Multisensory Immersion in Architectural Virtual Reality: Effects of Visual and Auditory Cues

by
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Author's Declaration

I hereby declare that I am the sole author of this thesis.
This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

The evolution of architectural representation has progressed from traditional analog methods such as hand-drawing to contemporary digital technologies like Virtual Reality (VR) which emerges as the latest architectural representation in spatial visualization and client communication. However, current implementations of architectural VR heavily focus on visual presentation, potentially underutilizing the capacity for comprehensive multisensory experiences that could significantly enhance users to have comprehensive understanding and more engagement within proposed space.

This paper investigates the role of spatial auditory effects in enhancing architectural VR experiences and examines how multisensory (particularly visual and auditory cues) design approaches can improve user engagement and spatial communication effectively. Through a comprehensive three-part methodology, this research addresses critical gaps in current architectural VR representations which visual-only approaches represent partial utilization of the contemporary potential of technology.

In PART 1, through trend extrapolation from historical evolution, 'what's the next?' was predicted that architects should utilize architectural VR representation to prepare for emerging technological paradigms. The analysis of various contemporary precedents in the architectural field shows that current architectural VR implementations primarily focus on providing better visualization and virtual experiences to clients and stakeholders, while insufficient attention is on multisensory architectural VR applications.

PART 2 introduces the cognitive foundation for sound integration in architectural representation and explains the necessity of applying spatial audio to architectural VR presentations for enhanced communication. This part outlines specific acoustic properties such as attenuation, overlapping, and diffraction and shows their potential applications in architectural design visualization. This foundation demonstrates how these properties can enhance the awareness of relationships in spatial hierarchy, active zones, and connectivity.

PART 3 presents experimental validation through repeated measures with 38 participants experiencing three conditions: PC-based non-VR, visual-only VR, and both visual and auditory VR. The results demonstrate progressive increases in participants' voluntary engagement, with multisensory VR achieving 198.1% improvement in play time compared to traditional PC-based presentation.

These findings provide architects experiment results based on numerical evidence and encourage them utilizing multisensory integration as fundamental to effective VR representations rather than optional enhancement. This research contributes to architectural practice by providing measurable advantages of comprehensive sensory experience in VR-based communication and spatial understanding.

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Introduction

The architectural field has been in a continuous evolution in representation methods throughout human history, from hand-drawings and physical models to sophisticated digital visualization technologies. Each technological advancement has tried to bridge the communication gap between architectural design intent and stakeholders' understanding. These attempts have been to resolve the fundamental challenge of delivering three-dimensional spatial experiences through various media. Today, Virtual Reality (VR) technology is one of the biggest breakthroughs in this effort, giving architects improved ways to create realistic visual experiences and communicate with clients about what it's like to be in the spaces they design.

Contemporary architectural firms have increasingly adopted VR technology for effective representations across diverse project types and scales and testified to significant advantages in client engagement, design evaluation, and communication with stakeholders.[1] The VR technology has allowed them over time to have a better sense of space through full-scale spatial experience and an increased level of realism with immersive environmental settings such as realistic material and texture. This emerging technology has transformed traditional architect-client relationships from delivering explanations on 2D media to sharing experiential understanding in 3D/4D media. Contemporary implementations by architectural firms such as Diamond Schmitt Architects, Mortenson, Gensler, and HOK have showcased VR's effectiveness in communicating complex spatial relationships, resolving design challenges, and enhancing informed decision-making processes that would be difficult to achieve through traditional representation methods.[2 3 4 5]

1 *Nikitha Sunil, "How AR and VR Are Transforming Client Experience in Architecture"*
2 *Rachel Chan, "Sharing a Vision with Andrew Chung of Diamond Schmitt Architects"*
3 *Unity Technologies, "Mortenson: A Unity for AEC Case Study: Better Hospital Designs, Lower Costs with VR"*
4 *Gensler, "Design Forecast 2017 — Making Design More Responsive"*
5 *Unreal Engine, "AR and VR at Foster + Partners"*

Figure 0.1 *Diagram of architectural representation advancement*



However, despite these successful applications, current architectural VR implementations show a limitation, which is that they mostly focus on visual presentations only while underutilizing the technology for multisensory experiences. This visual-centric approach represents only the partial potential of VR applications while these have significant advantages in many contexts. The predominant emphasis on visual presentation overlooks the important role that spatialized sound can play in creating more compelling, informative, and memorable architectural experiences, leading proposed projects to be more successfully brought to life.

Studies in cognitive psychology demonstrate that human spatial perception relies significantly on multisensory integration, with auditory stimuli providing crucial environmental cues that complement and enhance visual perception.[6] Spatial audio contributes to users processing comprehensive spatial information about environmental properties, object locations, and spatial relationships.[7] This process is achieved through mechanisms such as sound attenuation, overlapping, and diffraction, which enable users to better understand space boundaries and spatial hierarchies in a way that visual cues alone cannot provide.[8] This means the application of these acoustic properties to visual VR can significantly improve users' spatial memory, navigation accuracy, and overall environmental comprehension.

These theoretical foundations in cognitive context about multisensory perception support practical implications for design communication and client engagement. Studies indicate that the alignment of auditory and visual cues enhances spatial understanding through complementary processing of both types of information, and this process results in an enriched sense of presence, improved spatial memory, and a more accurate sense of space compared to presentations with a single modality.[9] Furthermore, multisensory VR environments have increased exploration behavior and enhanced subjective presence compared to visual-only VR environments, and this foundation supports the hypothesis that architectural VR has significant benefits from integrated multisensory design approaches.[10]

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6 *Daniel Paromov et al, "Body Representation Drives Auditory Spatial Perception"*
7 *Olli Santala, "Perception and Auditory Modeling of Spatially Complex Sound Scenarios"*
8 *Hans Joachim Maempel and Matthias Jentsch, "Auditory and Visual Contribution to Egocentric Distance and Room Size Perception"*
9 *Charles Spence, "Senses of Place: Architectural Design for the Multisensory Mind"*
10 *Takara E et al, "Evaluating the Effect of Multi-Sensory Stimulation on Startle Response Using the Virtual Reality Locomotion Interface"*

This paper addresses the necessity of reducing the gap between current architectural VR applications and the full potential of multisensory VR representations, in addition to investigating how auditory cues enhance architectural VR environments and examining the specific mechanisms of auditory properties that improve user engagement and spatial understanding. By illustrating both theoretical foundations and observed evidence from the experiment, this research encourages architects to be prepared for professionally utilizing multisensory VR representations in the upcoming future.

Methodology

This study implements a comprehensive three-part methodology to demonstrate both theoretical foundations and experimental validation for multisensory VR in architectural practice. The research approach combines theoretical examination such as historical analysis and cognitive research with experimental validation with repeated measures.

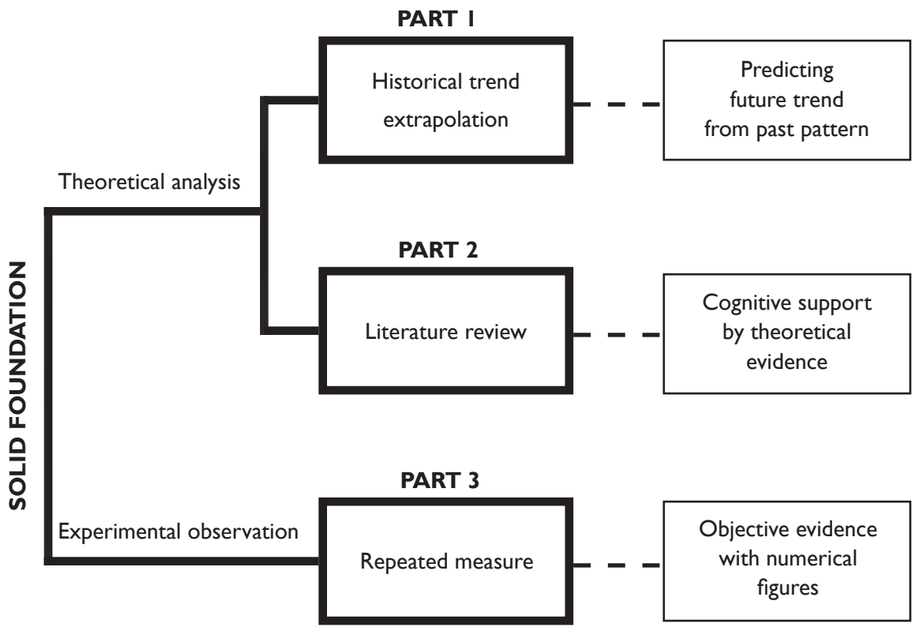


Figure 0.2 *Structure of methodology*

PART 1: Historical context and trend analysis

The first methodology in PART 1 employs historical trend extrapolation to forecast future trends in architectural representation technologies. This section illustrates the historical progression from analog foundations, through the digital revolution, to contemporary VR implementation by analyzing patterns of technological evolution in both architectural communication methods and VR advancements. The progression of architectural representations shows three distinct stages: analog foundations such as hand-drawings and physical models, the digital revolution with Computer-Aided Design (CAD) systems and 3D modeling software, and the virtual era with Virtual Reality (VR) technologies enabling immersive spatial experience.

This analysis of historical patterns allows architects to predict that the next emerging pattern will be Virtual Reality (VR), therefore, it emphasizes the need for architects to prepare for emerging paradigms. Furthermore, the research methodology includes comprehensive precedent analysis of contemporary architectural VR implementations by leading firms such as Diamond Schmitt Architects, Mortenson, Gensler, and HOK. This approach identified the implications and limitations in current architectural VR practice.

PART 2: Cognitive context and theoretical framework

The second methodology is analyzing theoretical background, such as cognitive psychology and spatial perception. PART 1 discovered that the primary application of contemporary architectural VR is to effectively deliver the intent of the proposed design to clients and stakeholders. However, the focus on visual representation led to the underutilizing of multisensory design, which enables users to have a more comprehensive understanding of the environment. Therefore, a literature review of human perception within spatialized sound demonstrated the necessity of incorporating auditory cues into architectural VR presentations. Furthermore, the study describes how multisensory VR presentations with auditory effects impact effective design delivery, thereby emphasizing once again the importance of auditory cues within the VR environments.

This theoretical analysis provides scientific support for implementing acoustic properties in architectural VR, outlining specific potentials for enhanced sense of scale, space, and immersion in the environment.

PART 3: Experimental Validation

PART 3 applies a repeated measure to the experiment to validate theoretical hypotheses regarding the effectiveness of multisensory VR. This experiment involves 38 participants who experience three distinct conditions: Condition 1 (PC-based exploration representing traditional representation as baseline of the experiment), Condition 2 (visual-only VR providing immersive visual experience without spatialized sound), and lastly Condition 3 (multisensory VR implementing auditory effects with visual presentation).

The experimental design focuses on behavioral measurement of users' engagement by observing voluntary play time and this data indicates users' spatial interest and environmental immersion level. This methodology includes realistic acoustic properties such as attenuation, overlapping, and diffraction effects that enhance spatial perception.

The data collection methodology applied both quantitative behavioral measurements and a qualitative user response survey, which provide a comprehensive evaluation of the multisensory VR impact on spatial understanding and engagement.

To summarize, this comprehensive methodological approach enables examination of multisensory VR representations from historical, theoretical, and experimental perspectives. Therefore, this evidence-based approach provides a more solid foundation for recommendations regarding architectural VR implementation.

PART I

HISTORICAL CONTEXT

Chapter 1

The Evolution of Architectural Representation and Communication: From Analog to Virtual Reality

This chapter examines the historical trajectory of architectural representation and communication methods, tracing the transformation from traditional analog methods to contemporary virtual reality applications.

From this perspective, the future of architectural representation and communication is expected to be gradually developed, and presenting immersive virtual experiences to stakeholders and clients is predicted to be increasingly essential. At the end of this chapter, the limitations of current architectural VR content are discussed, suggesting architects apply multisensory stimuli in VR representation.

1-1. The evolution of architectural representation methods

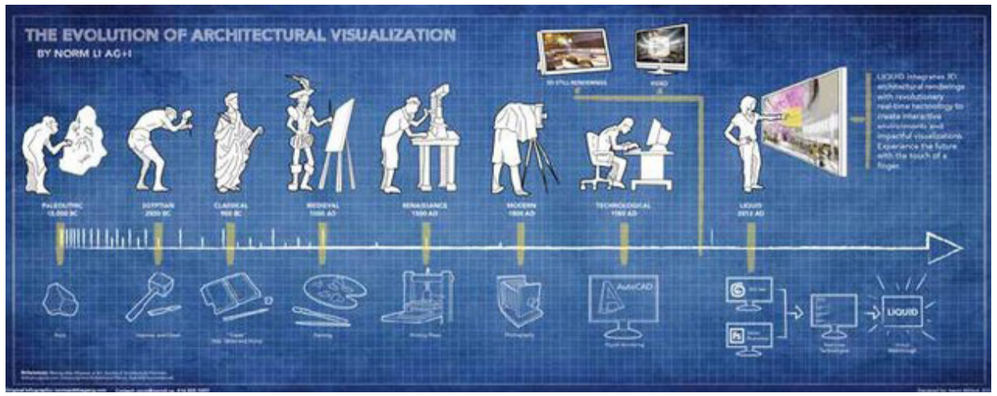


Figure 1.1 *Illustration showing evolution of architectural visualization*

The way that architects conceptualize, develop, and deliver their design has gone through three major phases: analog methods such as hand-drawings and physical models, digital technologies such as computational design and visualization, and virtual reality (VR) applications providing immersive spatial experiences.

Interpreting this development trend reveals a consistent movement toward improved accuracy, interactivity, and immersion in design presentations and client communications.

First stage: Analog foundations

Traditional analog techniques such as hand drawings and physical models are the base of architectural visualization even today. With hand drawings, architects translated 3D spatial concepts into 2D visual outputs, as these drawings help architects develop spatial imagination and serve as basic tools for conveying architectural ideas.[11] With physical models that complemented hand-drawing methods, architects provided more detailed and scaled representations so that both collaborators and clients better understood their design. However, these analog methods are limited because they can hardly be observed at eye level and require significant time for production and modification.[12]

11 Nurcan Yıldızoglu, "Sketching Versus Digital Design Tools in Architectural Design"
12 Architecture Lab, "Physical Scale Model: Visualization, Uses, Challenges, Prices, and More"



Figure 1.2 *Massachusetts Institute of Technology (MIT) Tange Design Studio (Boston, USA)*

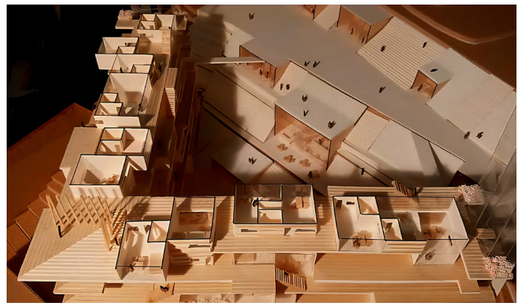


Figure 1.3 *Physical model of residential project*

Second stage: Digital revolution

The introduction of Computer-Aided Design (CAD) systems such as AutoCAD dramatically transformed how architects create and modify drawings with efficiency and precision.[13] The transition from manual drafting to CAD drawings provides capabilities of precise geometric control and efficient alteration since CAD allows the users to create drawings based on exact numeric figures.[14] Despite these advantages, these digital applications still have limitations because they are presented on a 2D medium, like a flat screen, which cannot provide an immersive sense of space.

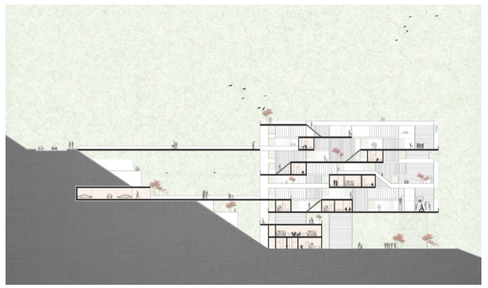


Figure 1.4 *Computational drawing of section*



Figure 1.5 *3D modeling in SketchUp*

13 Mike Wayne, "BIM vs. CAD: A Complete Guide for Modern Architects Comparison"
14 Flatworld Solutions, "Discovering the Edge – Why CAD Drafting Outperforms Manual Drafting Every Time"

Third stage: Virtual Reality and immersive experience

Virtual Reality (VR) technology has evolved in architectural visualization practices, altering the way architects design, collaborate, and communicate on architectural projects.[15] VR development helps overcome the limitation of traditional visualization methods such as 2D drawings, physical mock-up modeling, and 3D renderings. Particularly, current 3D rendering technology still has limitations in that it only shows a part of the space in the screen frame from a specific view with limited scale information despite providing relatively immersive content with photorealistic features. However, VR applications give users freedom for a walkthrough of the space at a 1:1 scale, providing a better sense of space, depth, and proportions that is superior to what can be perceived in traditional visualization methods.[16] Room-scale VR creates incredibly immersive experiences by allowing freedom of movement, which helps users navigate through virtual space and feel as if they are physically present in it.[17]



Figure 1.6 *Screenshot during experiencing VR environment, the sense of height observed at eye-level*

15 *E. V. Vishnevskaya and N. B. Strekalova, "Synthesis of virtual reality technologies and design"*
16 *Outer Realm VR, "Virtual Reality Architectural Visualization: A Game-Changer for Property Design"*
17 *Cuub Studio, "The Significance of Virtual Reality in Architecture: An Immersive Evolution"*

To sum up, architectural representation methods have evolved from analog hand drawings and physical models to digital CAD systems and finally to immersive Virtual Reality today. Each stage shows a trend of overcoming the limitations of the previous methods while advancing accuracy and efficiency in design communication. This technological transformation shows that architectural practice has shifted from static 2D representations that required interpretation to dynamic 1:1 scale immersive experiences that provide direct and comprehensive understanding. Through this historical evolution, architectural representation has consistently moved forward in the way of enhancing accuracy, improving efficiency, and not only delivering the design but also providing immersive virtual experiences that bridge the gap between conceptual design and built reality.

