitative data into a structured format suitable for statistical analysis.
Aggregation: To discern patterns and trends, data was aggregated based on specific criteria. For instance, responses were grouped by view direction preferences before and after the VR experience. Such aggregation provided a macro-level view of participants' preferences, enabling a comparative analysis of choices made in different contexts.

Normalization: Given the diverse range of questions and response scales, normalization was employed to bring all data onto a consistent scale. This process was particularly crucial for questions where participants ranked influencing factors. Normalization ensured that all data points were treated with equal weightage during analysis.

Handling Missing Data: While the data cleaning process removed incomplete responses, there were instances where participants might have skipped specific questions or provided ambiguous answers. In such cases, imputation techniques were employed to fill in missing data, ensuring the dataset's continuity.

Preparation for Analysis: Post the processing steps, the data was structured and segmented to facilitate in-depth analysis. This involved creating subsets of data based on specific criteria, such as participants' demographic information or their familiarity with VR. Such segmentation ensured that the analysis could delve into the nuances of different participant groups, offering a multi-faceted view

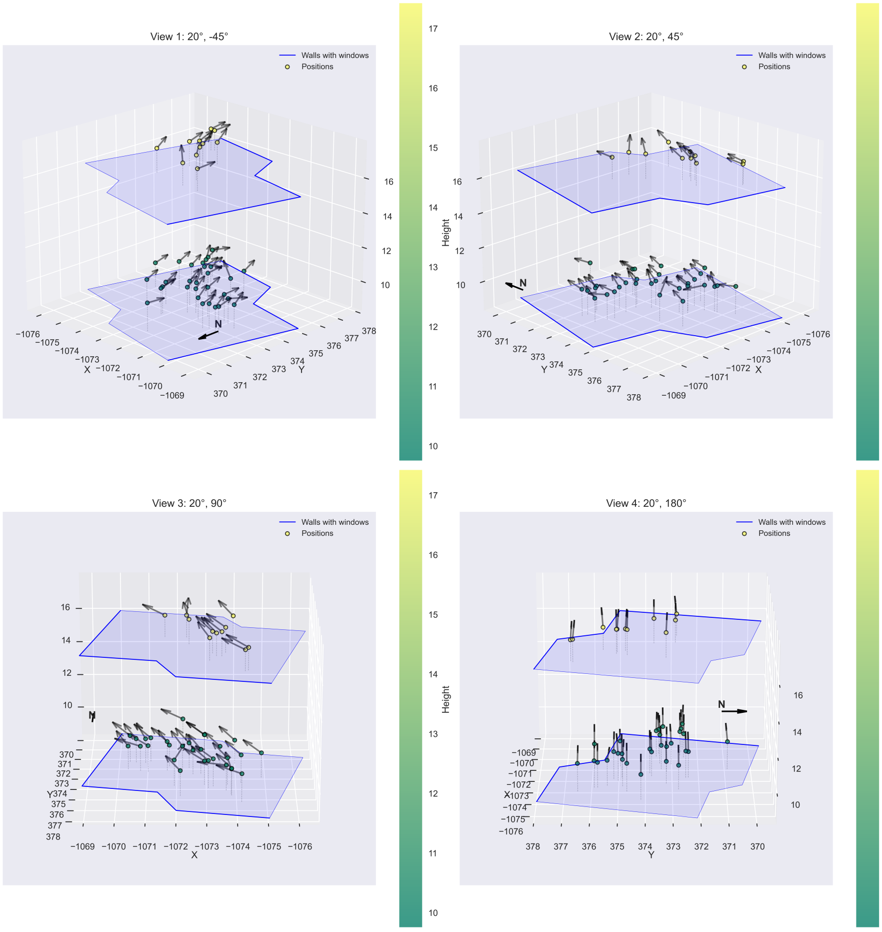


Figure 8.25. Chosen position of viewer with direction in flat in VR. Source: Author

of the survey results.

Composition data of the view

The composition of the view is determined by the colored urban model. The tool collects data based on the user-selected view and analyzes the pixel distribution for each color within that view. This analysis enables the calculation of the percentage representation of each layer, as well as the creation of a visual representation in the form of a frequency map for each layer. This method provides a detailed understanding of the visual composition and prominence of different elements in the urban environment.

During the pilot experiment, the views chosen by users were captured and their elements were analyzed. The primary elements considered in the analysis included the sky, river, inside of the flat (where the users were located), buildings, floor (pavements, roads, etc.), and greenery (trees, etc.). The design of the flat for this experiment was minimalistic, which resulted in a high percentage of the flat being present in the users' views. It would be interesting to explore how user reactions change with variations in flat design. However, for this discussion, we will focus on comparing the other elements while setting aside the flat.

The table [table 8.2] summarizes the proportions of each view element for the different users.

Table 8.2: Proportion of View Elements in User View. Source: Author

id	greenery	sky	buildings	river	floor	flat
1	3.23%	12.31%	1.75%	9.23%	1.68%	71.80%
2	5.84%	11.19%	3.56%	7.98%	2.46%	68.98%
3	3.33%	21.41%	3.66%	16.80%	4.43%	50.37%
4	2.54%	6.15%	1.48%	2.66%	1.79%	85.38%
5	3.20%	9.22%	2.39%	7.94%	2.32%	74.93%
6	3.12%	6.13%	3.49%	2.72%	1.33%	83.21%
7	3.83%	11.40%	2.06%	6.71%	1.76%	74.24%
8	4.37%	12.91%	2.22%	5.03%	1.74%	73.73%
9	3.10%	29.27%	3.58%	16.06%	1.24%	46.75%
10	4.60%	12.66%	3.50%	8.97%	1.74%	68.53%
11	5.88%	17.26%	3.55%	5.96%	4.96%	62.39%
12	5.50%	17.30%	2.44%	13.25%	23.53%	37.98%
13	3.71%	13.82%	1.21%	7.97%	9.85%	63.44%
14	5.45%	8.96%	1.28%	10.72%	5.47%	68.12%
15	3.89%	8.81%	2.08%	9.35%	4.85%	71.02%
16	4.60%	12.10%	2.47%	10.38%	8.02%	62.43%
17	4.72%	9.37%	2.13%	10.00%	13.34%	60.44%
18	5.11%	5.55%	1.45%	7.29%	2.10%	78.49%
19	2.51%	7.72%	1.28%	9.54%	4.59%	74.35%
20	3.03%	6.37%	1.29%	6.60%	4.68%	78.04%
21	4.18%	5.99%	2.33%	9.60%	4.63%	73.27%
22	5.61%	4.85%	2.19%	11.90%	5.28%	70.17%
23	3.55%	6.18%	1.70%	9.12%	7.27%	72.19%
24	3.81%	7.24%	2.37%	8.68%	5.55%	72.34%
25	2.79%	9.29%	1.66%	7.17%	5.84%	73.24%
26	7.02%	25.79%	0.91%	10.15%	22.42%	33.70%
27	3.59%	4.53%	1.88%	4.44%	1.52%	84.04%
28	4.16%	14.12%	2.68%	10.00%	16.51%	52.53%
29	3.14%	9.86%	1.13%	6.71%	9.81%	69.36%
30	2.40%	5.67%	1.46%	6.86%	7.24%	76.38%
31	3.32%	6.36%	1.38%	4.52%	1.90%	82.52%
32	7.41%	15.38%	2.39%	11.30%	16.32%	47.20%
33	3.38%	6.67%	1.16%	2.26%	8.83%	77.69%
34	2.48%	3.69%	1.96%	5.47%	3.29%	83.11%
35	2.77%	12.61%	1.96%	11.34%	12.29%	59.02%
36	2.96%	5.68%	1.24%	4.51%	4.74%	80.88%
37	5.59%	14.20%	2.07%	11.04%	8.32%	58.79%
38	4.68%	14.57%	1.82%	9.27%	3.82%	65.84%
39	6.62%	6.10%	1.42%	9.78%	17.05%	59.04%
40	2.05%	1.43%	1.01%	4.72%	0.81%	89.98%
41	2.76%	3.39%	1.81%	5.53%	3.56%	82.95%
42	1.01%	1.66%	0.70%	1.66%	1.45%	93.52%
43	3.85%	1.75%	0.14%	2.58%	2.65%	89.03%
AVERAGE	3.97%	9.93%	1.96%	7.99%	6.35%	69.80%

From the table, we observe the following trends among the elements:

- **Sky**: The average proportion of the sky in the users' views is 9.93%.Excluding the flat, the percentage of the sky increases to 31.59%.
- **River**: On average, the river constitutes 7.99% of the view. Without considering the flat, the river's proportion rises to 27.22%.
- **Greenery**: Greenery occupies about 3.97% of the view on average. Excluding the flat, greenery makes up 14.51% of the view.
- **Buildings**: The average proportion of buildings is 1.96%. When excluding the flat, buildings constitute 7.20% of the view.
- **Floor**: The floor element, consisting of pavements and roads, makes up about 6.35% of the view. Without the flat, the floor represents 19.48% of the view.

The output images were generated by testing the occurrence of each layer's color across multiple probes. Each layer is represented by a distinct color, and the occurrences of these layers are visualized in separate and combined images.

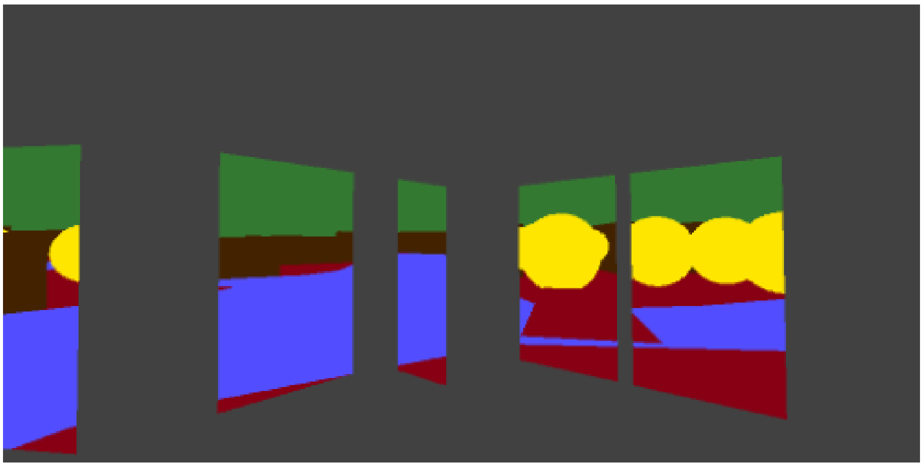


Figure 8.26. Example of colored layer result. Source: Author

Each layer in the analysis is associated with a specific RGB color. The colors and corresponding layers are listed below:

- **Sky**: RGB (52, 121, 49)
- **River**: RGB (82, 78, 255)
- **Greenery**: RGB (255, 230, 0)
- **Buildings**: RGB (67, 34, 0)

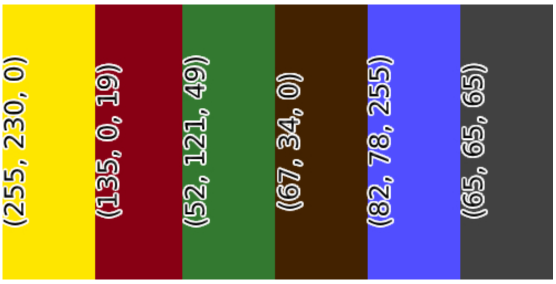


Figure 8.27. Color used. Source: Author

- **Floors**: RGB (135, 0, 19)
- **Flat**: RGB (65, 65, 65)

The generation of the frequency maps

The provided figure (fig. 8.28) illustrates the process of counting occurrences of a specific color (in this case, yellow) for each pixel across multiple images. Let us assume we are examining the pixel located at coordinates (x1, y1). The process can be explained as follows:

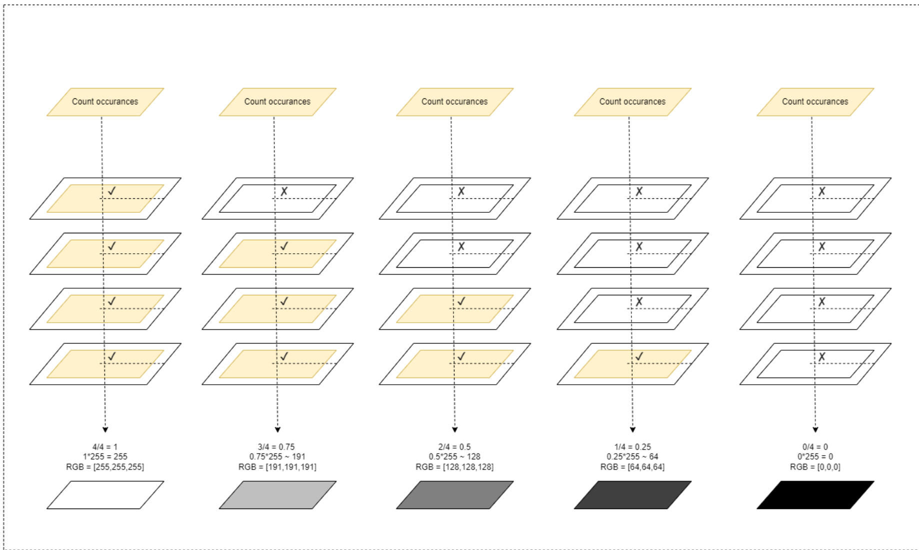


Figure 8.28. Process of counting color occurrences for each pixel across multiple images. Source: Author

(a) **Count Occurrences**: For each layer, the tool checks whether the pixel at (x1, y1) is yellow. The presence of yellow color is marked with a check, while its absence is marked with a cross.

(b) **Calculate Percentage**: The tool counts the number of layers in which the pixel at (x1, y1) is yellow. It then calculates the percentage of occurrences by dividing the count by the total number of layers. For example, if there are 4 layers and the pixel is yellow in 3 of them, the calculation would be:

$$\frac{3}{4} = 0.75$$

(c) **Determine RGB Value**: The percentage obtained is then used to adjust the RGB value for the pixel. The base RGB value for yellow is assumed to be (255, 255, 255). This value is multiplied by the calculated percentage to get the new RGB value. For example:

$$0.75 \times 255 \approx 191$$

Hence, the new RGB value for the pixel would be (191, 191, 191).

(d) **Visual Representation**: The final RGB value is used to generate a visual representation of the pixel in the output image. This process is repeated for each pixel across the images, resulting in a frequency map that visually represents the occurrences of the yellow color across the layers.

This method allows for a detailed analysis of color distribution in a given set of images, providing insights into the visual composition and prominence of specific colors within the urban model.

Frequency Maps Analysis Example

– **Input Results**: There are three sets of input results fig. 8.29, each represented by a grid of 2x2 pixels.
– **Color Probe**: The results from the three grids are fed into a central component labeled as the **Color Probe**.
  * The Color Probe's function is to analyze the color data from each pixel in the grids and convert the color information into grayscale values.
– **Grayscale Conversion**: The Color Probe processes the color values and converts them into grayscale values.
  * The grayscale values are calculated as fractions of 255, which is the maximum value for a pixel in an 8-bit grayscale image.
– **Output Result**: The final output is a single 2x2 grid of grayscale values.