1-2. The evolution of architectural communication medium

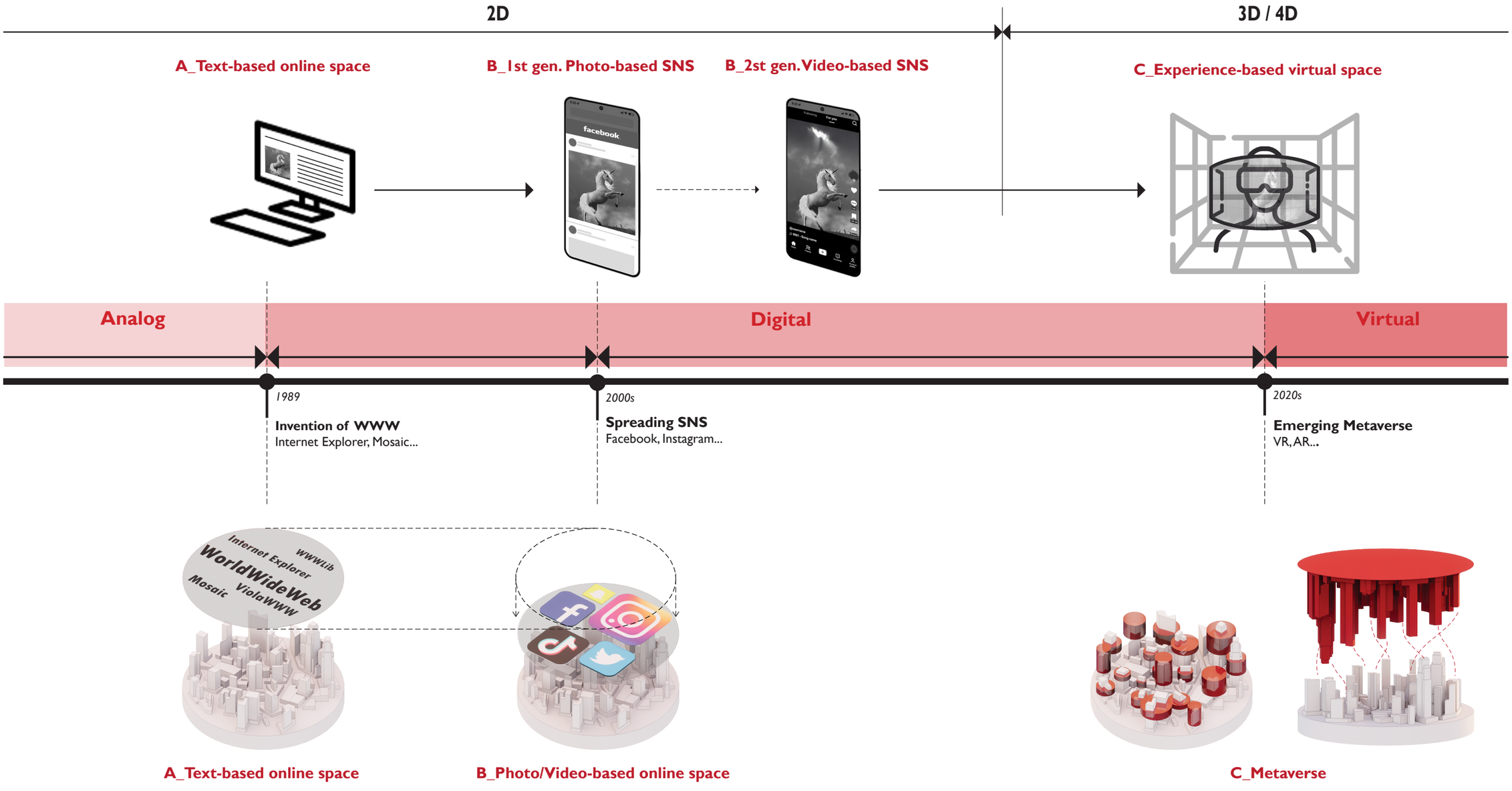


Figure 1.7 *Historical timeline for communication medium*

Communication mediums for humans have evolved from analog means in a physical space to digital realms such as the World Wide Web (WWW) in 1989[18] and Social Networking System (SNS) in the 2000s.[19] Furthermore, it has been expanded to immersive virtual worlds such as the metaverse in the 2020s,[20] leading to significant shifts in how human beings communicate and share information across time and space.

In the same context, architectural communication mediums have also evolved from text-based WWW and photo/video-based SNS into virtual space. This process ultimately resulted in immersive virtual realities, which question the traditional sense of space and the idea of presence.

First stage: Analog communication in the architecture

Traditional architectural communication relied on analog methods that required physical presence and direct interaction between architects, clients, and stakeholders. During this era, architects delivered their architectural ideas through hand-drawn sketches, technical drawings, and physical models that demanded face-to-face meetings and on-site presentations.[21] This communication process was limited by time and space, since the communication for design delivery required all parties to gather in the same physical location to check the drawings and models all together.

This analog communication medium in the architecture was characterized by physical engagement with the materials existing in physical space, where the clients and stakeholders could touch and see the materials in person to better understand spatial relationships.[22] However, this approach had significant limitations in terms of modifiability and accessibility, since design modifications demanded time-consuming manual updates to drawings and remanufacture of physical models. These communication methods show the limitations of both temporal efficiency workability.

18 *Qasem A. Al-Radaideh and Ehab Al-Hajri, "Development History of the World Wide Web"*
19 *Erwin Rimban, "Academic Social Networking Sites: Evolution, Usage Patterns, and Scholarly Implications"*
20 *Sivarethinamohan R, "The Evolution of Virtual Reality: A Historical Perspective"*
21 *Nurcan Yıldızoglu, "Sketching Versus Digital Design Tools in Architectural Design"*
22 *Architecture Lab, "Physical Scale Model: Visualization, Uses, Challenges, Prices, and More"*



Figure 1.8 *Architect Marcel Breuer meeting with Benedictine Sisters of Mary College during the early design process of their campus and monastery*



Figure 1.9 *Visitors looking at a physical model of Guggenheim Museum in Exhibition Frank Lloyd Wright, 60 years of living architecture*

Second stage: Digital communication revolution

The first release of the World Wide Web (WWW) by Tim Berners-Lee in 1989 was a milestone event in the evolution of the digital communication space and fundamentally transformed human communication patterns, establishing the foundation for digital architectural communication.[23] This technological advancement enabled architects to share their design concepts without the limitations of space and time by using digital and electronic communication, such as transferring digital files and communicating on emails. This transition from analog to digital communication in architecture was further accelerated by the development of Computer-Aided Design (CAD) systems, which allowed architects to create, modify, and deliver technical drawings electronically with time efficiency and precision.[24]

The digital revolution in architectural communication expanded significantly with the rapid spread of Social Networking Systems (SNS) in the 2000s,[25] which provided new platforms for design presentation and client engagement. Architects started utilizing digital media to showcase their work through online portfolios, project galleries, and SNS platforms, and this approach enabled them to reach broader audiences and collaborators. Particularly, architects shared their design outputs through photo-based SNS, which is the first generation including early Facebook and Instagram, and distributed their technique and design promotion through video-based SNS, which is the second generation including YouTube and TikTok. This evolution illustrates a crucial shift from location-dependent communication to distributed collaboration methods that enhanced project accessibility and stakeholder participation beyond the limitation of time and space.

23 *Qasem A. Al-Radaideh and Ehab Al-Hajri, "Development History of the World Wide Web"*
24 *Mike Wayne, "BIM vs. CAD: A Complete Guide for Modern Architects Comparison"*
25 *Erwin Rimban, "Academic Social Networking Sites: Evolution, Usage Patterns, and Scholarly Implications"*



Figure 1.10 *Screenshot of BIM360 of AutoCAD "What's New in AutoCAD 2017? Share Design View,"*

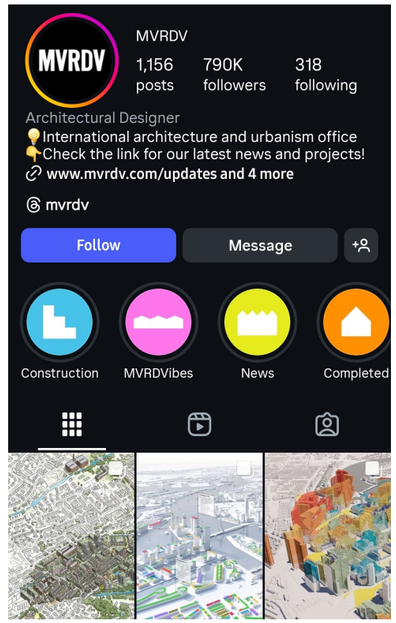


Figure 1.11 *Screenshot of MVRDV's Instagram profile, showcasing their works on SNS*

Third stage: From digital to virtual and immersive space

The contemporary evolution of architectural communication has progressed into immersive virtual environments, challenging traditional concepts of spatial experience in design delivery and collaboration. In this trend of progression, Virtual Reality (VR) technology has emerged as a revolutionary communication medium that enables architects to share immersive experiences in virtual environments where clients and stakeholders can perceive the spatial sense of their proposed space at full scale, regardless of the physical location.[21] This technological advancement represents a paradigm transition from representational communication to experiential communication, which enables architects to convey their design intent through direct spatial immersion rather than interpretive visualization.

This evolution toward immersive communications in virtual environments represents a significant transformation in the way architectural designs are shared, evaluated, and revised for architects and stakeholders, establishing new paradigms for client engagement and design validation in virtual environments.[22]



Figure 1.12 *An image of architect presenting design using VR in virtual environment*

26 *E. V. Vishnevskaya and N. B. Strekalova, "Synthesis of virtual reality technologies and design"*
27 *Wenhao Shen et al, "Toward immersive communications in 6G"*

To sum up, the evolution of architectural communication mediums shows a clear trend from analog and location-dependent methods through digital and electronical platforms to contemporary immersive virtual environments. This transformation enabled architects to overcome the challenges in architectural practice related to spatial understanding and client engagement on the way toward better accessibility and efficiency, reflecting technological advancements in human communication. Each stage has progressively lowered barriers of communication and enhanced the efficiency and accessibility of architectural design representations. This historical trend of the evolution implies that architectural communication mediums will be developed in the way of further emphasizing immersive and experiential methods that bridge the gap between conceptual design and the built environment.

1-3. The evolution of virtual reality (VR)

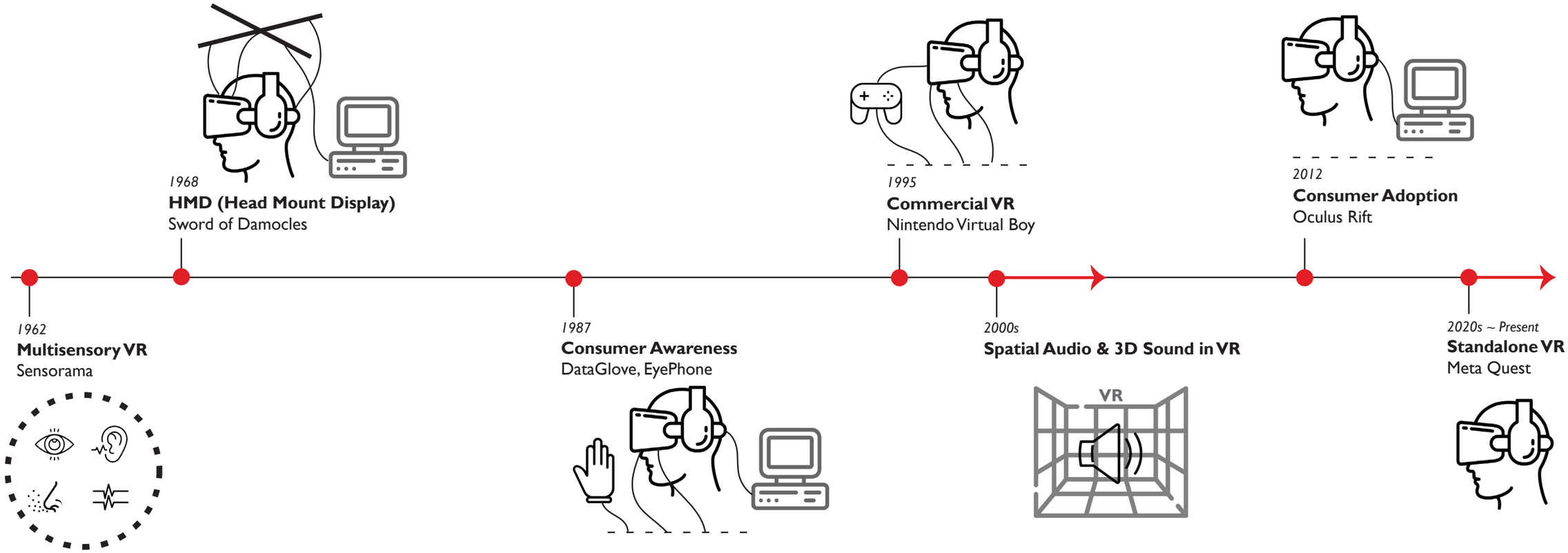


Figure 1.13 *Historical timeline for evolution of VR*

Virtual reality technology has progressively advanced from the early conceptual experiments in the 1960's to the consumer adoption of contemporary immersive systems, and this historical trajectory illustrates a significant transformation in the way humans interact with digital and virtual environments. This technological progression has had several key milestones regarding hardware developments, software innovations, and multisensory implementations, establishing VR as a practical platform for architectural visualization and spatial communication. This evolutionary history provides a comprehensive context to understand contemporary VR applications in architectural practice and illustrates the technological foundations of today's VR advancement, which enable immersive experiences in architectural design.

Milestone 1: The Sensorama experience (1962)

The first experimental attempt to create an immersive sensory experience was Morton Heilig's Sensorama, which was developed in 1962, and this milestone represented the foundation of modern virtual reality.[28] This early VR device combined stereoscopic 3D visuals, stereo sound, vibrations, and even scents to create a comprehensive multisensory environment that Heilig termed "cinema of the future."[29] The experimental attempt by Sensorama to implement multiple sensory modalities in virtual environments established the early concept that a better virtual experience requires more than just visual stimulation alone. This early recognition of applying multisensory cues to VR becomes a conceptual foundation of contemporary approaches to VR design presentations that combine immersive visual stimuli with spatialized auditory stimuli to enhance spatial understanding and client engagement.

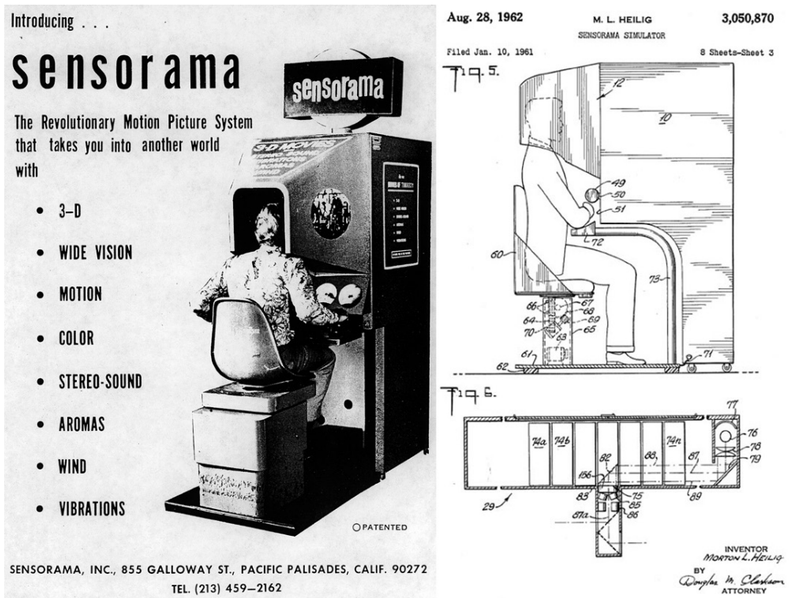


Figure 1.14 *Sensorama poster with description of sensory details*

28 *Sivarethinamohan R, "The Evolution of Virtual Reality: A Historical Perspective"*
29 *Immersive Archive. "The Sensorama"*

Milestone 2: The first head-mounted display (1968)

The first head-mounted display (HMD), known as the "Sword of Damocles," was developed by Ivan Sutherland and Bob Sproull in 1968.[30] This advancement established the core technological paradigm of current VR: head-tracking sensors that monitor users' movement and update visual displays accordingly to maintain the illusion of presence within virtual environments.[31] This HMD concept directly enabled architectural VR applications by allowing users to look around virtual environments with an enhanced sense of presence. This core concept serves as a foundation for current VR applications in the architectural field, enhancing virtual experiences for architectural design reviews and client presentations.

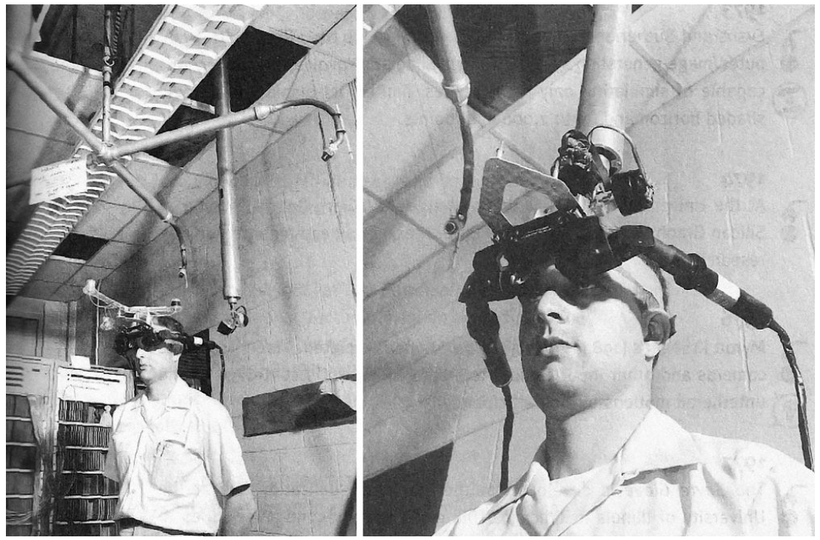


Figure 1.15 *Picture of user playing the Sword of Damocles, HMD is fixed to a huge structure*

30 *Sivarethinamohan R, "The Evolution of Virtual Reality: A Historical Perspective"*
31 *Virtual Reality Society. "History of Virtual Reality"*

Milestone 3: Virtual Reality terminology and consumer awareness (1987)

Jaron Lanier initially introduced the term "Virtual Reality" in 1987 while establishing VPL Research, the first company focused on developing and selling VR products including the DataGlove and EyePhone systems.[32] It was a transitioning period for the VR field from experimental research to commercial development, establishing the conceptual framework and vocabulary that help define the field today. Lanier's work introduced the key concepts such as presence and immersion, which became the main concepts for understanding VR's potential in architectural applications, where the sense of being physically present within the proposed space enables users to have a more intuitive design evaluation than the traditional visualization methods.