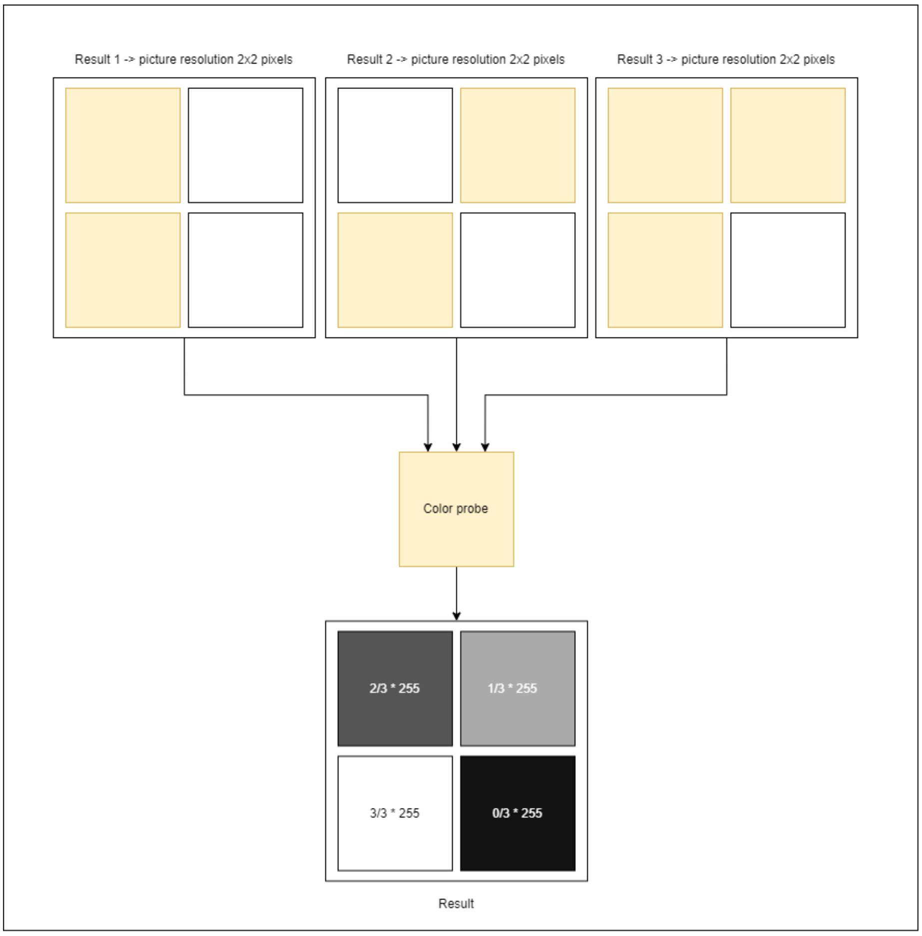


Figure 8.29. Example how to create Frequency maps. Source: Author

* Each cell in this grid shows the resulting grayscale value for the corresponding pixel from the input grids.
* For example:
  · $\frac{2}{3} \times 255$ results in a dark gray value.
  · $\frac{1}{3} \times 255$ results in a lighter gray.
  · $\frac{3}{3} \times 255$ results in white.
  · $\frac{0}{3} \times 255$ results in black.

Frequency maps for pilot experiment

To determine the frequency of each layer's appearance, 43 output images (probes) were analyzed. For each layer, the number of times its specific color appeared at each pixel location was recorded. The results are represented in a grayscale frequency map where the intensity of the color white corresponds to the frequency of occurrence. For instance, if a specific color appeared in all 43 images at a particular pixel, the pixel is colored white (255, 255, 255). If it appeared 23 times, the intensity would be $\frac{23}{43} \times 255$ for each color channel.

Additionally, a merged image was created to visualize the average occurrence of each layer. This combined occurrence map uses the actual colors associated with each layer and overlays them to show where different layers tend to appear on average. This image provides a comprehensive view of the spatial distribution of each layer across all probes.

The figures below provide examples of the frequency maps for each layer, followed by the combined occurrence map that illustrates the average layer distribution.

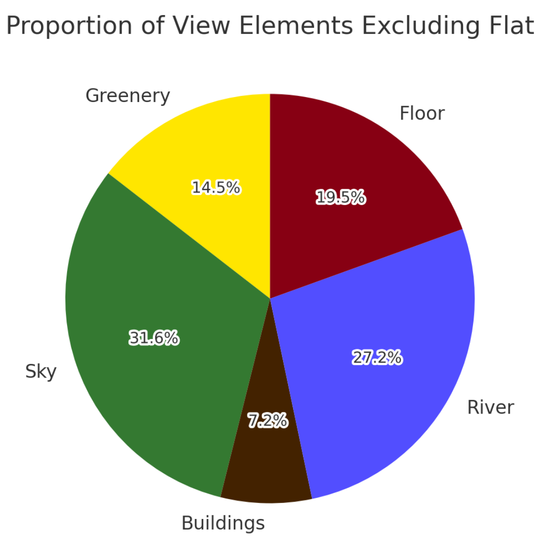


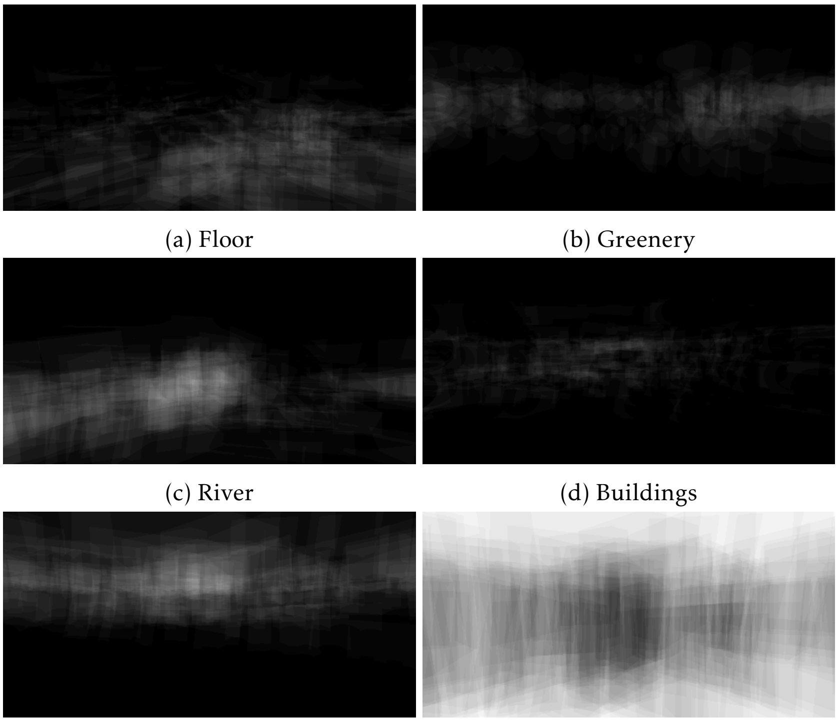
Figure 8.30. Proportion of View Elements Excluding Flat. Source: Author

These proportions highlight the balance among different elements that together create a quality view. The flat's dominance is a unique aspect of this experiment due to its minimalistic design. Future studies could explore how variations in flat design impact user preferences and the overall view quality.

Contextual Significance

In the broader context of the research framework, this grayscale conversion is a crucial step for standardizing the color data into a uniform format that can be easily analyzed. By reducing the color information to grayscale values, the researchers can focus on the intensity and contrast patterns, which are often more significant in visual and lighting studies.

This process allows for a simplified yet effective way to quantify and compare the visual data collected from the VR experience and questionnaires, facilitating a more objective analysis of the participants' responses and interactions with the virtual environment.



(a) Floor

(b) Greenery

(c) River

(d) Buildings

(e) Sky

(f) Flat

Figure 8.31: Frequency Maps. Source: Author

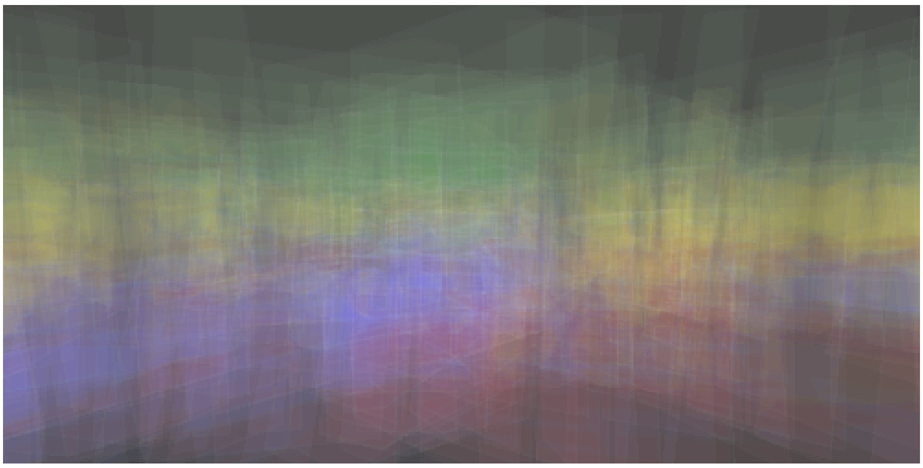


Figure 8.32. Combined frequency maps. Source: Author

When comparing these observations to the EN 17037 - Daylight Standard, which emphasizes access to daylight and quality views, it is clear that the presence of natural elements like the sky, river, and greenery plays a crucial role. The balance among these elements, excluding the flat, aligns with the standard's goals of providing a visually appealing and health-promoting environment.

8.7 Conclusions

The Arch ViewR allows for testing different urban scenarios, extending beyond considerations of daylighting. It provides a comprehensive framework for general experimentation within a VR environment. Researchers have the flexibility to create their own location, urban, and architectural banks, enabling them to design unique experiments tailored to their specific needs. This versatility facilitates a wide range of studies, from urban planning to architectural design, by providing a robust platform for simulating and analyzing various scenarios.

By incorporating VR into their research, scholars can gain deeper insights into user behavior and environmental interactions, leading to more informed decision-making and innovative solutions. The Arch ViewR's ability to support custom experiments enhances its utility, making it a valuable resource for researchers worldwide. This framework not only democratizes access to advanced VR technology but also fosters collaboration and knowledge sharing among the global research community. Consequently, the Arch ViewR can significantly advance the integration of VR into academic and practical applications, driving progress in various fields of study.

Chapter 9

Summary

This PhD thesis addressed key questions regarding the use of Virtual Reality (VR) in lighting research, with a particular focus on evaluating window views in compliance with EN 17037 standards. The thesis comprises several key chapters that explore various aspects of this issue in detail.

In **Chapter 3**, the tools and standards used in Poland and Europe for evaluating daylight in buildings are discussed, with a focus on window views. This chapter provides a detailed analysis crucial for understanding how VR can impact window design in compliance with standards, addressing Research Question 1.

In **Chapter 4**, the application of VR in daylighting research is examined. A comparison between traditional daylighting analysis methods and those based on VR is presented, highlighting the advantages and limitations of these technologies. This chapter addresses Research Questions 2 and 3, discussing how VR can improve decision-making and the challenges associated with its use in residential design.

In **Chapter 7**, the development of the main VR tool created for this research is described. This tool features a modular design, allowing for various input configurations and the generation of diverse results. Unique features, user interface, data processing, and security measures related to this tool are discussed. This chapter confirms Thesis Statements 1 and 2, demonstrating that new technologies can expand research tools to include VR and that it is possible to create user-friendly and accessible tools.

In **Chapter 8**, the design and implementation of the study are outlined, including participant details, experimental setup, and survey design. The data gathering process, encountered challenges, and study results are presented, including detailed analysis and graphical representation of the data. This chapter addresses all Research Questions (1, 2, 3, and 4) and provides evidence supporting the thesis statements, showing the impact of VR on design processes and the factors contributing to optimal window views.

The originality of the work lies in the creation of a VR tool that integrates functionalities used in daylighting analysis, allowing for interactive manipulation of the environment in real-time. This tool enables architects and designers to experiment with various design elements and observe the impact of natural light on architectural spaces.

This doctoral thesis provides comprehensive tools and methodologies that can significantly enhance the quality of architectural design, particularly in the context of daylighting, and serves as a solid foundation for further research in this field.

Answers to the Research Questions

– **Impact of VR on Evaluating Window Views:** Virtual reality (VR) significantly enhances the evaluation process by providing an immersive, realistic simulation of different window view scenarios. This allows architects to better understand how different window placements affect daylight distribution and overall spatial quality, thereby aiding compliance with European Standard 17037.

– **Influence on Window Design and Placement:** VR influences window design and placement by allowing architects to visualize and assess the impact of their decisions in a virtual environment. This helps in optimizing window size, placement, and orientation to maximize daylight penetration and ensure compliance with daylighting standards.

– **Improvement in Decision-Making:** The use of VR improves the decision-making process by offering a more interactive and detailed visualization tool. This allows for a better assessment of various design options, leading to more informed and confident decisions regarding daylighting and window placement in residential buildings.

– **Limitations and Challenges of Using VR:** Some limitations and challenges associated with using VR in residential design include the high cost of high-quality VR setups, potential motion sickness or eye strain experienced by users, and the learning curve associated with new technology. Future studies should focus on making VR tools more affordable and user-friendly, and on minimizing physical discomfort for users.

– **Factors Contributing to Optimal Quality View and Effectiveness of VR:** Key factors that contribute to the optimal quality view from a window include the size and placement of windows, the orientation of the building, and the specific uses of different spaces within the building. VR is effective in leveraging these factors into practice by providing a realistic simulation of how these variables interact, allowing for better design and planning decisions.

These insights highlight the transformative potential of VR in architectural design, particularly in the context of optimizing daylight and window views in compliance with relevant standards.

9.1 Lessons Learnt for Designing VR Experiments in Research

Designing Virtual Reality (VR) experiments requires careful planning and consideration of various elements to ensure the study's success and the validity of its results. These guidelines cover essential steps and considerations for researchers aiming to integrate VR into their experimental designs. By adhering to these guidelines, researchers can optimize their VR experiments for usability, reliability, and overall effectiveness.

– **Needs Assessment of Users:** Before designing the VR experiment, it is essential to assess the VR literacy of the users who will participate in the study. Understanding their familiarity with VR technology will help in deciding the complexity of the features to be included. For users with low VR literacy, incorporating a large number of steep learning curve features could hinder the experiment's effectiveness. Conversely, users with high VR literacy may benefit from more advanced features. This assessment ensures that the experiment is accessible and user-friendly for all participants.

– **Evaluating the Value of Features:** Each feature considered for inclusion in the VR experiment should be evaluated for its value to the research objectives. If a feature significantly enhances the research outcomes, it might be worth implementing even if it requires additional time for user familiarization. Balancing the feature's potential impact with the time and effort needed for users to become comfortable with it is crucial. High-value features that contribute significantly to the data and insights of the study should be prioritized.

– **Group Familiarization:** Preparing a comprehensive familiarization session for participants is crucial. This session should cover basic navigation, interactions, and any specific features of the VR environment relevant to the study. A well-designed familiarization process can reduce the learning curve and help participants focus on the research tasks. Ensuring that participants are comfortable and confident in using the VR setup can lead to more accurate and reliable data collection.