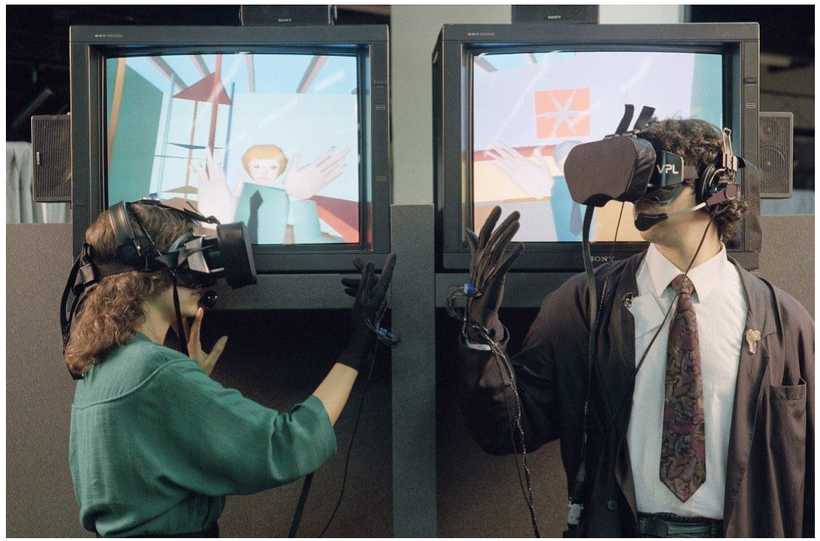


Figure 1.16 *Picture of user playing VPL's EyePhone with DataGlove*

32 *E.V. Vishnevskaya, "Synthesis of virtual reality technologies and design"*

Milestone 4: Application in gaming industry and consumer accessibility (1995)

Virtual Boy by Nintendo, released in 1995, represented the first attempt to widely commercialize VR technology to the public, despite its commercial failure.[33] The failure resulted from the monochromatic display with limited visual effects,[34] poor ergonomics, a small amount of content,[35] and hardware constraints that required users to lean forward while playing. This attempt identified both the potentials and limitations of early VR hardware and highlighted challenges in VR display technology, user convenience, and content development that would be the foundation of the subsequent innovations. From the perspective of architectural practice, this period emphasized the importance of user experience design in VR applications and revealed the limitation that technical capability alone is not enough to provide usability and meaningful content.



Figure 1.17 *Picture of Virtual Boy headset and controller with the content, which remains in low-resolution raster graphics*

33 *Matt Zachara and José P. Zagal. "Challenges for Success in Stereo Gaming: A Virtual Boy Case Study"*
34 *Steven Boyer, "A Virtual Failure: Evaluating the Success of Nintendo's Virtual Boy"*
35 *Matt Zachara and José P. Zagal. "Challenges for Success in Stereo Gaming: A Virtual Boy Case Study"*

Milestone 5: Spatial audio and 3D sound in VR (2000s)

The 2000s were a period of discovering significant advances in spatial audio technology for VR applications, including developments in 3D audio systems that could enhance more realistic sound effects within virtual spaces.[36] These auditory technologies introduced the potential for VR applications to provide directional sound cues, which enhance spatial understanding and realism in virtual environments. In an architectural context, the introduction of spatial audio in VR provides the possibility to implement acoustic stimuli within architectural VR environments, helping clients understand not only how the proposed spaces will look but also how they will sound.

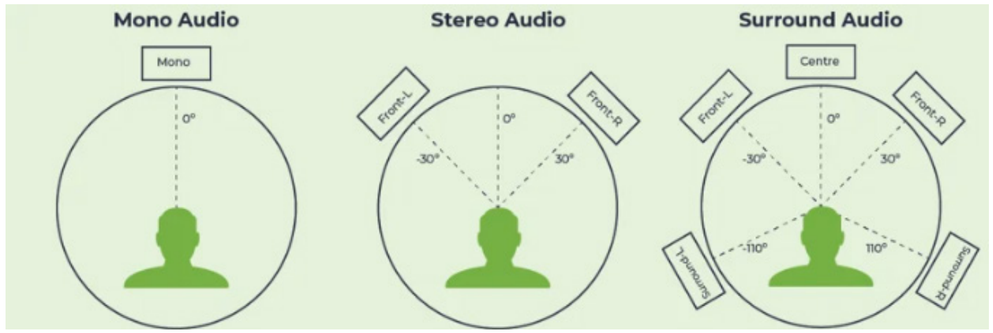


Figure 1.18 *Diagram of spatial 3D sound*

36 *Durand R. Begault, "3-D Sound for Virtual Reality and Multimedia"*

Milestone 6: Consumer adoption of modern VR (2012 - 2017)

The first attempt of VR's consumer adoption was the launch of the Oculus Rift development kit in 2012, and this breakthrough was followed by consumer releases of Oculus, HTC, and Sony between 2016-2017.[37] The successful launch of the Oculus Rift raised $2.4 million and attracted Meta, which bought the Oculus VR company for $2 billion in 2014.[38] This period was the beginning of modern VR's mainstream adoption, with improved display resolution, reduced latency, precise head tracking, and affordable pricing. These improved functions enabled the creation of viable platforms for professional applications and gave more accessibility to the public. This period established the potential of VR as a practical tool for architectural visualization, with software developers creating specialized applications for design review, client presentation, and collaborative design processes that boost VR's unique capabilities for spatial communication.



Figure 1.19 *Prototype of the first generation Oculus Rift with duct tape construction and large lenses*

37 *Mersus Technologies, "The Evolution of Virtual Reality: Past, Present, and Future"*
38 *Matthew Mongeon, "The Applications and History of Virtual Reality & VR Headsets"*

Milestone 7: Standalone VR systems and wireless freedom (2018 - present)

From the introduction of standalone VR headsets, beginning with the Oculus Go in 2018 and evolving through later models like the Meta Quest series, VR devices wasn't required to be connected to external computers and tracking systems.[39] These wireless and self-contained devices significantly expanded VR accessibility for architectural firms by reducing technical complexity and setup requirements.[40] Contemporary standalone systems enable architects to easily transport VR experiences to client meetings, construction sites, and design presentations, with increased portability due to standalone and wireless features. This advancement provides architects the potential that an immersive architectural visualization could be a practical component of standard design practices rather than a specialized technical demonstration.



Figure 1.20 *Meta Quest 3, which is wireless and standalone, was released in 2023*

39 *Samar Helou, et al. "Virtual Reality for Healthcare: A Scoping Review of Commercially Available Applications for Head-Mounted Displays"*

40 *Erdem Yıldırım, "Exploring Architectural Tools for Oculus Quest 2"*

To summarize, the evolution of VR technology demonstrates a consistent progression toward better accessibility, improved sensory integration, and enhanced user experience that are beneficial for architectural VR applications. Each milestone has contributed to significant potentials that enable contemporary architects to create more compelling and immersive VR experiences. From this perspective, these advancements have transformed how architectural designs are communicated, evaluated, and understood by clients and stakeholders. This technological foundation is ongoing to evolve in display resolution, spatial tracking, and multisensory integration and expected to be even more sophisticated as tools for architectural communication and presentation.

Chapter 2

The Potential of VR in Architecture

Virtual Reality (VR) applications in architecture help architects show clients and stakeholders a clearer view of space with life-sized visuals, make it easier for them to understand the environment by creating an immersive experience, and improve communication by closing the knowledge gap between experts and non-experts.

This chapter highlights four of the advantages with architectural precedents and identifies the implications and limitations of contemporary architectural VR.

2-1. Enhanced scale and spatial perception

VR applications in the architecture enable users to experience architectural spaces from an eye-level perspective using full-scale visualization.[41] The technology allows users to have realistic perspectives and scaling that contribute to a more accurate comprehension of space. Research states that VR enables superior spatial awareness compared to traditional 2D methods and shows that VR significantly improves perception of complex spatial layout.[42] Furthermore, the visualization on a human scale paired with natural body movements of users enables them to interact with virtual environments that closely mirror the spatial experiences in the real world.[43] This enhanced spatial perception is particularly beneficial for noticing design details such as material and texture and for perceiving a sense of scale, which are difficult to convey through conventional drawing methods.[44]

Precedent: Ingenium's Collection and Conservation Centre in Ottawa by Diamond Schmitt Architects, 2019

Diamond Schmitt Architects demonstrated the critical importance of enhanced scale and spatial perception in their VR project for Ingenium's Collection and Conservation Centre in Ottawa. They faced a unique challenge of accommodating Canada's vast science and technology museum collection from three separate warehouses into a single building. The firm discovered that traditional 2D drawings and blueprints failed to communicate the true scale of the massive artifacts which ranged from early agricultural hand tools to full-sized locomotives and spacecraft. This challenge required VR modeling to design with a better understanding of scale. Through VR visualization, Andrew Chung and his team were able to create a comprehensive design, apply the proper scale to the massive artifacts and solve the communication challenge of designing for artifacts of extraordinary scale and diversity.[45]

41 Emerson G, "Architecture, Virtual Reality, and User Experience"
42 Michael K, "Improved Perception of AEC Construction Details via Immersive Teaching in Virtual Reality"
43 Emerson G, "Architecture, Virtual Reality, and User Experience"
44 Michael K, "Improved Perception of AEC Construction Details via Immersive Teaching in Virtual Reality"
45 Rachel Chan, "Sharing a Vision with Andrew Chung of Diamond Schmitt Architects"



Figure 2.1 *Image of VR project for Ingenium's Collection and Conservation Centre*



Figure 2.2 *DSAI created VR space to facilitate diverse scale of artifacts in the project*

2-2. Realistic sense of presence and immersion

The most distinct point of VR experiences is the sense of presence and immersion when users are fully enveloped within virtual environments and without being disturbed by scenes outside the virtual environment. Multiple factors, such as visual fidelity, interaction capabilities, and environmental immersion, influence presence in VR. Research indicates that a careful balance of technological and perceptual factors is required for achieving high presence.[46] Immersion in VR enables users to feel more engaged in the virtual environments and architects to develop their designs in better details. The degree of how much users feel immersed significantly enhances comprehensive understanding of design.[47] Research demonstrates that immersive VR experiences generate elevated levels of presence, which correlate with enhanced positive perceptions and improved comprehension of design concepts.[48] The immersive nature of VR allows for experiences that traditional representation methods such as floor plans and 3D renderings on a flat screen cannot provide; therefore, architects could deliver their design in a more efficient way.

Precedent: Interventional radiology room of Kaiser Permanente by Mortenson, 2017

Mortenson collaborated with virtual mock-ups for Kaiser Permanente's interventional radiology room, and this precedent proves how realistic presence and immersion enable stakeholders to experience better environmental engagement. The surgical teams could physically reach out to light booms, tables, and medical equipment in the virtual space as if they were in the actual room. This VR approach creates convincing immersion so that surgical teams could fully understand and evaluate how procedure rooms would function for their workflows before construction. This process eliminates the need for post-construction remodeling that costs much and typically occurs when the stakeholders cannot properly engage with traditional 2D plans. Through faithful VR representation of all specified equipment and realistic spatial interactions, this project achieves the high level of presence necessary for medical professionals to make better decisions about room dimensions and workflow efficiency. This proves VR representation delivers comprehensive spatial understanding with enhanced presence and immersion.[49]



Figure 2.3 *VR simulation of hospital design*



Figure 2.4 *VR simulation of interventional radiology room in Unity*

46 *R Peinl and T Wirth, "Presence in VR experiences – an empirical cost-benefit-analysis"*
47 *E Boulatova, "Redressing the Ocularcentric Culture of architectural design: A Phenomenological and Participatory Approach in VR"*
48 *E Behm-Morawitz and H Shin, "Using VR for Science Communication: Presence, Message Perception, and Pro-Environmental Effects"*
49 *Unity Technologies, "Mortenson: A Unity for AEC Case Study: Better Hospital Designs, Lower Costs with VR"*

2-3. Benefits for design revision and scale adjustment

VR technology supports architects with testing realistic scaling and perspectives during design development and revising designs with a more accurate sense of scale and dimension. Research indicates that VR has advantages in design evaluations and reviews due to its potential of detailed visualization and immersion.[50] This technology enables architects to identify design issues such as an awkward sense of proportion or scale and to adjust them during virtual examination in VR. This virtual examination of proposed designs is significantly advantageous to reduce design errors;[51] therefore, utilizing VR during the design process allows architects to have a comprehensive assessment of design elements that might be missed in traditional review processes.

Precedent: Waiting Room in Eagle County Regional Airport by Gensler, 2019

Gensler applied VR to the new terminal addition for the waiting area at Eagle County Regional Airport, and this precedent implements how VR enables architects to test and revise structural design by assessing accurate scale. In an interview with Yulio Technologies, Alex Garrison explained how they evaluated different structural ideas including large trusses that extended into the space by assessing the sense of scale in VR. This firm discovered that VR's true-scale visualization allowed them to experiment with design elements such as window sizing for mountain views and spatial proportions under trusses that would have been difficult to assess through traditional methods. Through VR examinations, Gensler could uncover and resolve potential design issues related to the scale of the space and structural element placement before construction. This precedent demonstrates how VR assists architects by providing a comprehensive evaluation of the element in scale and facilitating revisions that reduce potential errors while enhancing the accuracy of architectural decision-making.[52]

50 Waseem Weshahi, "Virtual Reality Empowered Proecedural Modeling"
51 D. H. Tran et al,
"Metaverse Immersive Virtual Reality Enhances Multiple Collaboration in the Construction Design Review Phase"
52 Robert Kendal, "Interview with Alex Garrison (architect, Gensler)"

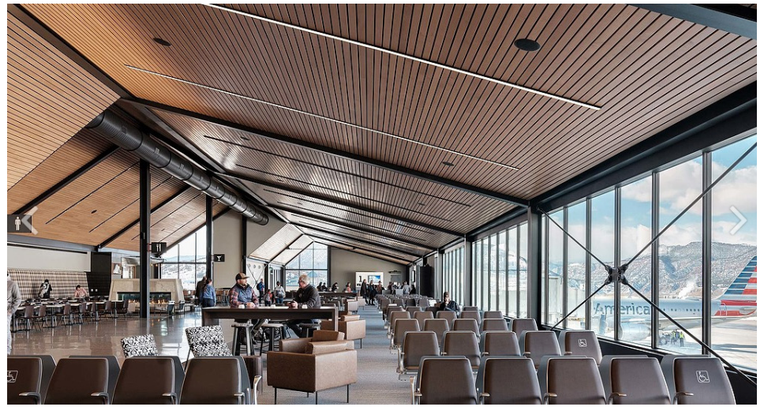


Figure 2.5 *Waiting room in Eagle County Airport. Gensler revised large trusses design through VR*

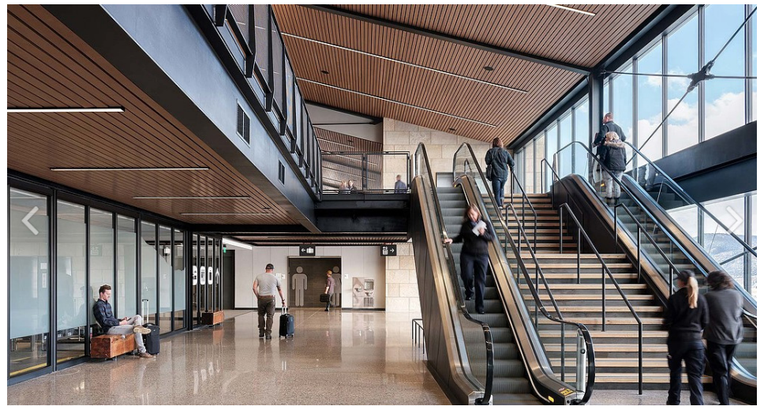


Figure 2.6 *Lobby in Eagle County Airport. Gensler revised large trusses design through VR*

2-4. Improved client communication and persuasion

Presenting VR environments of proposed designs to clients is currently the primary way that the architecture industry utilizes VR. One of the most significant advantages of VR in architecture is that it bridges the knowledge gap between architectural professionals and clients who might have less knowledge in architecture. Research demonstrates that perception variations in proposed spaces are significantly linked to the knowledge gaps between professionals and non-experts.[53] For example, the up and down markings on stairs or fixture locations such as lighting on floor plans are familiar and easy to read for architectural professionals, while they are not easily recognized by non-professionals who are not accustomed to interpreting such drawings. VR technology serves as an effective communication medium that helps clients better understand architectural concepts regardless of their technical background.[54] In addition to efficiently conveying professional representation to non-professionals, presenting VR to clients enhances communication and persuasion by increasing their engagement and immersion. Studies reveal that people rate VR experiences as more enjoyable and engaging ways to understand architectural designs.[55] In this context, this technology enables clients to learn and experience proposed spaces firsthand, leading them to have improved understanding and increased enthusiasm for the proposed the projects.



Figure 2.7 *HOK presenting VR to their clients*



Figure 2.8 *Architect in HOK assessing space through VR*

53 G Emerson, "Virtual Reality Empowered Proecedural Modeling"
54 J. M. Noble, "Virtual reality as a communication medium: investigating the impact of virtual embodiment on various stakeholders of an architecture project"
55 Michael K, "Improved Perception of AEC Construction Details via Immersive Teaching in Virtual Reality"

Precedent: HOK'S VR workflow that immersed clients in design, 2019,
Interview on YouTube, titled 'HOK Immerses Clients in Design'
In the interview of HOK with Unreal Engine in 2019, HOK demonstrated how VR effectively bridges the knowledge gap between architectural professionals and clients. The firm recognized that clients "don't have to be literate in spreadsheets and technical drawings but they most definitely will understand a beautiful image and how the space will feel in the future."The global architecture firms such as HOK have transformed the communication approach to their clients by replacing time-consuming static renderings and videos with VR environments that allow clients to experience proposed spaces dynamically. This enables HOK to attract better engagement from clients and to have persuasive presentations that help clients understand exactly what they are getting regardless of their technical architectural background. Through Unreal Engine's visual fidelity and real-time capabilities, HOK mentioned that they could deliver "any kind of content, new kinds of content, in ways that they couldn't have done before."Therefore, HOK successfully improved their most important task of communicating designs with clients in a more efficient, accessible, and compelling method that enhances clients' understanding.[56]

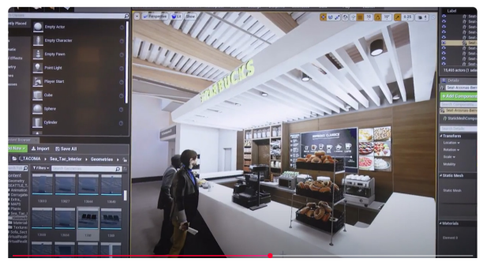


Figure 2.9 *Showing visual fidelity in VR environment through Unreal Engine by HOK*



Figure 2.10 *Presenting proposed design in VR using teleporting function in Unreal Engine by HOK*

56 Unreal Engine, "HOK Immerses Clients in Design"

2-5. Implications from architectural VR precedents

The various precedents in this chapter enhanced the projects by leveraging the diverse advantages of VR; however, the common approach to utilizing architectural VR was to deliver more effective and persuasive presentations to clients and stakeholders through high-quality visualization and experience.[57]

Diamond Schmitt Architects' project on Ingenium's Collection and Conservation Centre proves how VR presentation enables architects to deliver complex spatial designs that traditional 2D drawings cannot convey enough.[58] Their approach to visualizing massive artifacts at the proper scale within the proposed building by VR presentation resolved critical design challenges by providing clients with a deeper understanding of spatial requirements and design solutions. Similarly, Mortenson's implementation of VR for Kaiser Permanente's interventional radiology room showcased how immersive visualization enables clients and stakeholders to experience and evaluate complex environment design before construction so that they reduce design revision costs much and improve functional outcomes.[59]

These precedents consistently show that architectural VR works as a powerful communication method that bridges the knowledge gap between architectural professionals and clients who are not familiar with interpreting architectural documentation.[60] HOK's design team reported significantly improved client engagement and decision-making when their projects are experienced through immersive environments rather than traditional 2D presentation methods, and the data proves that their workflow with architectural VR in client presentations is practically advantageous.[61] This enhanced communication capability transforms the architect-client relationship from one of explanation and interpretation to one of shared experiential understanding.

Furthermore, these precedents indicate that architectural VR's major value is creating compelling and memorable experiences that enhance more informed design decisions and stronger client confidence in design proposals.[62] The consistent theme across all precedents in this chapter is the transformation of architectural presentation from static visualization on a 2D medium to experiential communication that significantly enriches project understanding and engagement of stakeholders.

57 *Nikitha Sunil, "How AR and VR Are Transforming Client Experience in Architecture"*
58 *Rachel Chan, "Sharing a Vision with Andrew Chung of Diamond Schmitt Architects"*
59 *Unity Technologies, "Mortenson: Better Hospital Designs with Virtual Reality"*
60 *Robert Kendal, "Interview with Alex Garrison (architect, Gensler), Building Dialogue"*
61 *Unreal Engine, "HOK Immerses Clients in Design"*
62 *Robert Kendal, "Interview with Alex Garrison (architect, Gensler), Building Dialogue"*

2-6. Research gap: Recognition of limitations in contemporary architectural VR

Despite the significant advances in Virtual Reality (VR) technology for architectural applications, fundamental limitations that constrain the full potential of immersive VR experiences still persist. Studies about leading architectural firms' contemporary VR practices demonstrate the limitations of visual-only representation in VR, which fails to engage the complete spectrum of human sensory perception that is necessary for truly comprehensive spatial understanding.[63]

Foster + Partners' innovative approach to outdoor VR experiences shows both the achievements and limitations of current architectural VR representation. In a narrative video demonstrating their project, the firm developed a sophisticated system that combines virtual visuals in high quality with spatial navigation in the real world. This innovation by Foster + Partners allows stakeholders to walk around an actual plaza at 1:1 scale while experiencing the proposed space through VR headsets.[64] However, the architect in the video described the experience that "an incredible, multisensory experience of walking around the plaza, seeing the very powerful virtual visuals, but feeling the real plaza beneath your feet and hearing the sounds of the city around you". This technique reveals a critical limitation in contemporary VR applications.

Foster + Partners approach is innovative in its site-specific implementation; however, it shows current architectural VR technology remains significantly limited to visual stimuli only. The "multisensory" experience they mentioned is achieved not through comprehensive VR representation, but through a hybrid approach that relies on physical presence at the actual site to provide tactile and auditory perception. For this kind of approach, users must physically travel to the site to feel "the real plaza beneath their feet and hear the ambient sounds of the city," while their VR system delivers only visual information about the proposed design.[65] Although this approach is still effective for specific site-based presentations, it exposes the limitation that true multi-sensory VR representation is absent from current architectural practice.

63 *Z Cheng et al, "The Application Status and Thinking of VR in Architecture"*
64 *Unreal Engine, "AR and VR at Foster + Partners"*
65 *Unreal Engine, "AR and VR at Foster + Partners"*



Figure 2.11 *Architects from Foster + Partners demonstrating their VR on site, but it's experience limited to visual stimuli only*

This limitation becomes even more problematic when considering the practical constraints of architectural design processes. Stakeholders cannot physically visit their project site every time for each design review, especially for international projects or for multiple design revisions. If the VR experience requires a physical presence at the site for non-visual sensory input, it severely limits accessibility for truly immersive design experiences. Furthermore, this approach cannot provide the sophisticated design evaluation when specific acoustic sound conditions or material textures need to be precisely simulated and revised for design optimization.[66]

The absence of integrated multisensory capabilities in contemporary architectural VR represents a significant gap between the potential of the current technology and its current implementation. The lack of sophisticated spatial audio simulation and other sensory modalities limits the comprehensive representation of architectural VR experience, while the technologies for visual rendering engines such as Unreal Engine have advanced significantly.[67] Research demonstrates that visual-only VR systems sometimes cause wrong estimation of depth and distance, and these errors degrade accurate spatial assessment that is necessary for architectural design decisions.[68]

66 *Marey A, "Simulating Human Senses to Improve Thermal Comfort"*
67 *Xavier R, et al, "Pseudo-Haptics Survey: Human-Computer Interaction in Extended Reality & Teleoperation"*
68 *Markin L, et al, "Tactile and Kinesthetic Feedbacks Improve Distance Perception in Virtual Reality"*

This limitation is particularly significant since architectural spaces are multisensory environments where all of the material properties, acoustic characteristics, and spatial proportions contribute to the overall quality of experience in built environments.[69] Furthermore, the inability to accurately simulate acoustic environments using spatial audio, or to replicate environmental conditions through thermal or olfactory simulations, restricts architects' capacity to assess and convey the complete qualities of experiences in their designs.[70] This limitation becomes problematic as architectural practice moves toward design approaches with comprehensively immersive experience in VR.

Acknowledging these limits in contemporary architecture shows the need for more thorough methods that include visual and additional stimuli, such as audio. Although the current focus on visual-only VR experiences is valuable, it provides only a limited perspective for developing truly immersive architectural VR experiences. The development of multisensory VR systems that can integrate auditory and potentially other sensory modalities would significantly enhance the accuracy and comprehensive understanding of architectural representations and client communication processes.

PART 2 will explain the necessity of multisensory VR, especially audio, in architectural representations and will provide supporting evidence from a cognitive context perspective.

69 *Sebastian G, et al, "Assessing the Influence of Visual Cues in Virtual Reality on the Spatial Perception of Physical Thermal Stimuli"*
70 *Villa S, et al, "An Examination of Ultrasound Mid-air Haptics for Enhanced Material and Temperature Perception in Virtual Environments"*

PART 2
COGNITIVE CONTEXT

In PART 1, contemporary architectural representation was confirmed to have reached a stage where VR provides experience rather than just conveying information. However, Chapter 2 examined current architectural VR precedents and identified the limitation that architectural representation in VR remains overly focused on visuals only while multisensory representations stay underdeveloped. Therefore, PART 2 will focus on sound, the most potential element that is achievable to implement within current VR technology levels. It aims to demonstrate the necessity of actively utilizing sound in architectural VR.

To prove this claim, this section explores how sound affects human perception and understanding in architecture, and the theoretical foundation for why architects must actively apply sound into their VR presentations will be established. Chapter 3 examines the cognitive mechanisms by which certain kinds of sound contribute to spatial awareness, and Chapter 4 investigates how these mechanisms could create more compelling and persuasive architectural communications. Understanding these foundations will demonstrate why integrating sound in architectural VR is essential for architects who want to create truly engaging presentations that effectively convey their design intent to clients and stakeholders.

Chapter 3

Sound in Perception

3-1. The cognitive foundation of sound perception in space

When humans perceive spatial information, they heavily rely on auditory information for comprehensive understanding of the environment since vision alone cannot process it enough. The brain processes acoustic information through sophisticated cognitive mechanisms that enable people to build detailed mental maps, which refer to the way people create simplified spatial representations in their minds within architectural spaces. Research demonstrates that people can perceive coherent spatial representations of building layouts through auditory exploration alone and indicates that sound provides fundamental spatial information independently from visual cues.[71]

The cognitive processing of spatial sound involves several key mechanisms explained in the following paragraphs.

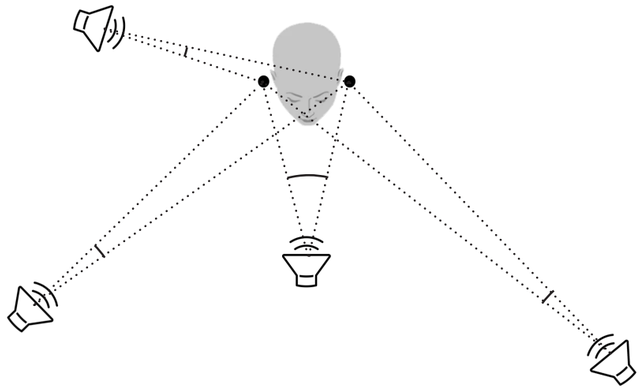


Figure 3.1 *Diagram of binaural cues affecting spatial perception at different locations*

Binaural cues mean differences in timing and intensity between the two ears and provide the primary computational basis to determine the location of the sound source and relative distance. For example, if water is falling on the right side, the right ear perceives the sound louder and slightly faster than the left ear. The brain uses statistical knowledge about natural acoustic environments, including learned pattern of reverberation and energy decay, to distinguish sound sources from their environmental characteristics.[72] This separation allows listeners to simultaneously understand both what is making the sound and what the space containing the sound is.

71 *Lorenzo Picinali, et al, "Exploration of Architectural Spaces by the Blind Using Virtual Auditory Reality for the Construction of Spatial Knowledge"*
72 *James T and Josh H. M, "Statistics of Natural Reverberation Enable Perceptual Separation of Sound and Space"*

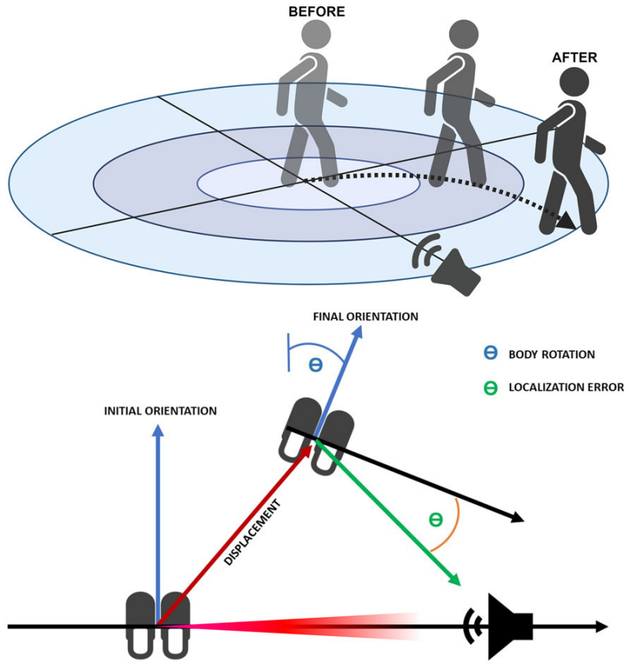


Figure 3.2 *Diagram of relationship between body position and sound localization in spatial perception*

Active listening strategies enhance spatial understanding with head movements and body positioning. When people move through acoustic environments, they gather dynamic binaural information that resolves ambiguities and improves localization' accuracy.[73] This combination of movement and acoustic feedback is essential to build a cognitive map of comprehensive spatial information. This cognitive map is particularly necessary in complex architectural environments where multiple reflections and sound sources interact.[74]

73 *Daniel P, et al, "Body Representation Drives Auditory Spatial Perception"*
74 *William L. M and Michael C, "Spatial Soundscape Superposition, Part I: Subject Motion and Scene Sensibility"*

3-2. How sound properties shape spatial understanding

Three properties of sound (attenuation, overlap, and diffraction) directly influenced the way humans perceive and understand architectural spaces. These properties work together to provide rich spatial information that often exceeds the extent that visual perception alone can achieve.

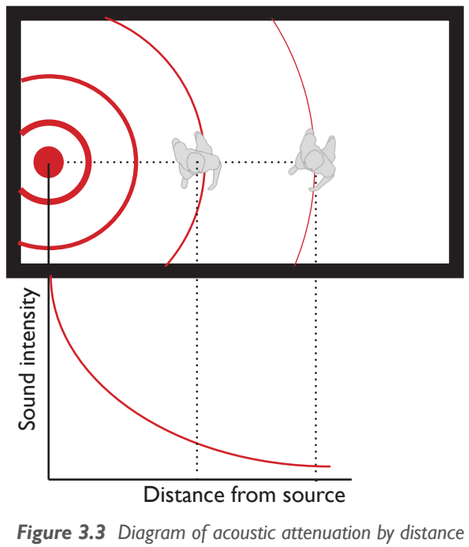


Figure 3.3 *Diagram of acoustic attenuation by distance*

Attenuation and distance perception

Attenuation means the way sound fades in intensity as a listener moves away from its source; for example, the sound of water falling into a spa tub should gradually fade as the listener moves away from the spa tub. This gradient refers to distance and enriches a sense of spatial depth that visual effects cannot convey alone. When sound gradually fades as a listener moves away from the location of the source, the brain interprets this decreased energy pattern to estimate both distance and environmental information.[75]

In an architectural context, attenuation allows users to have more accurate information about depth so that they understand the three-dimensional relationship between different areas in space. This relationship between auditory information and spatial perception shows how sound provides quantitative information about dimension and proportions in architectural environments.

75 *Nicola P, et al, "Comparing the Effects of Scattered and Specular Sound Reflections on Speech Intelligibility in Rooms"*

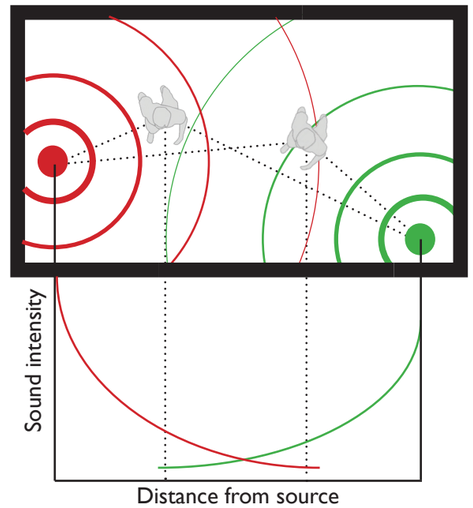


Figure 3.4 *Diagram of acoustic overlap by location*

Overlap and spatial relationships

Overlapping sound describes the layering of multiple sounds that occur simultaneously in space; for example, when birds chirping from outside a living room with an open window and background music is playing on the radio in the living room, the volume and direction of the two sounds gradually change as the listener moves between the two sources. By observing the changes in volume and direction of multiple sound sources, the listener can better understand their physical locations relating to one another. The brain can separate overlapping sounds into distinct auditory objects while maintaining awareness of their spatial relationships. This process provides significantly important information about the layout and activity patterns in environments.[76]

In an architectural context, overlapping sound provides environmental information about spatial connectivity and activity zones. In other words, this acoustic information enables listeners to have a comprehensive understanding on how different spaces are connected and related to each other within the overall architectural composition.

76 *Olli Santala, "Perception and Auditory Modeling of Spatially Complex Sound Scenarios"*

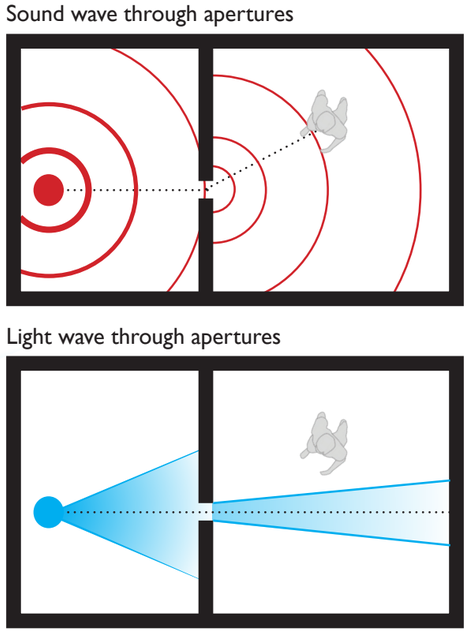


Figure 3.5 *Diagram of acoustic diffraction compared with light through apertures*

Diffraction and environmental boundaries

Diffraction represents the bending of sound waves through apertures or around obstacles; for example, if a dog is barking behind a door and the sound is coming through a tiny crack in the door, the listener senses both the existence of space and the presence of a dog beyond the door. Diffraction shows the difference between visual and auditory stimuli. Visual elements behind obstacles cannot be transmitted, but auditory elements can be transmitted through even very narrow gaps.

In an architectural context, diffraction provides spatial information about environmental boundaries and hidden spaces that visual perception cannot access when it is obstructed. This property of diffraction enables listeners to have awareness of adjacent spaces, circulation patterns, and architectural features even when vision cannot perceive them.[77]

77 *Auditory and Visual Contribution to Egocentric Distance and Room Size Perception*

3-3. Multisensory integration and spatial cognition

Integrating auditory information with other sensory modalities creates a comprehensive spatial understanding that surpasses the perception achievable by any single sense. Research shows that auditory cues primarily provide perceiving distance while visual cues support estimating the size of space when both are available.[78] This integrated understanding achieved by multisensory perception plays a critical role in figuring out what the space looks like when visual information is limited or ambiguous. The cognitive mapping process, based on the comprehensive results of multisensory perception, creates detailed mental representations of architectural spaces that support memory, navigation, and decision-making. These cognitive maps reflect both topological information (connectivity, relationships, and boundaries) and metric information (distance, proportions, and sizes) that is achieved from acoustic experience in architectural space.[79]

78 *Auditory distance perception in humans: a review of cues, development, neuronal bases, and effects of sensory loss*
79 *Exploration of Architectural Spaces by the Blind Using Virtual Auditory Reality for the Construction of Spatial Knowledge*

Chapter 4

Sound in Architectural Representations

4-1. The necessity for sound cues in architectural VR

Architects must acknowledge that contemporary representation methods cannot ignore sound as a fundamental component of spatial experience.[80] When architects deliver their design intent using only visual information, it could be an incomplete and potentially misleading representation of the proposed spatial experience. Sound provides the users critical information about scale, material qualities, environmental atmosphere, and implication of visually obscured space that clients and stakeholders need to be aware of for proper decision-making about the architectural projects.[81]

The integration of sound into architectural VR presentations enables users to transform passive visual observation into active spatial engagement.[82] Clients who experience multisensory architectural representations can have a more profound understanding of proposed spaces without professional knowledge of architectural representations since they don't need effort to read and interpret the visual materials but just experience the space.[83] Therefore, this comprehensive understanding leads to more meaningful feedback and more confident decision-making. This enhances communication reduces the risk of unexpected issues after occupancy and improves client satisfaction with final built outcomes.