– **Pre- and Post-Experience Surveys:** Conducting surveys before and after the VR experience is an effective approach to gather data on user expectations, experiences, and feedback. Pre-experience surveys can help in understanding the baseline VR literacy and expectations of the participants, while post-experience surveys can provide insights into their actual experience and areas for improvement. This feedback loop is essential for refining the VR experience and addressing any issues that arise.

– **Trained Moderator:** Assigning a trained moderator to guide participants through the VR experience can significantly enhance the experiment's success. The moderator can provide real-time assistance, troubleshoot issues, and ensure that participants remain focused on the research tasks. This approach minimizes disruptions and maximizes data quality. A skilled moderator can also help in interpreting participant reactions and interactions within the VR environment.

– **Data Recording:** Recording data during the VR experience is a must. This includes logging user interactions, behavior, and physiological responses if applicable. High-quality data recording ensures that researchers can analyze the participants' actions in detail and draw accurate conclusions from the study. Comprehensive data collection allows for a deeper understanding of participant behavior and the effectiveness of the VR environment.

– **Portability of the VR Experience:** Making the VR experience portable is highly beneficial, especially for multi-site studies or when participants cannot travel to a central location. Using standalone head-mounted displays (HMDs) or simulations that can run on laptops with HMDs allows for flexibility and convenience, ensuring a broader range of participants can be included in the study. Portability increases the accessibility and scalability of the VR experiment.
– **Clear Instructions and Objectives:** Providing clear instructions and objectives within the VR environment helps participants understand what is expected of them. This reduces confusion and ensures that the data collected is relevant to the research goals. Clear guidance helps maintain the focus of participants on the critical aspects of the experiment, leading to more accurate and useful data.
– **Technical Support:** Having technical support readily available can prevent minor issues from becoming major disruptions. Technical support can assist with hardware or software problems, ensuring the experiment runs smoothly. This support can also provide peace of mind to participants, knowing help is available if needed. Quick resolution of technical issues ensures that the experiment continues without significant interruptions.
– **Pilot Testing:** Conducting pilot tests with a small group of participants before the main study can identify potential issues with the VR setup and procedures. This allows researchers to make necessary adjustments to improve the overall design and implementation of the experiment. Pilot testing helps ensure that the final experiment runs smoothly and that any unforeseen problems are addressed beforehand. This preparatory step is critical for fine-tuning the VR experience and ensuring that all elements work as intended.

By following these guidelines and incorporating these additional elements, researchers can design effective and efficient VR experiments that yield valuable and reliable data. Careful planning and thorough preparation are key to

9.2 Recommendations and Future Research

The research demonstrates VR's transformative potential in architectural design. By bridging the gap between abstract design concepts and tangible spatial experiences, VR emerges as an invaluable tool for architects and designers. Its capacity to influence design decisions, as evidenced by the study, hints at a future where VR becomes an integral part of architectural curricula and professional practices.

While the study provides significant insights, it also paves the way for future research avenues. Exploring VR's potential in other architectural elements, understanding its role in collaborative design, and integrating augmented reality are potential areas for exploration. Additionally, as VR technology continues to evolve, its integration with other emerging technologies could further redefine architectural practices.

It is possible to extend the application of the VR tool to perform various tests, including:

- **Different Room Setup**: Evaluating the impact of varying room configurations on lighting and view quality, including alterations in furniture arrangements, room dimensions, and interior designs.
- **Different Colours**: Studying how different color schemes within a room affect the perception of natural light and window views, such as changes in wall colors, furniture colors, and decor.
- **Different City**: Simulating window views from different cities to compare how urban environments influence lighting and view satisfaction.
- **Remove Landmarks**: Analyzing the importance of specific landmarks in the overall perception of the window view by removing them from the VR simulations.
- **Put New Landmarks**: Understanding how additional visual elements contribute to the aesthetic and psychological impacts of a window view by adding new landmarks.
- **Change Weather**: Simulating various weather conditions, such as sunny, cloudy, rainy, or snowy days, to study their effects on lighting quality and view satisfaction.
- **Change Time of the Day**: Assessing how different times of day, from dawn to dusk, influence the perception of natural light

and the quality of the view.

– **Do a Night Experience**: Creating night-time simulations to evaluate the impact of artificial lighting and nocturnal views on occupant satisfaction and comfort.
– **Add People**: Introducing virtual people into the simulations to study social dynamics and their influence on the perception of window views and interior lighting.
– **Add Sounds**: Incorporating ambient sounds, such as city noise, nature sounds, or interior sounds, to provide a more immersive experience and allow for the study of auditory influences on visual and lighting perceptions.

These possible adjustments and additional tests demonstrate the versatility of the developed VR tool, enabling its application across a broad spectrum of research scenarios in environmental psychology, urban planning, and interior design. By leveraging this tool, researchers can gain deeper insights into the factors that influence human interaction with their built environment, ultimately contributing to the design of more effective and satisfying living and working spaces.

Throughout this thesis, I have demonstrated the utility of VR tools for architectural lighting research and outlined potential future steps. The integration of VR technology, particularly in compliance with the EN 17037 standard, offers a new, more natural way to design and evaluate building lighting through first-person view.

Future research should refine these tools to improve accuracy, usability, and effectiveness. This includes expanding virtual environments, enhancing user interfaces, and conducting longitudinal studies on the impact of VR-assisted design.

Building on this work, future research can bridge the gap between traditional architectural methods and modern VR technology, contributing to more sustainable and innovative design practices. This thesis serves as a foundation for realizing the full potential of VR in architectural research.

QR Code for Accessing the Digital Assets

Figure 9.1. QR code - link to the project files and videos

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List of Figures

1.1 Method and structure 7

2.1 Lascaux Cave Paintings 17
2.2 Proto-Cuneiform tablet 18
2.3 Apparatus and equipment for making daguerreotypes 19
2.4 Early Tomb Raider game view 20
2.5 2018 Tomb Raider game view 21
2.6 3DoF vs 6DoF 22
2.7 Virtual Boy by Nintendo 23
2.8 Milgram's et al. Reality-Virtuality Continuum. Source: Milgram & Kishino (1994) 31
2.9 Burdea's et al. I^3 triangle. Source: Burdea & Coiffet (2003) 32

3.1 Sun ruler. Source: (Twarowski 1960) 41
3.2 Quality of the View. Source: Author 47

5.1 Apple Vision Pro 68
5.2 Uncanny Valley 72

6.1 Walkthrough tool 83
6.2 ALTO screenshot 86
6.3 ALTO tool during session 88

7.1 Diagram illustrating the modular architecture of the Arch ViewR System. 100
7.2 Tree system of banks concept 103
7.3 Example of the blockout in game engine 106

8.1 Arch ViewR development phases 121
8.2 Diagram illustrating variables chosen from the bank system to be used in pilot experiment. 123
8.3 Urban analysis of chosen area. Source: A. Zackiewicz . 126