Clients these days increasingly expect sophisticated and engaging presentation methods that allow them to truly experience proposed designs rather than simply viewing them. Application of sound in architectural VR meets this client expectation while providing architects with more persuasive and effective communication tools. This competitive advantage achieved by compelling multisensory presentations can differentiate architectural practices and enhance professional reputation.[84]

80 *Charles Spence, "Senses of place: architectural design for the multisensory mind"*
81 *Tianchen D and Xing Z, "Understanding How Multi Sensory Spatial Experience Influences Atmosphere, Affective City Image and Behavioural Intention"*
82 *Keith Yates Design, "Virtual Acoustic Reality in Architectural Design"*
83 *Unreal Engine, "HOK Immerses Clients in Design"*
84 *Smith, J. Scott, "7 Key Challenges in The Impact of Virtual Reality on Architectural Presentations"*



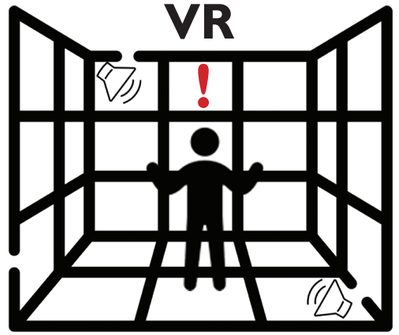


Figure 4.1 *Diagram comparing client's experience in documents and VR*

4-2. Implementing acoustic properties for enhanced VR

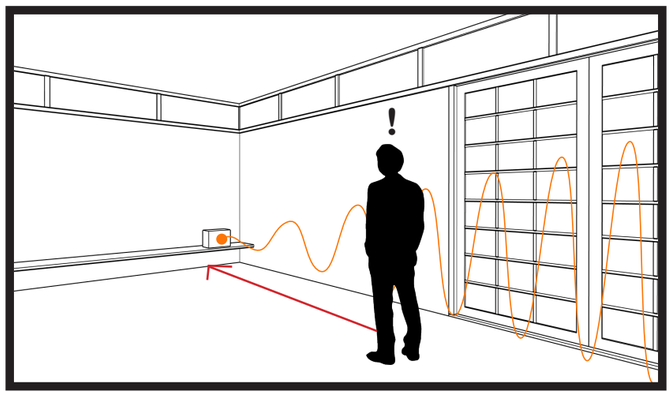


Figure 4.2 *Diagram showing acoustic attenuation in spatial perception*

Attenuation and distance perception

Architects can apply attenuation effects to deliver spatial hierarchies and circulation patterns to clients and stakeholders in their VR presentations. In addition, architects can attract users' attention to notice important spatial relationships and help them understand the intended circulation and organization of the proposed designs by carefully controlling how sounds fade and increase with distance.[85] This acoustic wayfinding enables intuitive navigation that enhances users' understanding of complex spatial arrangements.[86]

The strategic use of attenuation also helps users understand the relationship of the level between privacy and public spaces. To be more specific, areas where sound fades quickly reflect acoustic separation, while areas where sound carries further represent spatial connectivity.[87] This acoustic information helps users evaluate the functional relationship between proposed spatial layouts and provides immediate feedback for design revision.

85 *Barry Truax, "Acoustic Space, Community, and Virtual Soundscapes"*
86 *Mehmet Dereli, "Acoustic Wayfinding Support in Real Environments without the Sense of Sight"*
87 *BAP Acoustics, "Office Acoustics: Speech Privacy and Security"*

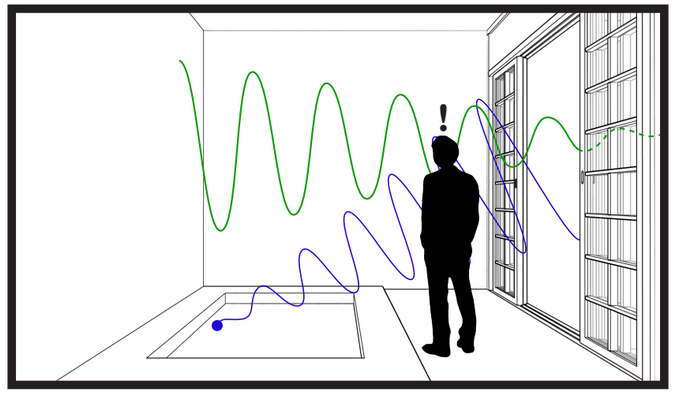


Figure 4.3 *Diagram showing acoustic overlapping in spatial perception*

Overlapping for active zone demonstration

The layering of multiple sound sources in VR presentations allows architects to efficiently show how different activities will coexist in proposed spaces and to create a comprehensive understanding of functional activities. Research on the analysis of acoustic scenarios within spaces demonstrates that clients and stakeholders can effectively recognize overlapping sound sources to understand activity relationships, compatibility, and potential conflicts within architectural environments.[88] This acoustic perception helps users visualize how the space shapes and functions in the proposed layouts, leading to more informed feedback and design revision.

Acoustic overlapping also helps users intuitively understand the activities occurring in the proposed space by presenting various activity scenarios within the same spatial framework. Studies demonstrate that experiencing various acoustic scenarios enhances clients' understanding of design versatility and functional performance, and in turn contributes to increasing project value and client satisfaction.[89]

88 *Brady Peters, "Integrating Acoustic Analysis in the Architectural Design…"*
89 *Barry B and Linda R. S, "Spaces Speak, Are You Listening? Experiencing Aural Architecture"*

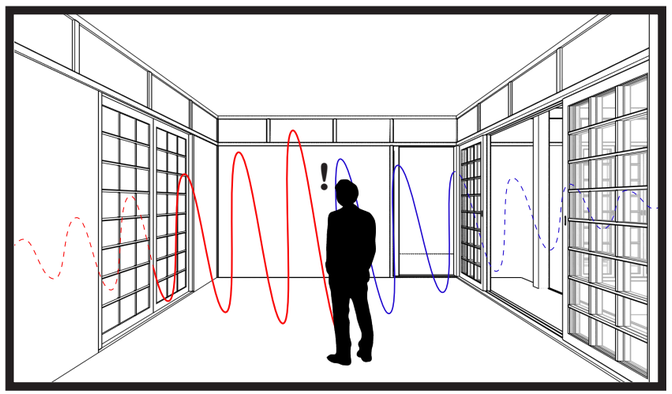


Figure 4.4 *Diagram showing acoustic diffraction in spatial perception*

Diffraction for spatial connectivity and privacy balance

Diffraction effects in architectural VR presentations help clients and stakeholders understand how sound travels between spaces and around architectural elements, providing essential information about spatial connectivity in proposed spaces. Research shows that diffraction cues enable better assessment of acoustic barriers and spatial boundaries.[90] In addition, users can experience the environment with sound cues and expect how noise will carry between rooms, how activities in adjacent spaces will be perceived, and how the space will functionally work.[91]

Applying diffraction effects in the proposed space also shows sophisticated design thinking; therefore, clients have more appreciation for architectural attention to experiential details and functional performance.[92] Consequently, it is expected that clients who experience a carefully planned acoustic delivery in the proposed presentation can have enhanced credibility in design thoroughness and their recognition of the project value.

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90 *Paul Thomas Calamia, "Advances in Edge Diffraction Modeling for Virtual Acoustic Simulations"*
91 *Finnur K. P. J, et al, "Acoustic Virtual Reality – Methods and Challenges"*
92 *Nikitha Sunil, "How AR and VR Are Transforming Client Experience in Architecture"*

PART 3
EXPERIMENT PROCEDURE

Chapter 5

Experiment Preparation

5-1. Experiment outline

Participants

38 participants were recruited from the School of Architecture, University of Waterloo. All of them participated in the experiment voluntarily, following the guidance of Ethics Clearance (#47603) by the University of Waterloo.

Hypothesis

This experiment is designed to investigate how different modes of exploring architectural virtual environments affect the level of immersion and realism. In further detail, it compares how the participants perceive immersion and a sense of space in three conditions in the same architectural space. Each condition varies in its method of delivery and sensory details.

There are three experimental hypotheses. **First**, each participant's playtime increases in the order of condition A-B-C. **Second**, each participant's perceived immersion rate, realism rate, and emotional engagement rate increase in the order of condition A-B-C. **Third**, participants respond to the highest immersion in condition C, which has more sensory inputs.

To identify the differences between each condition and prove these hypotheses, participants were guided to experience the three conditions in a fixed sequence: A – B – C.

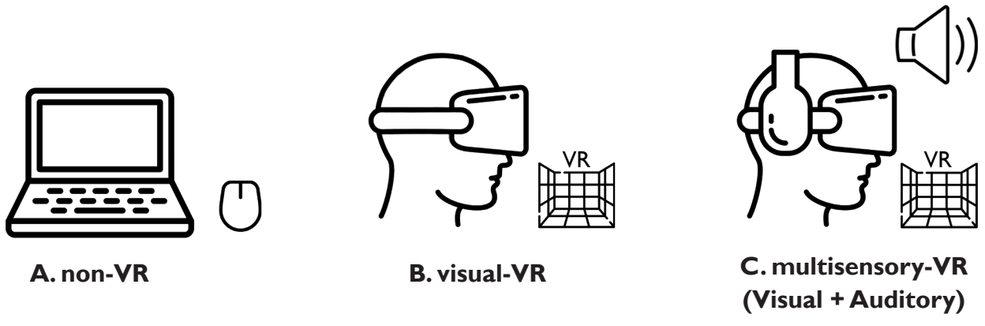


Figure 5.1 *Specification of each experimental condition*

Specification of each condition

A. non-VR visual condition

A detailed 3D model of an architectural space is explored using a PC, keyboard and mouse. This version includes realistic rendering features such as materials, textures, objects, and animated effects but is experienced on a PC screen without VR device.

B. visual-VR condition

The same space is presented with a VR headset (Meta Quest 3), allowing participants to have immersive first-person exploration. All the visual elements are the same as version A (non-VR condition), but the level of spatial immersion is enhanced to the participants by using the VR headset.

C. multisensory-VR (Visual + Auditory) condition

This version builds upon version B (VR visual condition) with spatialized auditory effects such as attenuation, overlap, and diffraction. The sound effects are placed at 5 different spots where they are aligned with the context of sound cues in the virtual space to enhance the sense of space and realism.

After exploring all three versions, participants are asked to fill out a questionnaire. This includes questions measuring their perceived level of immersion for each condition on a numeric scale (from 1 to 7), as well as an open-ended section for additional qualitative feedback.

This study aims to demonstrate how the VR architectural design and multisensory design, which incorporates spatialized sound, influence the perception and immersion levels reflected in statistical figures by collecting and comparing the scales of three conditions. The findings are expected to contribute to ongoing discussions about the necessity of VR design and the role of sensory integration in architectural visualization and digital spatial design.

5-2. A rationale for experimental design

The design of this experiment is structured with the aim to investigate how varying conditions of delivery mediums and sensory inputs influence the perceived immersion of users in architectural virtual environments. Sensory richness and realism often enhance immersion, which is considered the central concept of virtual reality (VR) studies. However, much of architectural VR research has traditionally emphasized visual representation alone, leaving the multisensory dimension underexplored. This study seeks to address that gap by testing the effects of both visual and auditory stimuli on spatial experience in virtual reality and showing it in statistical figures.

The experimental framework was designed to allow each participant to experience all three varying conditions. This framework is intended to prove two hypotheses. In a comparison of conditions A and B, participants will report a higher level of immersion when experiencing the architectural space in VR with visual effects, compared to exploring the same space in the traditional way with a PC screen navigated with a keyboard and mouse. Next, comparing conditions B and C, participants will report the higher level of immersion when experiencing the VR space with both visual and auditory (spatialized) effects, compared to VR with visual effects alone.

Presenting the conditions in a fixed order (screen-based, VR with visuals, and VR with both visual and sound) reflects progress in sensory engagement, which is intended to prevent premature bias from more immersive modalities influencing participants' responses to less immersive ones.

The first condition, experienced on a PC, establishes a baseline by setting the least spatial immersion. The second condition, explored with a VR headset in the same visual environment, enabled the evaluation of immersive visual experiences alone. The third condition adds spatialized sound effects such as birds chirping and water flowing to the visual VR experience of the second condition, allowing for a focused examination of multisensory integration.

This structure supports a comparative analysis methodology across different modalities (on 2D screen, in VR without sound, and VR with sound), enabling the experiment to explore not only whether VR enhances the level of immersion but also how additional sensory cues, particularly sound, may further enhance spatial engagement. Ultimately, this approach intends to offer evidence-based insight with specific numbers on how multisensory design can enrich architectural visualization and communication in digital environments.

5-3. Experiment specifications

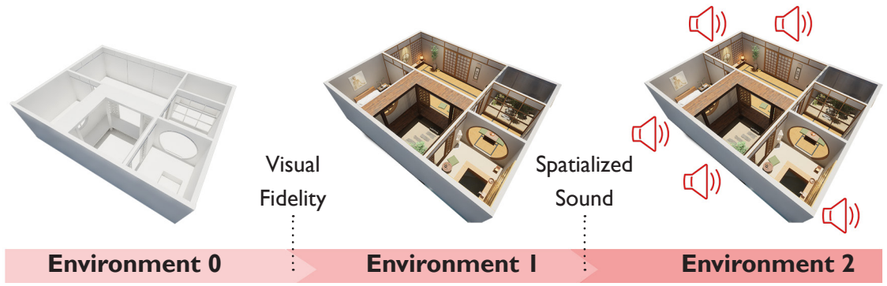


Figure 5.2 *Process of developing experimental environments*

This experiment was designed to assess how varying sensory inputs and delivery mediums affect participants perceiving immersion in a consistent architectural setting: a single virtual environment with the same visual effects such as realistic material, texture, lighting, furniture, vegetation, layered decal patterns and animated effects. To ensure that a meaningful comparison was observed, all three conditions of the experimental environments were developed using the same visual configuration but differed only in auditory effects, which were added in the third condition. The sequence was fixed for all participants to maintain internal consistency, and the results allow a focused evaluation of visual and auditory contributions to the virtual experience.

There are two experimental environments. Environment 1 was designed to achieve visual fidelity by employing realistic materials, textures, and props, enabling sufficient immersion and realism through visual stimuli alone. Environment 2 adds auditory stimuli that complement the visual elements in the first version.
For further details:

- Audio of water splashing at the visual effect location where water flows in a spa
- Audio of birds chirping at the location of a bamboo figure
- Radio noise and piano music at the spots where the radio props are placed
- Audio of a dog barking beyond a door

These auditory cues were designed to improve the recognition of visual cues using auditory information, allowing participants to have an enhanced sense of direction and space solely through audio cues, even when visual cues are absent.

These two versions of the environment are played under three conditions. The first model, with visual fidelity implemented, is explored under two conditions: A (non-VR visual condition) and B (visual-VR condition). This ensures that the visual fidelity remains consistent while comparing immersion levels between the non-VR and visual-VR conditions, thus only varying in the 'non-VR vs visual-VR' aspect. The second model, featuring visual fidelity with spatialized audio added, is explored under condition C (multisensory-VR condition).

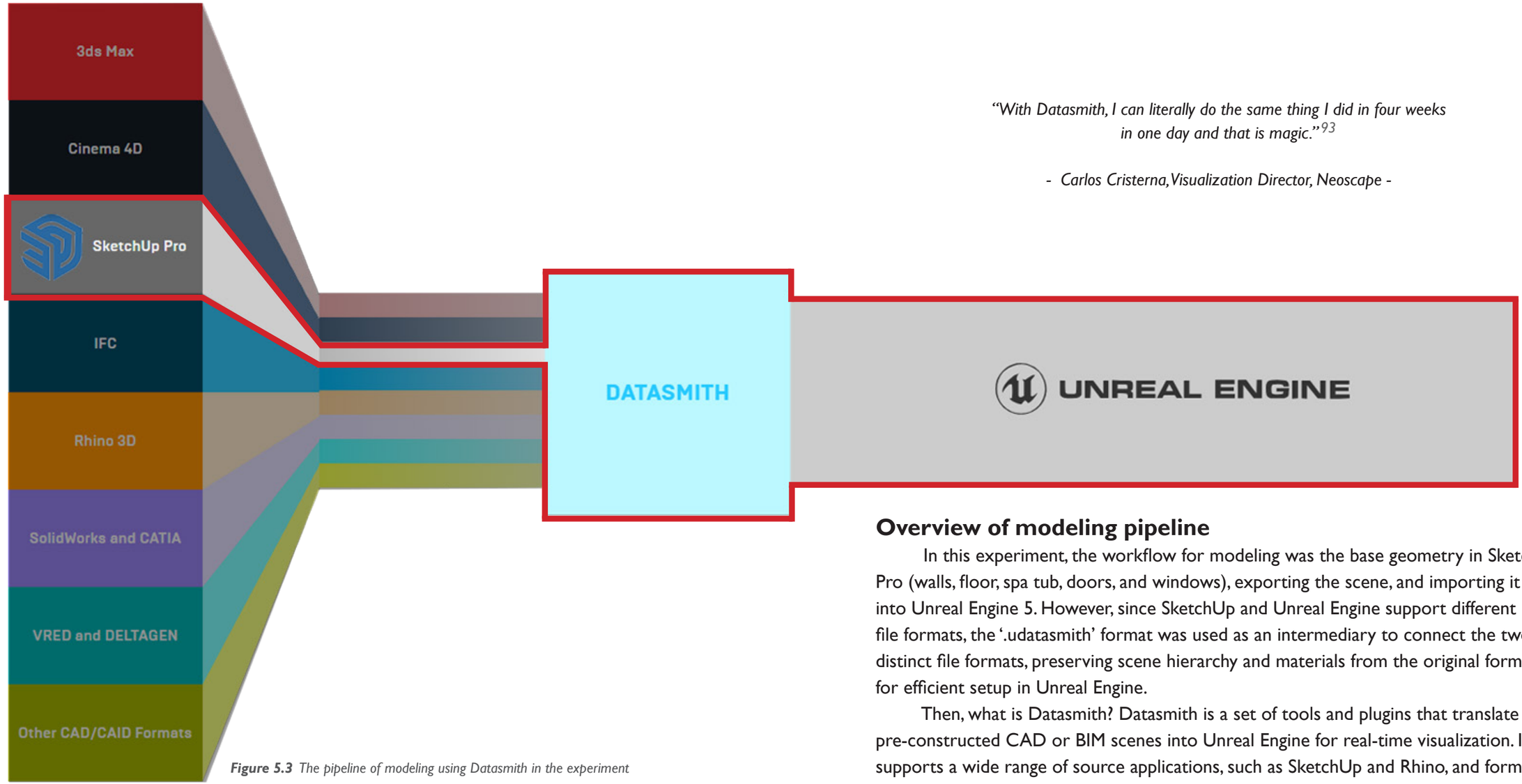


Figure 5.3 *The pipeline of modeling using Datasmith in the experiment*

93 *Carlos Cristerna, "Quoted in Datasmith, Unreal Engine documentation"*
94 *Epic Games Developer Community, "Datasmith Plugins Overview"*

"With Datasmith, I can literally do the same thing I did in four weeks in one day and that is magic."[93]

- Carlos Cristerna, Visualization Director, Neoscape -

Overview of modeling pipeline

In this experiment, the workflow for modeling was the base geometry in SketchUp Pro (walls, floor, spa tub, doors, and windows), exporting the scene, and importing it into Unreal Engine 5. However, since SketchUp and Unreal Engine support different file formats, the '.udatasmith' format was used as an intermediary to connect the two distinct file formats, preserving scene hierarchy and materials from the original format for efficient setup in Unreal Engine.

Then, what is Datasmith? Datasmith is a set of tools and plugins that translate pre-constructed CAD or BIM scenes into Unreal Engine for real-time visualization. It supports a wide range of source applications, such as SketchUp and Rhino, and formats while maintaining layout fidelity and enabling reimport to develop upstream changes. In a file-based workflow, an original applications, such as SketchUp, export a '.udatasmith' file via a plugin, and then it is brought into Unreal Engine through the Datasmith Importer. Accordingly, the experiment in this paper employed a SketchUp Pro – Datasmith (.udatasmith) – Unreal Engine 5 pipeline to import and prepare the architectural base model.[94]

Details of modeling pipeline

Unreal Engine also allows designers to build models; however, the modeling is primarily based on x, y, and z coordinates using functions such as scale and rotation, rather than modeling based on precise dimensions. Therefore, for more precise modeling in numbers, the base model (walls, floor, doors, etc.) was built in SketchUp, which is one of the architectural modeling software better suited for dimension-based modeling, and then imported into Unreal Engine via the '.udatasmith' format.

A significant number of realistic assets (props, materials, animated visual effects, etc.) were imported from Unreal Engine's own platform, Fab. However, the assets unavailable on Fab were imported via the '.udatasmith' format from external platforms such as SketchUp's Warehouse.

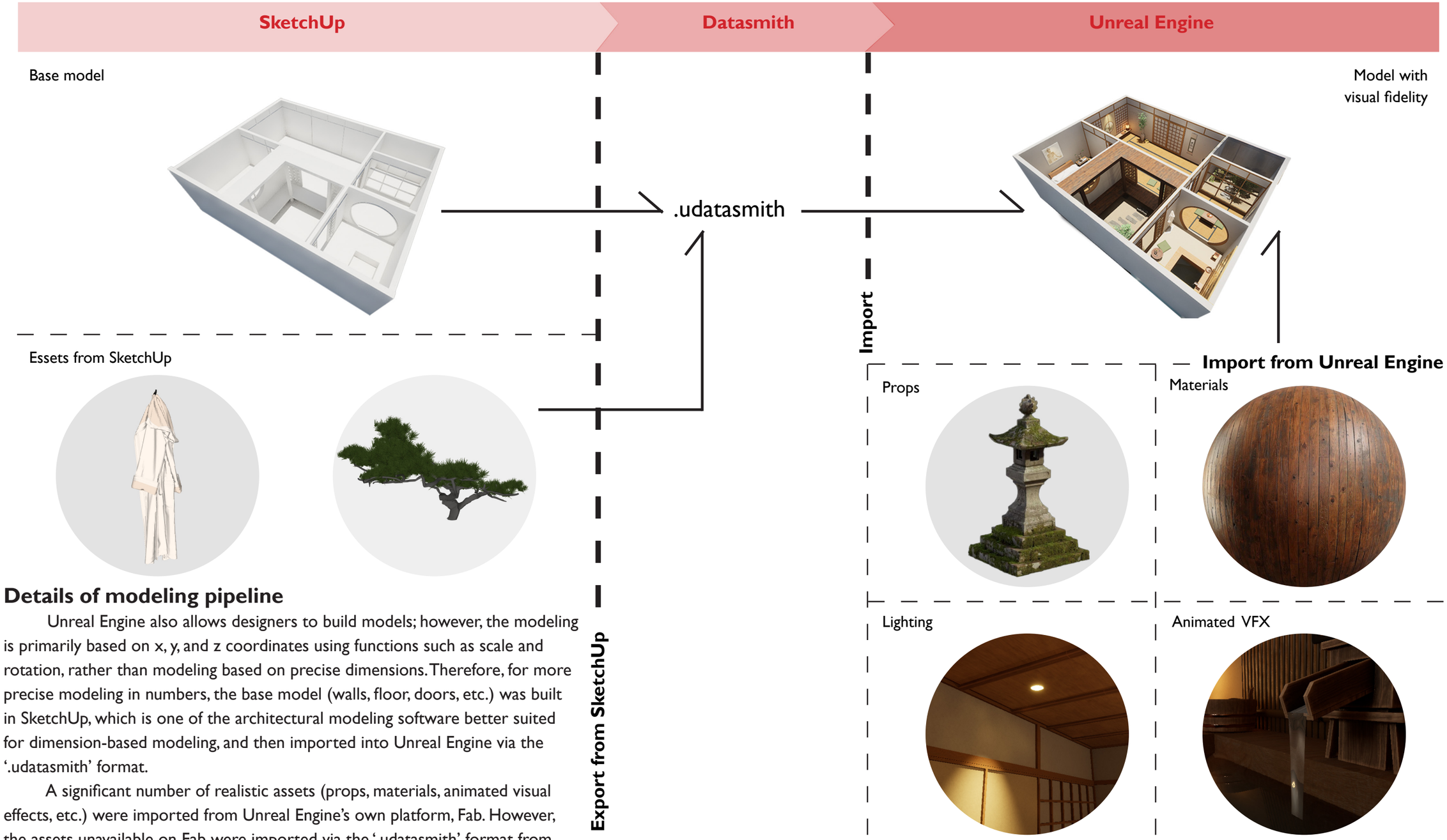


Figure 5.4 *The workflow of modeling environments for visual fidelity*

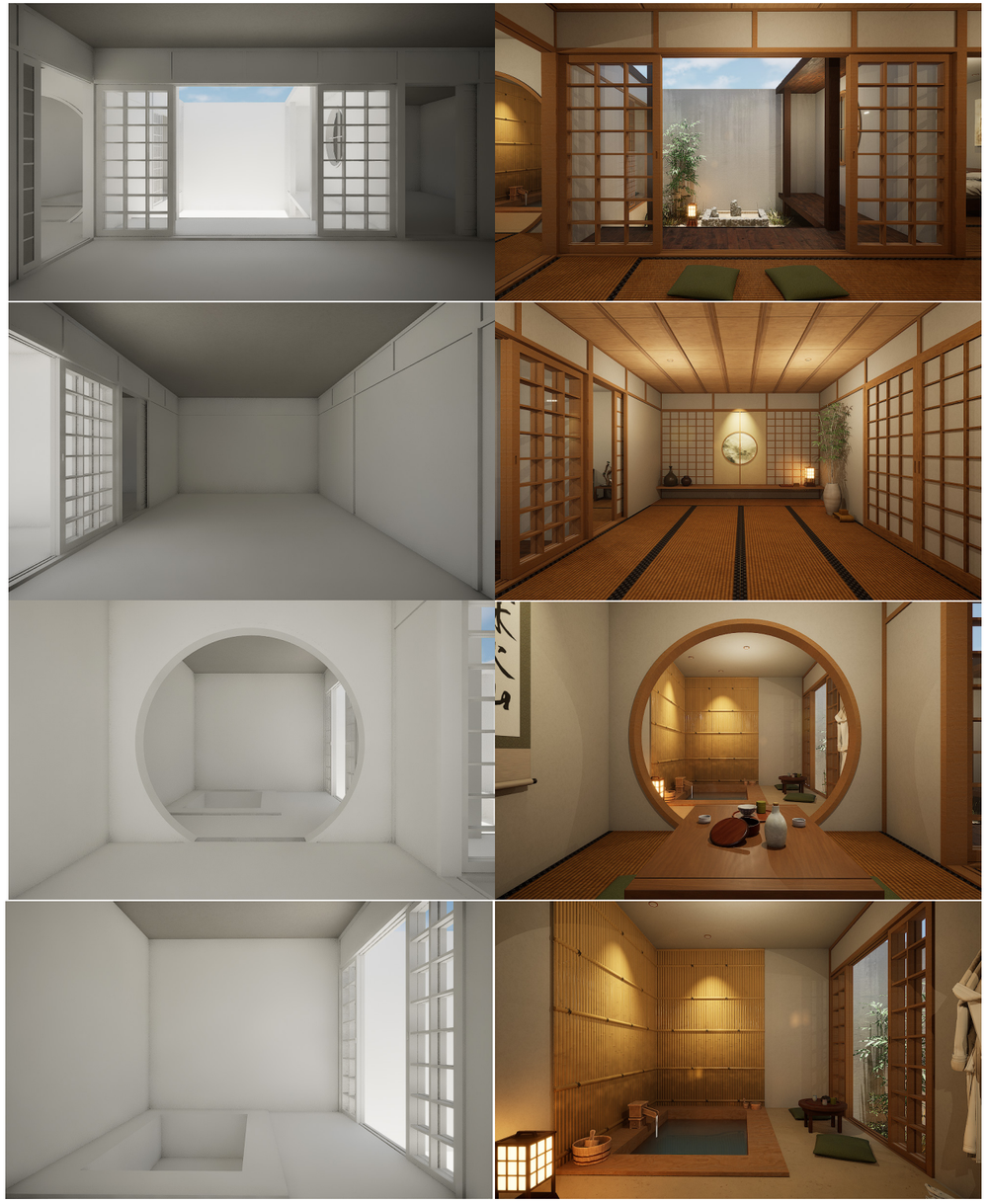


Figure 5.5 *Before and after developing visual fidelity 1*

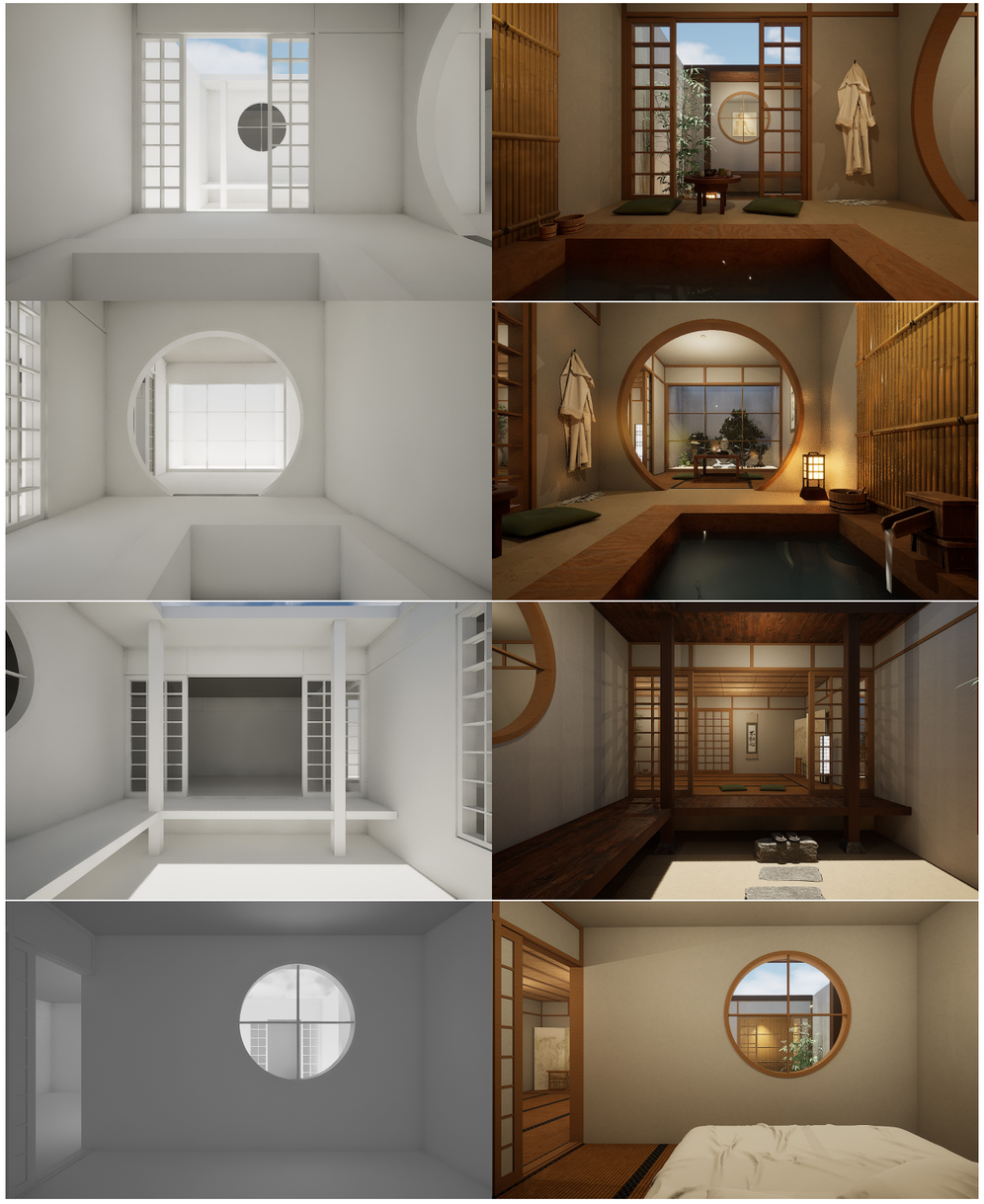


Figure 5.6 *Before and after developing visual fidelity 2*

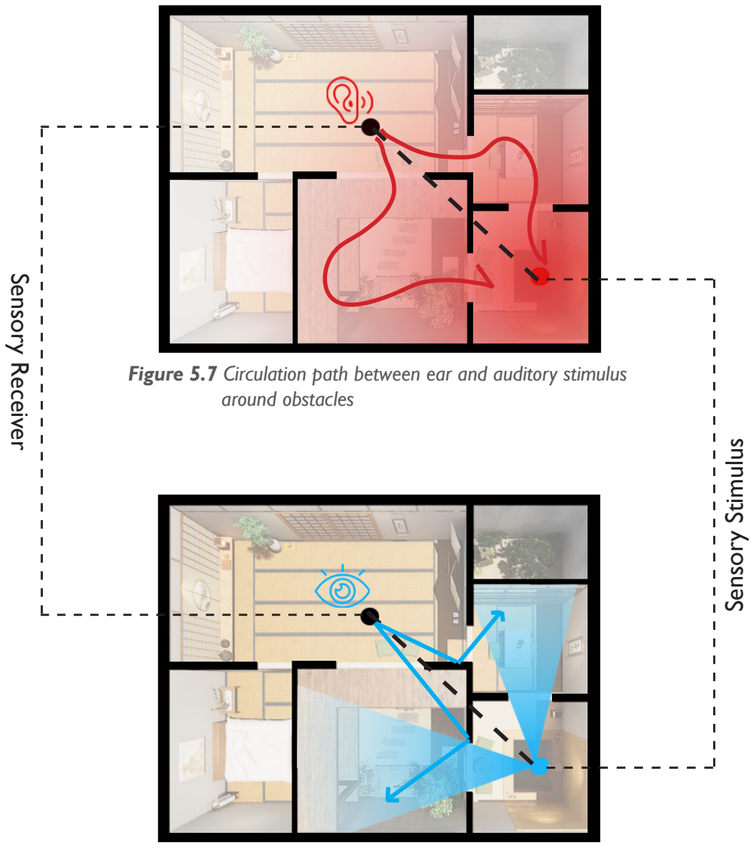


Figure 5.7 *Circulation path between ear and auditory stimulus around obstacles*

Figure 5.8 *Path of sight between eye and visual stimulus around obstacles*

Overview of environmental design

The environment is designed as a Japanese-style vacation villa, with four rooms arranged in a C-shape around a small courtyard in the center. This creates points where visual cues are obscured at three distinct locations (the center of the C-shape and the two wings' locations). This layout is intended to create situations where participants perceive only audio cues in visually obscured locations so that they could be navigated to follow the location with curiosity.



Figure 5.9 *Site plan of the experimental environment*

The overall interior design blends traditional elements such as wood and tatami flooring with modern glass and furniture to create a contemporary Asian style. The meditation space is located at the front of the courtyard, so let it fully embrace the natural surroundings from the courtyard when the sliding doors are fully opened. From the meditation space, looking toward the courtyard, there is a tearoom facing a small indoor garden on the left, and it connects to a wood-toned spa room, which is intended to allow the guests to enjoy teatime and spa time together. This spa room is adjacent to the courtyard like the meditation space, and it is designed to connect it seamlessly with the courtyard when the sliding doors are fully open so that the guests enjoy nature while having spa time. Opposite the spa room, on the right side of the meditation space, a bedroom is located, with a round-shaped oriental window offering a view of both the courtyard and the spa space from the bed.

Process of environment development:Visual stimuli

The overall design development went through two major stages: implementing visual fidelity to the basic structure and applying spatialized sound effects to the visually detailed model. The visual details listed as A-F were added to the basic structure model to improve realism and immersion by enhancing visual fidelity.