8.4 Urban analysis of chosen area. Source: A. Zackiewicz . 126
8.5 Urban analysis of chosen area. Source: A. Zackiewicz . 127
8.6 3D model of Gdańsk acquired from the Gdańsk City Development Office implemented in the Unity 3D. Source: Author 128
8.7 Example of the colored urban layer in the Unity 3D. Source: Author 128
8.8 Living room and view from the chosen flat. Source: J. Martyniuk-Pęczek 129
8.9 View from the chosen flat. Source: J. Martyniuk-Pęczek130
8.10 Building that the flat is situated in. Source: J. Martyniuk-Pęczek 130
8.11 3D model of the flat, simplified and reproduced in white. Source: Author 131
8.12 Author during Arch ViewR setup for the experiment. Source: J. Martyniuk-Pęczek 132
8.13 Ongoing experiment. Source: J. Martyniuk-Pęczek . . 133
8.14 Structure of the pilot experiment. 134
8.15 Factors that influenced the positioning of the window. Source: Author 136
8.16 Factors that influenced the positioning of the window. Source: Author 136
8.17 Sections of the flat. Source: Author 137
8.18 Heatmap showing the results of the questionnaire. Source: Author 137
8.19 Declaration of influence vs actual choice. Source: Author 138
8.20 Direction of view with marked directions for landmarks. Source: Author 139
8.21 Comparison of Questionnaire Pre-VR choice and in-VR choice. The squares and numbers indicates answers in Questionnaire. Source: Author 141
8.22 Comparison of Questionnaire Post-VR choice and in-VR choice. The squares and numbers indicates answers in Questionnaire. Source: Author 141
8.23 Heatmap for VR experience. Source: Author 142
8.24 Chosen position of viewer in flat in VR. Source: Author144
8.25 Chosen position of viewer with direction in flat in VR. Source: Author 146
8.26 Example of colored layer result. Source: Author 149

8.27 Color used. Source: Author 150
8.28 Process of counting color occurrences for each pixel across multiple images. Source: Author 150
8.29 Example how to create Frequency maps. Source: Author 152
8.30 Proportion of View Elements Excluding Flat. Source: Author 154
8.31 Frequency Maps. Source: Author 155
8.32 Combined frequency maps. Source: Author 155

9.1 QR code - link to the project files and videos 164

Appendix A

Appendix

A.1 Complete Code Listing

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

public class CamPosApprox : MonoBehaviour
{
  [SerializeField]
  Transform camTransform;
  [SerializeField]
  Transform camColor;
  [SerializeField]
  GetColorValuesBib colorCount;
  [SerializeField]
  Text timerText;
  [SerializeField]
  SavingResults saveRes;



  // Update is called once per frame
  public void _StartApprox()
  {
    StartCoroutine(Apporximation(5f));
```

```
      StartCoroutine(TimeDown(5f));
    }


    IEnumerator Apporximation(float duration)
    {
      float timeStamp = Time.time;
      Vector3 appPos = Vector3.zero;
      //Vector3 appRot = Vector3.zero;
      Quaternion appQua = camTransform.rotation;
      int counter = 0;

      while (Time.time - timeStamp < duration)
      {
        appPos += camTransform.position;
        //appRot += camTransform.rotation.
eulerAngles;
        appQua *= transform.rotation;
        Debug.LogWarning($"{appQua}::{
camTransform.rotation}");
        counter++;
        yield return new WaitForEndOfFrame();
      }
      camColor.position = appPos / counter;
      //camColor.rotation = Quaternion.Euler(
appRot / counter);
      camColor.rotation = appQua;
      yield return new WaitForSeconds(1f);
      //zapisz do csv\/\/\/
      colorCount._StartSampling();
      yield return new WaitForSeconds(10f);
      saveRes._AddNewData(camColor.position,
camColor.rotation.eulerAngles);
      timerText.enabled = true;
      timerText.text = "DONE";
    }

    IEnumerator TimeDown(float timeToCount)
    {
      float timeTC = timeToCount;
```

```
      timerText.enabled = true;
      while (timeTC >= 0)
      {
        timerText.text = $"{timeTC}";
        yield return new WaitForSeconds(1f);
        timeTC--;
      }
      timerText.enabled = false;

    }
  }

```

Listing A.1: Complete Code Listing

```
using System.Collections;
using System.Collections.Generic;
using System.Linq;
using UnityEngine;
using UnityEngine.Events;
using System.Threading.Tasks;
using System;

public class GetColorValuesBib : MonoBehaviour
{
    public RenderTexture sample;
    private Texture2D converted;
    private List<Vector3> listOfColors = new List
   <Vector3>();

    private Dictionary<Vector3, int> colourCount;

    private Vector3 c = Vector3.zero;
    public float samplesCount = 3f;
    public UnityEvent<float> progresUpdated;

    int calculations = 0;
    public int calculationsLimit = 1000;
    // Start is called before the first frame
   update
    /// <summary>
```

```
  public CreateGraph createGraph;
  private int notUsedPixels = 0;
  /// </summary>


  void ConvertTo2DTex()
  {
    RenderTexture.active = sample;
    converted = new Texture2D(sample.width, sample.height);
    converted.ReadPixels(new Rect(0, 0, sample.width, sample.height), 0, 0);
    converted.Apply();
  }


  async void ReadColorValue(int x, int y)
  {
    colourCount = new Dictionary<Vector3, int>();
    float total = x * y;
    float currentProgress = 0;
    Debug.Log($"Waka {total} {currentProgress}");

    for (int i = 0; i < x; i++)
    {
      for (int j = 0; j < y; j++)
      {
        Color color = converted.GetPixel(i, j);
        c.x = Mathf.Floor(color.r * samplesCount) / samplesCount;
        c.y = Mathf.Floor(color.g * samplesCount) / samplesCount;
        c.z = Mathf.Floor(color.b * samplesCount) / samplesCount;

        if (!colourCount.ContainsKey(c))
        {
          colourCount.Add(c, 0);
```

```
          }
          colourCount[c]++;
          currentProgress++;
          progresUpdated?.Invoke(currentProgress / total);

          if (calculations > calculationsLimit)
          {
            calculations = 0;
            await Task.Yield();
          }
          else
          {
            calculations++;
          }
        }

      }
      GetOccurance(x, y);
    }

    async void GetOccurance(float x, float y)
    {
      //nieuzywane pixele
      foreach (KeyValuePair<Vector3, int> kpv in colourCount)
      {
        if(kpv.Value/(x*y)<0.03)
        notUsedPixels += kpv.Value;
        Debug.Log(notUsedPixels);
      }
      //nieuzywane pixele

      foreach (KeyValuePair<Vector3, int> kpv in colourCount)
      {
        Debug.Log($"Color of value x: {kpv.Key.x}, y: {kpv.Key.y}, z: {kpv.Key.z} is: {(float)kpv.Value / (x * y) * 100f}% ({kpv.Value} pixels)");
```

```
        if (kpv.Value / (x * y) > 0.02)// 2
  procent na wszelki wypadek
        PassToGraphs(new Color(kpv.Key.x, kpv.Key
  .y, kpv.Key.z), (float)kpv.Value / (x * y -
  notUsedPixels) * 100f);
      }

      await Task.Yield();
    }

    public async void PerformAsyncAction()
    {
      ConvertTo2DTex();
      int x = sample.width;
      int y = sample.height;

      ReadColorValue(x, y);
    }


    public void _StartSampling()
    {
      PerformAsyncAction();
    }

    void PassToGraphs(Color col, float perc)
    {
      createGraph.CreateGraphNow(perc, col);
      createGraph.SaveGraphNow(perc, col);
    }
}

```

Listing A.2: Complete Code Listing

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

public class LABCamera : MonoBehaviour
{
```

```
    [SerializeField]
    private float velocity = 20f;
    [SerializeField]
    private float angularVelocity = 10f;

    // Update is called once per frame
    void Update()
    {
      //Controlling moving front/back /left/right
      transform.parent.Translate(Vector3.forward
   * Input.GetAxis("Vertical") * Time.deltaTime *
    velocity);
      transform.parent.Translate(Vector3.right *
   Input.GetAxis("Horizontal") * Time.deltaTime *
    velocity);
      transform.parent.Translate(Vector3.up *
   Input.GetAxis("Mouse ScrollWheel") * Time.
   deltaTime * velocity * 50f);
      //Controlling the looking angle with mouse
   // look input.getaxis

      if (Input.GetMouseButton(1))
      {
        transform.parent.Rotate(Vector3.up, Input
   .GetAxis("Mouse X") * angularVelocity);
        transform.Rotate(Vector3.left, Input.
   GetAxis("Mouse Y") * angularVelocity);
      }

    }
}
```