A. Realistic material
   and texture
B. Proper lightings
C. Realistic objects
   detailed material and texture
D. Realistic vegetation in
   courtyard and indoor garden
E. Decal pattern layered
   over exterior wall
F. Animated effects such as
   steam from the spa tub

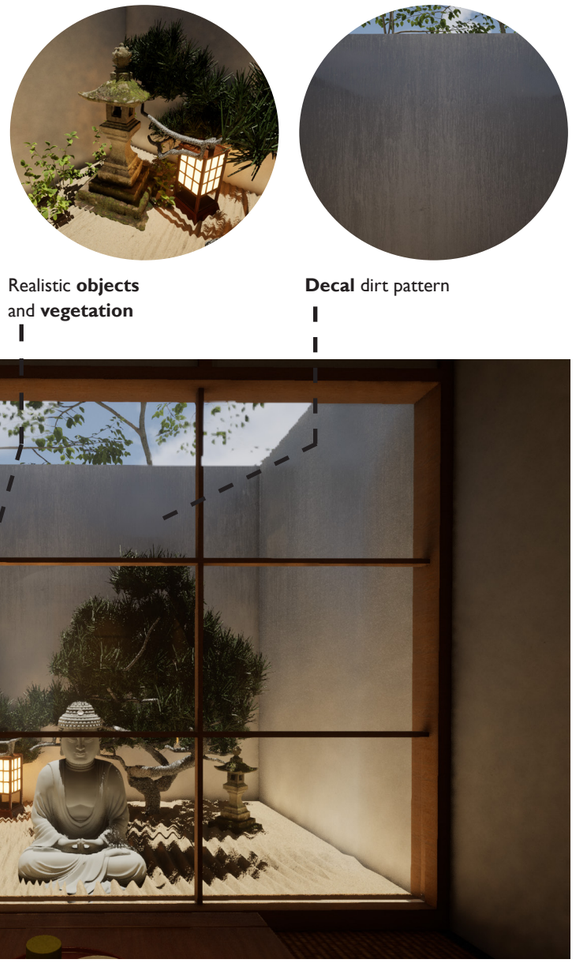


Figure 5.10 *Illustration 1 of detailed visual stimuli in a scene*

Figure 5.11 *Illustration 2 of detailed visual stimuli in a scene*

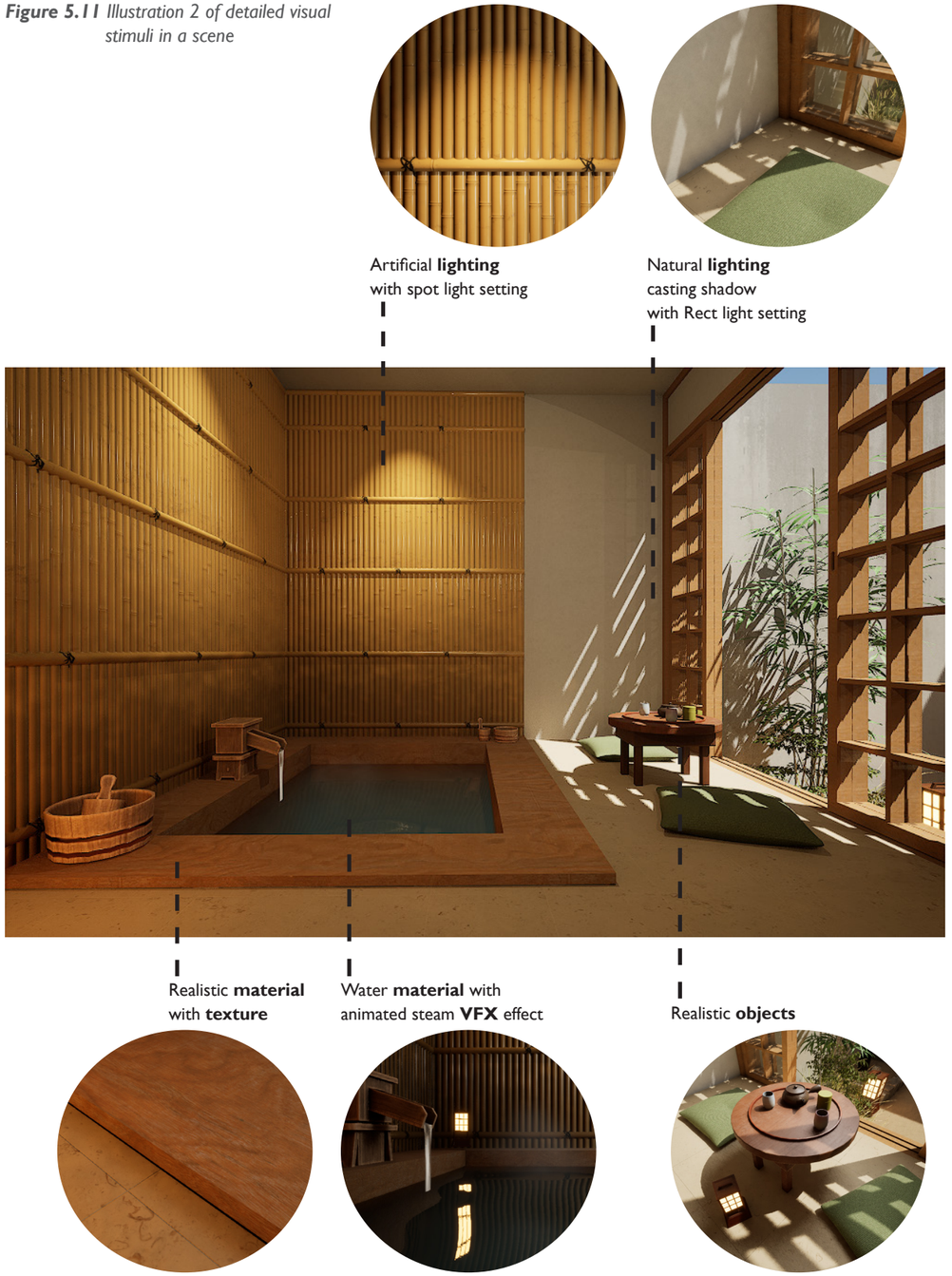


Figure 5.12 *Illustration 3 of detailed visual stimuli in a scene*





Figure 5.13 *Rendered scene 1 with realistic visual stimuli*



Figure 5.14 *Rendered scene 2 with realistic visual stimuli*

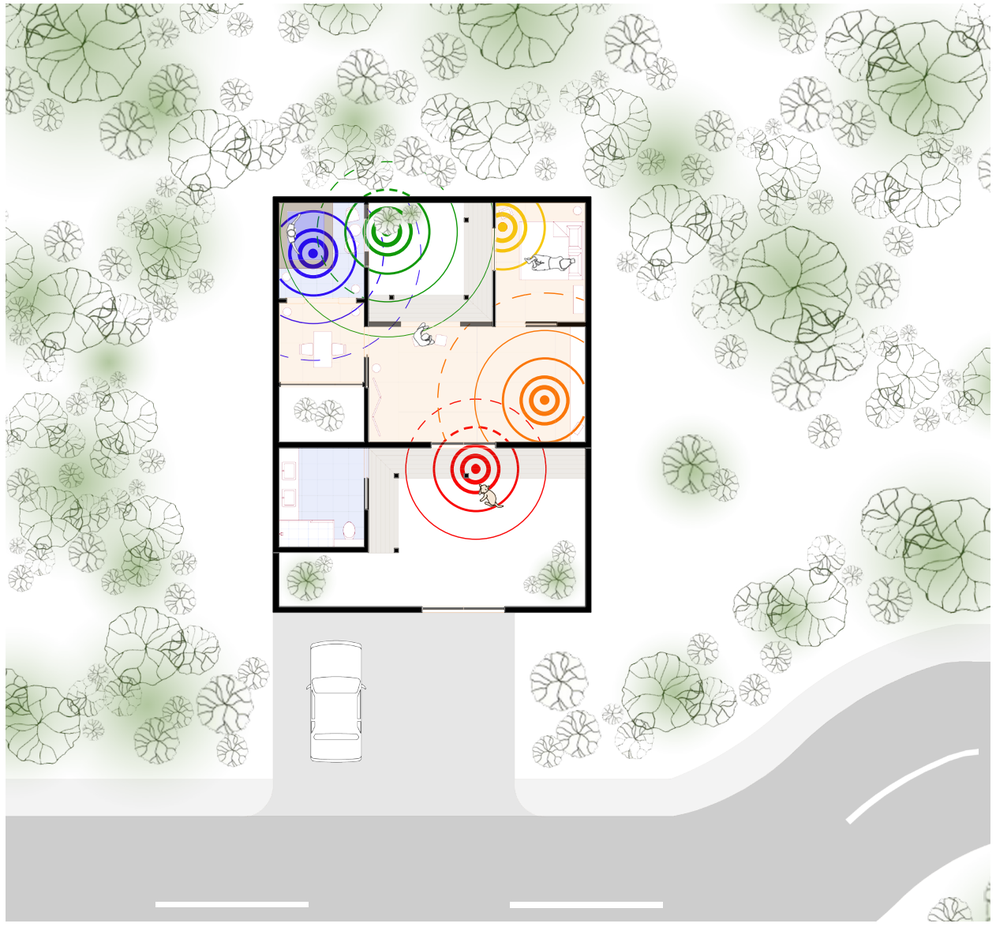
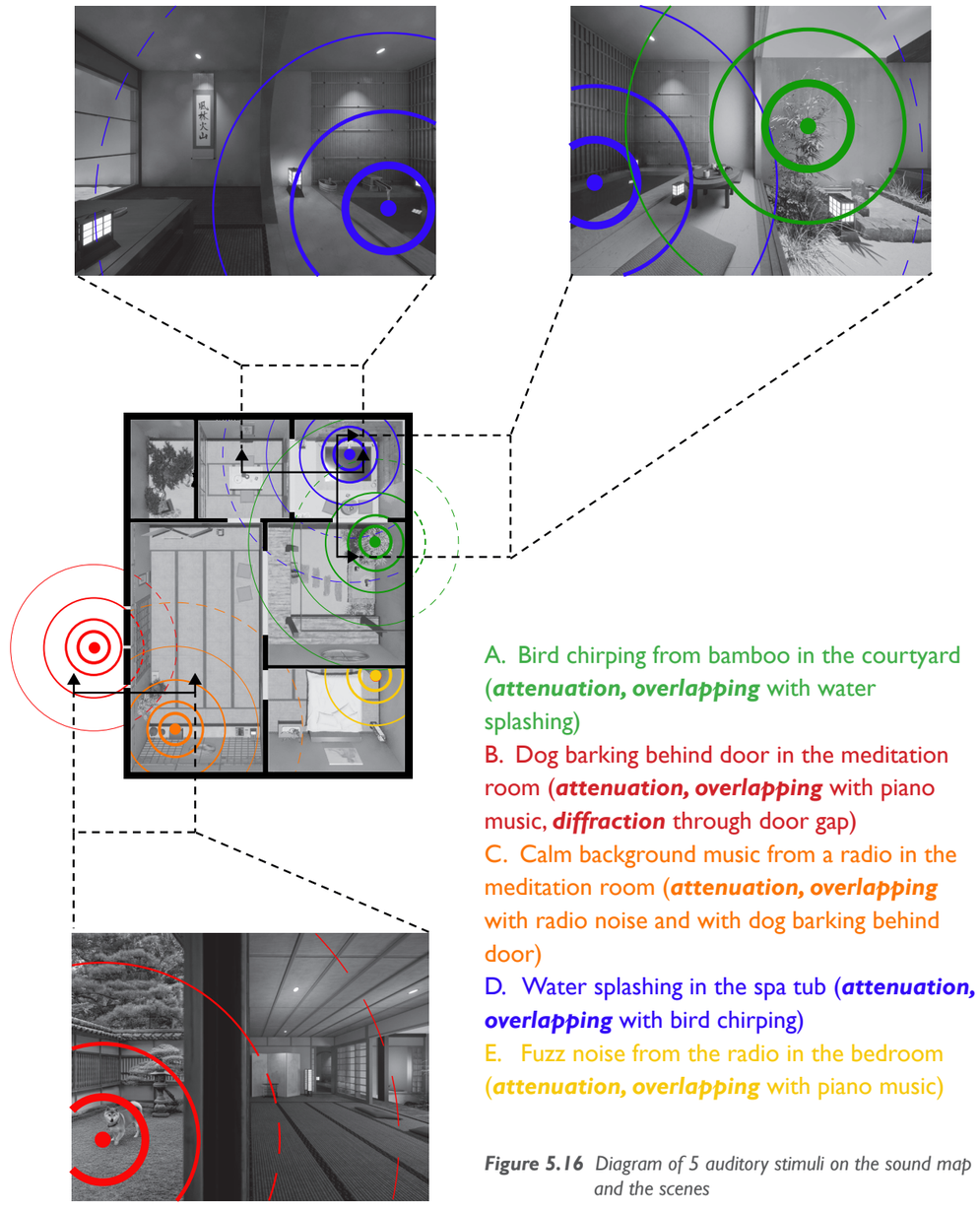


Figure 5.15 *Sound map illustrating 5 auditory stimuli on the site plan*

Process of environment development: Auditory stimuli

In the next stage, spatialized sound effects (A – E), which applied attenuation, overlapping, and diffraction, were placed on specific points in the model in line with the context of detailed visual elements.



A. Bird chirping from bamboo in the courtyard (***attenuation, overlapping*** with water splashing)
B. Dog barking behind door in the meditation room (***attenuation, overlapping*** with piano music, ***diffraction*** through door gap)
C. Calm background music from a radio in the meditation room (***attenuation, overlapping*** with radio noise and with dog barking behind door)
D. Water splashing in the spa tub (***attenuation, overlapping*** with bird chirping)
E. Fuzz noise from the radio in the bedroom (***attenuation, overlapping*** with piano music)

Figure 5.16 *Diagram of 5 auditory stimuli on the sound map and the scenes*

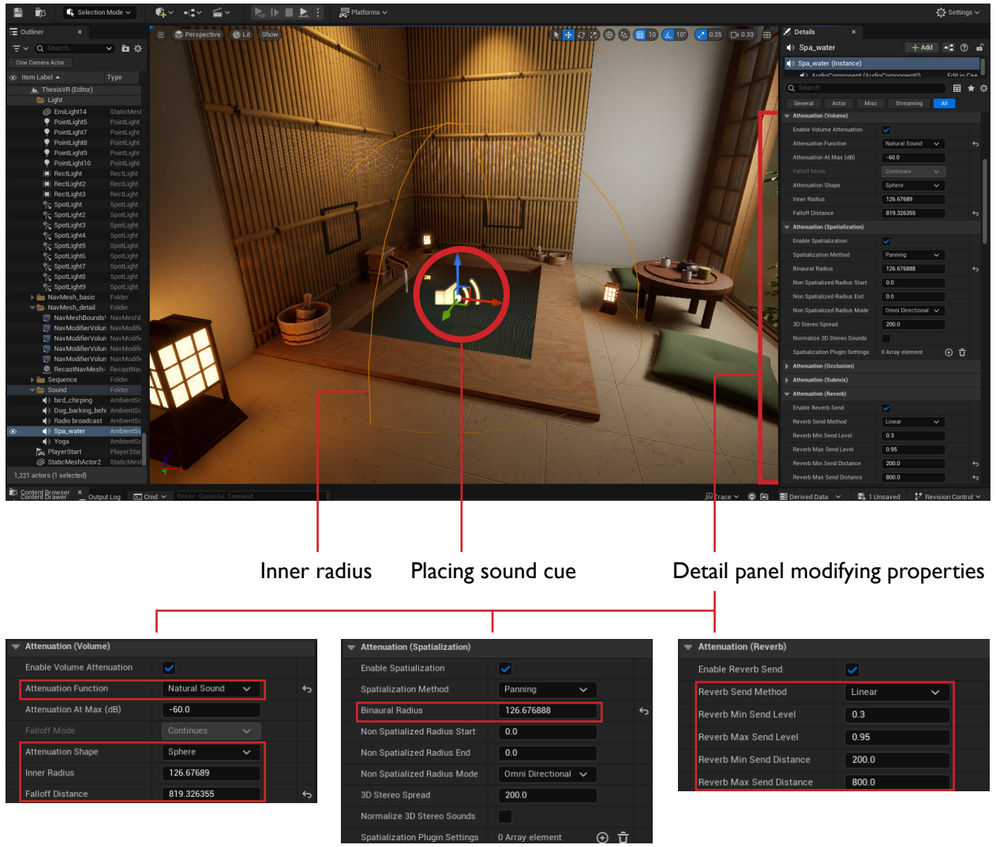


Figure 5.17 *Diagram of spatialized sound setting in Unreal Engine*

In Unreal Engine, the five sound cues were placed at each location and modified on the detail panel. The attenuation function was set as 'Natural sound' to make the sound fade naturally as users move away from the source. To set up the natural attenuation effect, 'Inner radius' (the range at maximum volume) and 'Falloff distance' (the range from Inner radius to a point completely fade out at zero volume) were modified on the detail panel. In addition, spatialization using 'Binaural radius' and 'Reverb' with volume level and distance was also modified to implement more realistic sound effects.

Process of environment development: VR setting

To implement proper VR setting, two actors were set: '***Collision***' and '***Navigation mesh***'. Each physical element, including walls, floors, and doors, was assigned a 'Collision' setting to prevent users from passing through them, while a 'Navigation mesh' was mapped onto the floor to effectively guide users and enable the teleport function in VR mode.

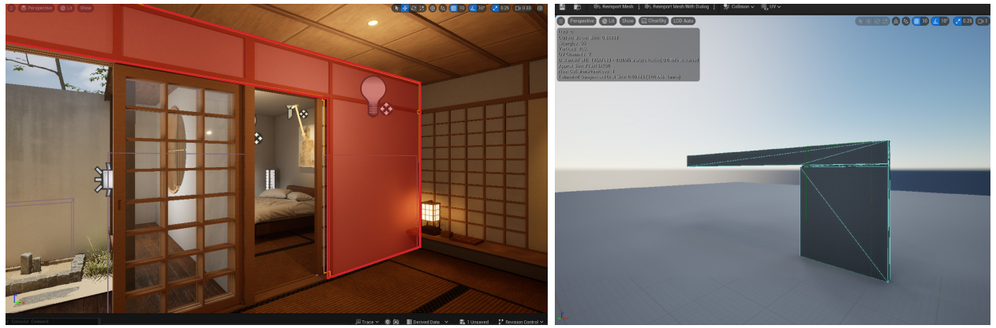


Figure 5.18 *Screenshot of 'Collision' applied to one of the walls in Unreal Engine*

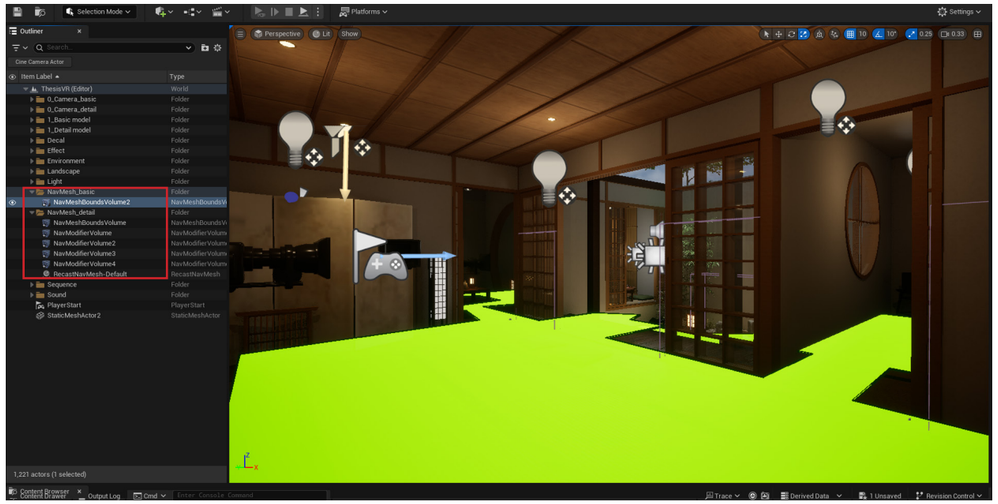


Figure 5.19 *Screenshot of 'Navigation Mesh' applied to the circulation route for teleporting mode in VR through Unreal Engine*

Chapter 6

Experiment Process

6-1. Experiment calibration

Problem identification and correction

In the first phase of the experiment, three participants took part in the experiment. During this phase, an error, in which participants reduced their playtime in the later condition due to learning effects from the previous conditions, was identified. To correct this error, the progress of the experiment was modified.