Listing A.3: Complete Code Listing

```
using UnityEngine;
using UnityEngine.UI;

public class CreateGraphReport : MonoBehaviour
{

    public Image baseImage;
```

```
  public Canvas myCanvas;
  [HideInInspector]
  public int counter = 0;
  public Transform graphContainer;

  public void CreateGraphNow(float percentage,
 Color col)
  {
    Image editableImage = Instantiate(baseImage
 ,graphContainer);
    //editableImage.transform.parent = myCanvas
 .transform;
    editableImage.transform.position = new
 Vector2(editableImage.transform.position.x +
 150f*counter, editableImage.transform.position
 .y);
    editableImage.color = col;
    editableImage.rectTransform.sizeDelta = new
  Vector2(45,percentage);
    Text editableText = editableImage.
 GetComponentInChildren(typeof(Text)) as Text;
    editableText.text = $"{Mathf.Floor(
 percentage * 100f)/100f}%";
    counter++;
  }

}

```

Listing A.4: Complete Code Listing

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

public class CreateGraph : MonoBehaviour
{
  [SerializeField]
  GetColorValuesBib bib;

  public Image baseImage;
```

```
    public Canvas myCanvas;
    private int counter = 0;

    public List<Color> cols = new List<Color>();
    public List<float> perc = new List<float>();

    public void CreateGraphNow(float percentage, Color col)
    {
        Image editableImage = Instantiate(baseImage);
        editableImage.transform.parent = myCanvas.transform;
        editableImage.transform.position = new Vector2(editableImage.transform.position.x + 50f*counter, editableImage.transform.position.y);
        editableImage.color = col;
        editableImage.rectTransform.sizeDelta = new Vector2(45,percentage);
        Text editableText = editableImage.GetComponentInChildren(typeof(Text)) as Text;
        editableText.text = $"{Mathf.Floor(percentage * 100f)/100f}%";
        counter++;
    }

    public void SaveGraphNow(float percentage, Color col)
    {
        cols.Add(col);
        perc.Add(percentage);
    }

}

```

Listing A.5: Complete Code Listing

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

```
using UnityEngine;
using UnityEngine.UI;

public class Report : MonoBehaviour
{
  string path;
  bool exists = false;
  int currentPage = 1;

  [SerializeField]
  Text pageText;
  [SerializeField]
  Text id;
  [SerializeField]
  Text timeOfTest;


  [SerializeField]
  Transform realCamera;
  [SerializeField]
  Transform colorCamera;
  [SerializeField]
  Transform head;

  [SerializeField]
  CreateGraphReport graph;


  ES3Spreadsheet sheet = new ES3Spreadsheet();
  void Start()
  {
    path = Application.persistentDataPath + "/
 myData.csv";
    Debug.Log(path);

    try
    {
      sheet.Load(path);
      exists = true;
      Debug.Log("File loaded");
```

```
    }
    catch
    {
      Debug.Log("File doesn't exist!!");
    }
    if(exists)
    {
      LoadPage(currentPage);
    }
  }

  public void LoadPage(int pageNumber)
  {
    int posStart = 2;
    Vector3 position = new Vector3( sheet.GetCell<float>(posStart, pageNumber),
    sheet.GetCell<float>(posStart+1, pageNumber),
    sheet.GetCell<float>(posStart+2, pageNumber));

    Vector3 rotation = new Vector3( sheet.GetCell<float>(posStart + 3, pageNumber),
    sheet.GetCell<float>(posStart + 4, pageNumber),
    sheet.GetCell<float>(posStart + 5, pageNumber));

    Quaternion rotConverted = Quaternion.Euler(rotation);

    id.text = "ID of test: #" + sheet.GetCell<int>(0, pageNumber).ToString();
    timeOfTest.text = "Date and time: " + sheet.GetCell<string>(1, pageNumber).ToString();

    head.position = position;
    head.rotation = rotConverted;
    colorCamera.position = position;
    colorCamera.rotation = rotConverted;
```

```
    realCamera.position = position;
    realCamera.rotation = rotConverted;

    pageText.text = $"{currentPage} / {sheet.RowCount - 1}";

    graph.counter = 0;

    foreach (Transform child in graph.graphContainer)
    {
      GameObject.Destroy(child.gameObject);
    }

    for (int i = posStart + 6; i < sheet.ColumnCount; i += 2)
    {
      graph.CreateGraphNow(sheet.GetCell<float>(i + 1,pageNumber), sheet.GetCell<Color>(i, pageNumber));
    }
  }

  public void _NextPage()
  {
    if (currentPage == sheet.RowCount - 1)
    {
      currentPage = 1;
    }
    else
    {
      currentPage++;
    }
    LoadPage(currentPage);
  }
  public void _PreviousPage()
  {
    if (currentPage == 1)
    {
      currentPage = sheet.RowCount - 1;
```

```
      }
      else
      {
        currentPage--;
      }
      LoadPage(currentPage);
    }



}

```

Listing A.6: Complete Code Listing

```
using UnityEngine;

public class SavingResults : MonoBehaviour
{
  string path;
  [SerializeField]
  CreateGraph graphInfo;
  ES3Spreadsheet sheet = new ES3Spreadsheet();

  private void Start()
  {
    path = Application.persistentDataPath + "/
myData.csv";
    Debug.Log(path);

    try
    {
      sheet.Load(path);
      Debug.Log("File exists");
    }
    catch
    {
      CreateNewSpreadsheet();
      Debug.Log("File created");
    }
  }
```

```
void CreateNewSpreadsheet()
{
  int i = 0;
  sheet.SetCell(i++, 0, "ID");
  sheet.SetCell(i++, 0, "Time");

  sheet.SetCell(i++, 0, "Px");
  sheet.SetCell(i++, 0, "Py");
  sheet.SetCell(i++, 0, "Pz");

  sheet.SetCell(i++, 0, "Rx");
  sheet.SetCell(i++, 0, "Ry");
  sheet.SetCell(i++, 0, "Rz");

  sheet.SetCell(i++, 0, "Color1");
  sheet.SetCell(i++, 0, "Percentage");
  sheet.SetCell(i++, 0, "Color2");
  sheet.SetCell(i++, 0, "Percentage");
  sheet.SetCell(i++, 0, "Color3");
  sheet.SetCell(i++, 0, "Percentage");
  sheet.SetCell(i++, 0, "Color4");
  sheet.SetCell(i++, 0, "Percentage");
  sheet.SetCell(i++, 0, "Color5");
  sheet.SetCell(i++, 0, "Percentage");
  sheet.SetCell(i++, 0, "Color6");
  sheet.SetCell(i++, 0, "Percentage");

  sheet.Save(path);
}

public void _AddNewData(Vector3 position,
Vector3 orientation)
{
  int placeInput = sheet.RowCount;
  int i = 0;
  sheet.SetCell(i++, placeInput, placeInput);
  sheet.SetCell(i++, placeInput, System.
DateTime.Now.ToString());

```

```
    sheet.SetCell(i++, placeInput, position.x);
    sheet.SetCell(i++, placeInput, position.y);
    sheet.SetCell(i++, placeInput, position.z);

    sheet.SetCell(i++, placeInput, orientation.x);
    sheet.SetCell(i++, placeInput, orientation.y);
    sheet.SetCell(i++, placeInput, orientation.z);

    sheet.SetCell(i++, placeInput, graphInfo.cols[0]);
    sheet.SetCell(i++, placeInput, graphInfo.perc[0]);

    if (graphInfo.cols.Count > 1)
    {
      sheet.SetCell(i++, placeInput, graphInfo.cols[1]);
      sheet.SetCell(i++, placeInput, graphInfo.perc[1]);
    }
    else
    {
      sheet.SetCell(i++, placeInput, 0);
      sheet.SetCell(i++, placeInput, 0);
    }

    if (graphInfo.cols.Count > 2)
    {
      sheet.SetCell(i++, placeInput, graphInfo.cols[2]);
      sheet.SetCell(i++, placeInput, graphInfo.perc[2]);
    }
    else
    {
      sheet.SetCell(i++, placeInput, 0);
      sheet.SetCell(i++, placeInput, 0);
```

```
    }

    if (graphInfo.cols.Count > 3)
    {
      sheet.SetCell(i++, placeInput, graphInfo.cols[3]);
      sheet.SetCell(i++, placeInput, graphInfo.perc[3]);
    }
    else
    {
      sheet.SetCell(i++, placeInput, 0);
      sheet.SetCell(i++, placeInput, 0);
    }

    if (graphInfo.cols.Count > 4)
    {
      sheet.SetCell(i++, placeInput, graphInfo.cols[4]);
      sheet.SetCell(i++, placeInput, graphInfo.perc[4]);
    }
    else
    {
      sheet.SetCell(i++, placeInput, 0);
      sheet.SetCell(i++, placeInput, 0);
    }

    if (graphInfo.cols.Count > 5)
    {
      sheet.SetCell(i++, placeInput, graphInfo.cols[5]);
      sheet.SetCell(i++, placeInput, graphInfo.perc[5]);
    }
    else
    {
      sheet.SetCell(i++, placeInput, 0);
      sheet.SetCell(i++, placeInput, 0);
    }
```

```
    sheet.Save(path);
  }
}
```

Listing A.7: Complete Code Listing

Appendix B

Result Screenshots

Figure B.1: Result number 1 of the experiment

Figure B.2: Result number 2 of the experiment

Figure B.3: Result number 3 of the experiment

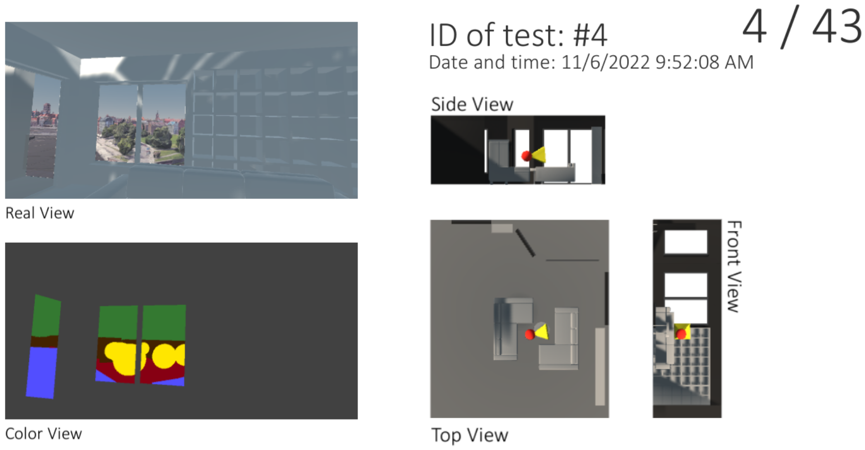

Figure B.4: Result number 4 of the experiment

Figure B.5: Result number 5 of the experiment

Figure B.6: Result number 6 of the experiment

Figure B.7: Result number 7 of the experiment

Figure B.8: Result number 8 of the experiment

Figure B.9: Result number 9 of the experiment

Figure B.10: Result number 10 of the experiment

Figure B.11: Result number 11 of the experiment

Figure B.12: Result number 12 of the experiment

Figure B.13: Result number 13 of the experiment

Figure B.14: Result number 14 of the experiment

Figure B.15: Result number 15 of the experiment

Figure B.16: Result number 16 of the experiment

Figure B.17: Result number 17 of the experiment

Figure B.18: Result number 18 of the experiment

Figure B.19: Result number 19 of the experiment

Figure B.20: Result number 20 of the experiment

Figure B.21: Result number 21 of the experiment

Figure B.22: Result number 22 of the experiment

Figure B.23: Result number 23 of the experiment

Figure B.24: Result number 24 of the experiment

Figure B.25: Result number 25 of the experiment

Figure B.26: Result number 26 of the experiment

Figure B.27: Result number 27 of the experiment

Figure B.28: Result number 28 of the experiment

Figure B.29: Result number 29 of the experiment

Figure B.30: Result number 30 of the experiment

Figure B.31: Result number 31 of the experiment

Figure B.32: Result number 32 of the experiment

Figure B.33: Result number 33 of the experiment

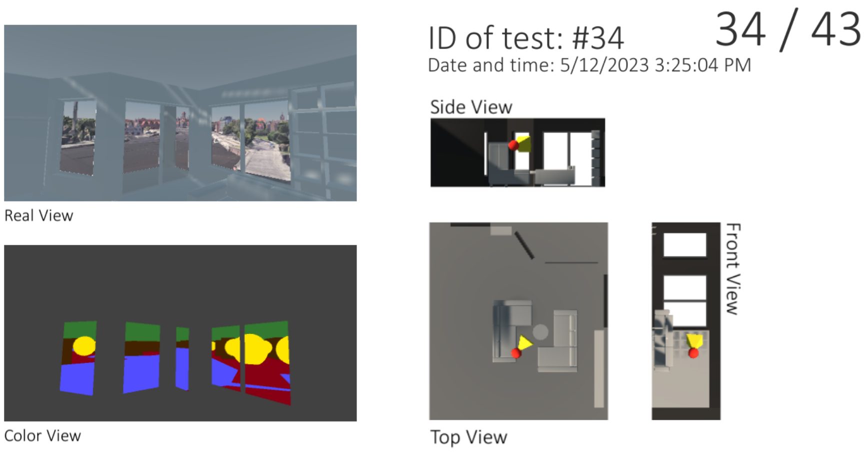

Figure B.34: Result number 34 of the experiment

Figure B.35: Result number 35 of the experiment

Figure B.36: Result number 36 of the experiment

Figure B.37: Result number 37 of the experiment

Figure B.38: Result number 38 of the experiment

Figure B.39: Result number 39 of the experiment

Figure B.40: Result number 40 of the experiment

Figure B.41: Result number 41 of the experiment

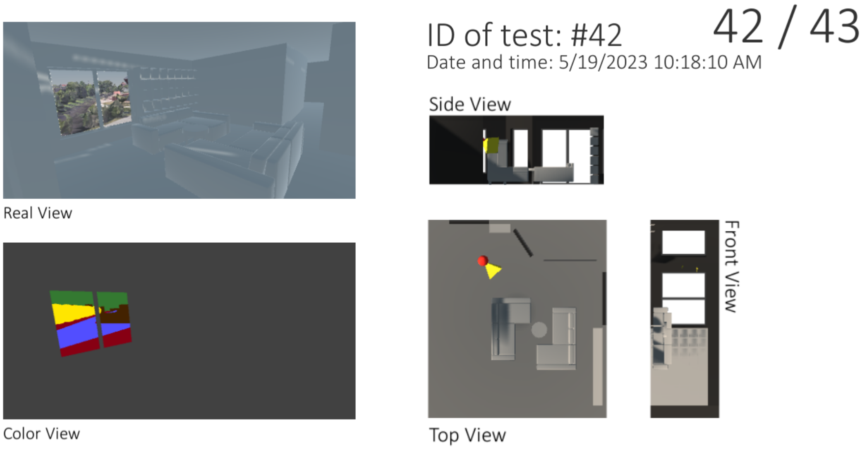

Figure B.42: Result number 42 of the experiment

Figure B.43: Result number 43 of the experiment