One of the hypotheses of this experiment was that "the playtime of the participants in each condition would increase in the order A-B-C." The results showed a pattern of increasing playtime in the A-B-C as expected; however, an unexpected pattern was observed: the participants in condition B reduced playtime for exploring layout or visual details that they had already recognized from condition A. This error was due to the learning effect from the previous condition; therefore, an additional step was added to correct it. From the second phase, participants were given a brief explanation with the entire floor plan before exploring each condition.

Results after calibration

A change was observed in the slope of the line graph showing the variation in participants' playtime between conditions A and B. In phase 1, the graph showing the playtime difference between conditions A and B was relatively gentle. However, in phase 2 after the calibration, the slope of the graph becomes steeper, showing a clearer difference in playtime between conditions A and B.

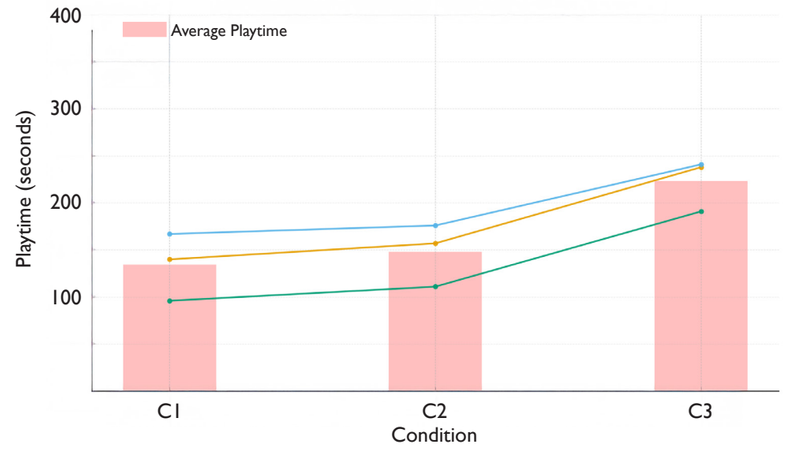


Figure 6.1 *Participant Playtime across conditions (C1–C3) with average bars before calibration of experiment. Note: lines show individual participants (n = 3) and translucent bars show average playtime by condition (n = 3)*

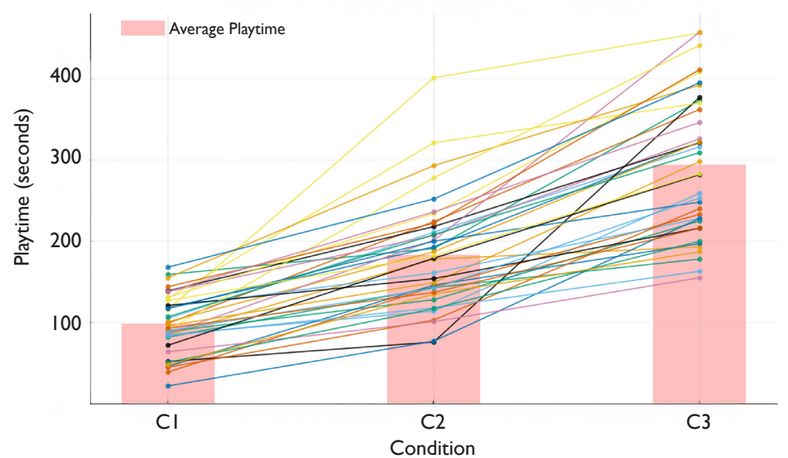


Figure 6.2 *Participant Playtime across conditions (C1–C3) with average bars after calibration of experiment. Note: lines show individual participants (n = 38) and translucent bars show average playtime by condition (n = 3)*

6-2. Spatial experience and survey

Before experience

At the start of the experiment, participants filled out a screening questionnaire and consent form, and they were informed of the precautions and possible side effects beforehand. All the processes followed the guidance of Ethics Clearance (#47603) by the University of Waterloo. Thereafter, they had a brief explanation, including the layout of the environment and the overall process of the experiment.

During experience

Each participant engaged in a single experimental session for approximately 5 to 15 minutes, and each session allowed them to experience three conditions of the same architectural environment in a fixed sequence, which is designed to progressively increase immersion complexity and to keep the contrast in the extent of immersion between each condition. While participants were free to explore each condition at their pace, the investigator didn't limit the time but observed and recorded the duration of playtime in each session manually using a stopwatch to assess whether increased sensory input influenced voluntary engagement time.

The sequence began with a screen-based condition on a PC and then moved onto an immersive VR condition with visual effects. Lastly, it is explored within a VR condition that applies both visual and spatialized auditory effects.

In the first condition, participants navigated the 3D architectural environment using a keyboard and mouse on a 2D laptop screen. In the second condition, they experienced the same environment using a head-mounted VR device (Meta Quest3), which allowed them to have immersive interaction with the environment applying only visual cues. Lastly, they experienced the third condition, built upon the second condition, by adding spatialized sound effects synchronized with specific visual elements such as water flowing in a spa tub, birds chirping in a yard, and a dog barking behind a door.



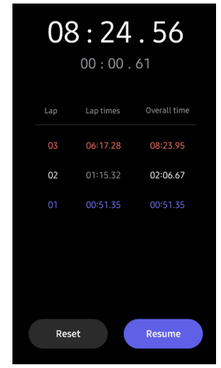


Figure 6.3 *Screenshot of time record during experiment*

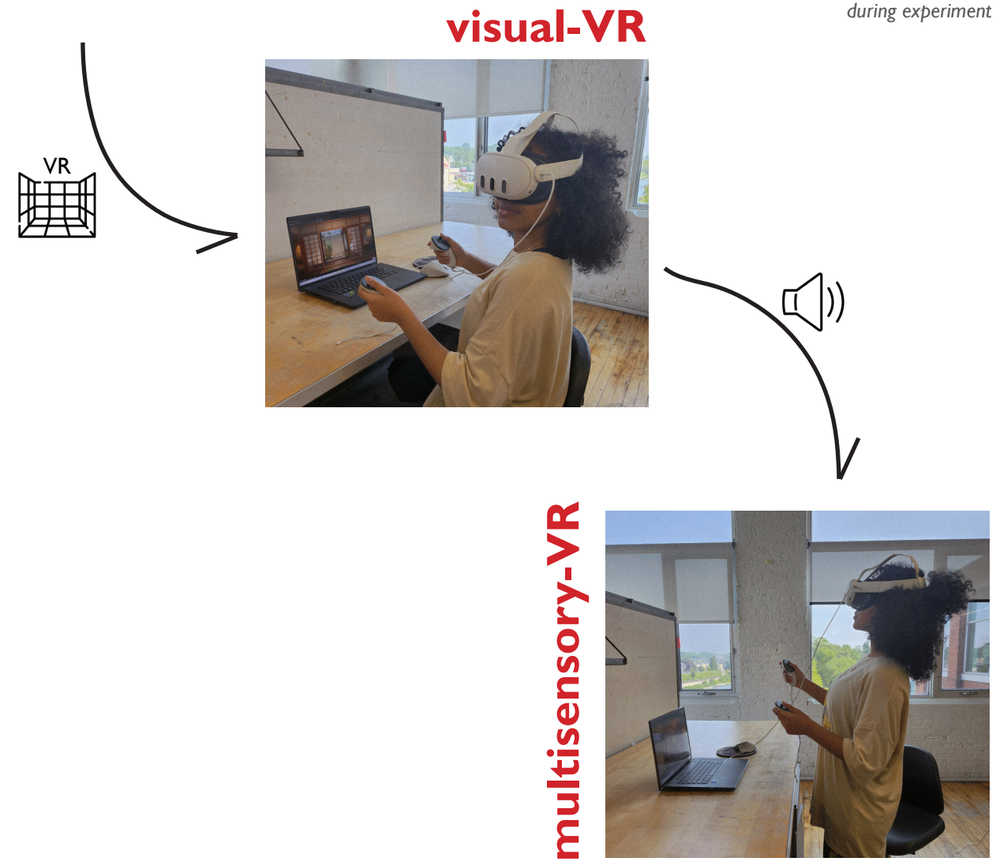


Figure 6.4 *Diagram showing participant experiencing each condition : non-VR > visual-VR > multisensory-VR*

After experience; Survey

After exploring all three conditions, participants were asked to fill out a survey. The questionnaire included a standardized immersion level in a numeric scale (from 1 to 7) for each condition and an open-ended section to obtain qualitative impressions and feedback. This combined approach was intended to have both quantitative comparisons of immersion levels and analysis of subjective experience.

VR Immersion Experience Survey

Participant ID: _____
Date: _____

Section 1: Demographic Information

1. What is your age?
   ___ years old

Section 2: Immersion Questionnaire

(To be completed after experiencing all 3 versions)

Instructions: Please rate your level of immersion, realism, and emotional engagement for each version of the VR environment you experienced.

VR Version	Description
Version 1	3D model with visual effects on laptop (keyboard + mouse)
Version 2	Same space in VR with visual effects
Version 3	Same VR space with additional spatialized sound effects

---

1. Immersion Rating

VR Version 1 2 3 4 5 6 7 (Not immersed '1' – Completely immersed '7')

Version 1 ☐☐☐☐☐☐☐

Version 2 ☐☐☐☐☐☐☐

Version 3 ☐☐☐☐☐☐☐

Figure 6.5 *Survey form page1*

2. Realism Rating

VR Version 1 2 3 4 5 6 7 (Not realistic '1' – Extremely realistic '7')

Version 1 ☐☐☐☐☐☐☐

Version 2 ☐☐☐☐☐☐☐

Version 3 ☐☐☐☐☐☐☐

3. Emotional Engagement Rating (Not engaged '1' – Extremely engaged '7')

VR Version 1 2 3 4 5 6 7

Version 1 ☐☐☐☐☐☐☐

Version 2 ☐☐☐☐☐☐☐

Version 3 ☐☐☐☐☐☐☐

Section 3: Open-ended Feedback

4. **Which version of the VR environment did you find the most immersive?**
   ☐ Version 1 – 3D model (laptop)
   ☐ Version 2 – VR (visual only)
   ☐ Version 3 – VR (visual + sound)

5. **In your own words, what differences did you notice in your sense of immersion between the three versions (optional)?**

6. **Do you have any additional comments or feedback about your experience with the VR environments (optional)?**

Figure 6.6 *Survey form page2*

Chapter 7

Experiment Results

7-1. Overview of data collection

The data was collected from 38 participants who experienced all three conditions of a single architectural space in a specific order: Condition 1 (PC-based exploration), Condition 2 (VR with visual stimuli only), and Condition 3 (VR with both visual and auditory stimuli). The way of collecting data in this experiment referred to and followed standard practices for VR research, combining time measurements with rating scales to understand both how long participants spent exploring voluntarily and how they felt about each experience.[95] To elaborate further, this research used a mixed approach that combines objective measurements, such as the length of time that participants spent exploring, with subjective feedback, such as rating scales.

This combined measurement provides a comprehensive understanding of user engagement. Participants were asked to answer on 7-point scales to rate their sense of immersion, sense of realism, and their emotional engagement with each condition. This measurement using 7-point scales aimed to quantify participants' subjective feelings with objective numbers. In addition, each participant was guided to experience all three conditions in a fixed order; therefore, fair comparisons were achieved by controlling the individual differences in technological experience or spatial skills. For example, one participant responded 1-3-6 for each of the three conditions, while another participant responded 2-4-7. Although the quantitative values differ between the two participants' responses, when plotted on a single graph, they ultimately show trend lines with the same slope.

All participants were between 18 and 35 years old with an average age of 23.5 years, representing a range of technological familiarity levels. For example, younger generations who are more familiar with PC games tend to grasp navigation methods quickly in Condition 1 (PC-based exploration), resulting in somewhat reduced playtime. Among the seven participants who completed playing Condition 1 within one minute, five were in their early twenties or younger.

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95 Sara V, et al. "A Survey of Challenges and Methods for Quality of Experience Assessment of Interactive VR Applications"

7-2. Playtime analysis

Key findings

The playtime participants spent exploring each condition showed a clear and substantial tendency to increase as more stimuli were added, condition by condition. Based on the data from all 38 participants:

- Condition 1 (PC): average of 1.64 minutes (98.7 seconds)
- Condition 2 (visual-VR): average of 3.05 minutes (183.2 seconds)
- Condition 3 (multisensory-VR): average of 4.91 minutes (294.4 seconds)

The increased playtime between conditions were substantial:

- Condition 1 (PC) to Condition 2 (visual-VR): 84.5 seconds increase in exploration time.
- Condition 2 (visual-VR) to Condition 3 (multisensory-VR): 111.2 seconds additional increase.
- Condition 1 (PC) to Condition 3 (multisensory-VR): 195.7 seconds total increase.

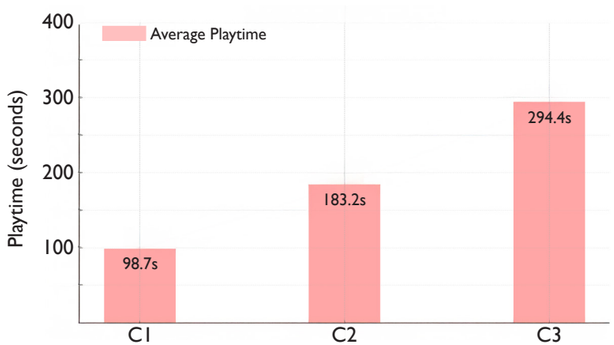


Figure 7.1 *Average playtime across conditions (n = 38)*

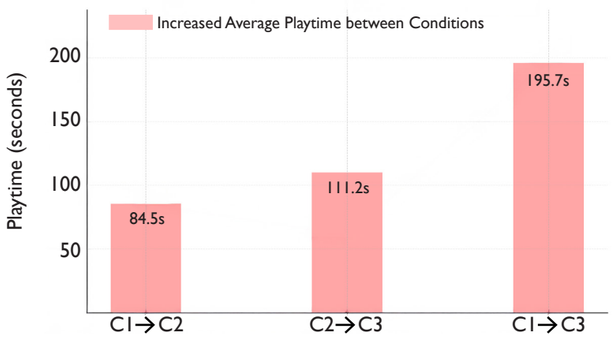


Figure 7.2 *Increased average playtime between conditions (n = 38)*

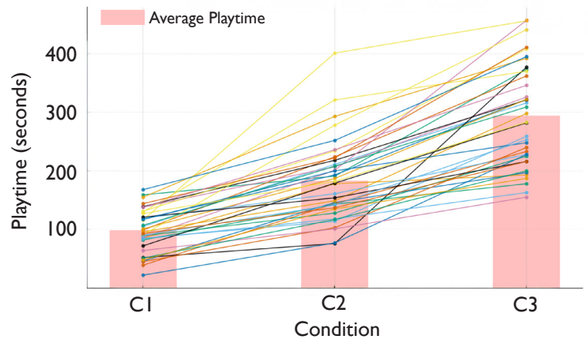


Figure 7.3 *Participant Playtime across conditions (C1–C3) with average bars. (repeat of* ***Figure 6.2****)*

Interpretation of these results

These data showing a dramatic increase in playtime are meaningful since voluntary exploration time represents a reliable indicator of users' engagement in the VR experiment. Studies demonstrate that people naturally spend more time exploring VR environments when they locate the experience more engaging or interesting.[96] The progressive increases across all three conditions suggest that each technological and stimulative enhancement, which is from flat screen to VR headset with spatialized sound, made the experience more compelling for participants. To explain in more detail, visual stimuli is increased from Condition 1 (PC) to Condition 2(visual-VR) and auditory stimuli is enhanced from Condition 2 (visual-VR) to Condition 3 (multisensory-VR). As evidence of this, some participants responded that they could notice the wall patterns or wood-frame textures in Condition 2, whereas they didn't recognize them in Condition 1, and other participants reported that the audio effect such as water splashing in the spa room guided them to navigate themselves to the point of the sound source even when the spa room was visually obstructed.

The relatively short playtime (under 5 minutes even for the highest engagement condition) is normal for architectural VR studies. Studies found that brief exploration sessions help capture meaningful behavioral differences while preventing people from participant fatigue.[97] The substantial percentage increases within these timeframes (4 minutes and 54 seconds of average playtime in Condition 3) show that the technological and stimulative enhancements had measurable effects on how participants engaged in the architectural space.

96 *Daniel Paes, et al. "Investigating the Relationship Between Three-Dimensional Perception and Presence in Virtual Reality–Reconstructed Architecture"*

97 *"Comparing the Effects of Immersive and Non Immersive Real Estate Experience on Behavioral Intentions"*

7-3. The role of spatial sound in participants' experience

"When I moved away from the spa the water sound faded naturally,
so it made the room feel deeper and gave me a better sense of space."

- Participant #13 -

How sound enhances spatial understanding

The significant increase (111.2s more playtime on exploration) from Condition 2 (visual-VR) to Condition 3 (multisensory-VR) proves the powerful effect of adding spatial sound to architectural VR experiences. The architectural environments in the real world are never silent, and sound provides important cues that help people understand distance, scale, and atmosphere while visual elements alone cannot achieve.

Particularly, three specific properties of sound had significant impacts on how participants experienced the virtual architectural space: attenuation, overlap, and diffraction.

According to the participants' responses, they could have more sense of spatial depth and scale with fading sound (attenuation) as they moved away from a point of auditorial source and were helped to understand the spatial relationships between different areas by changing volume and direction from layered sounds (overlap). They could also perceive spaces and activities that were visually obstructed, such as a dog barking behind closed doors, which helped them navigate the environment despite the visual limitations.

From these spatial sound effects, participants had a better sense of space and a mental map of the space[98] so that they could understand the environment comprehensively.

98 *Sabah Boustila, et al.*
"Evaluation of Factors Affecting Distance Perception in Architectural Project Review in Immersive Virtual Environments"

"The layered sounds changed in volume and direction
as I moved around. It helped me figure out the layout of the space."

- Participant #5 -

Impact on Participant Responses

The results of implementing these spatial sound properties in Condition 3 indicated a significant measurable change in participants' behaviors. The 111.2s increase in exploration time from Condition 2 to Condition 3 suggests that spatial sound made participants more curious about different areas in the virtual environment and more motivated to explore thoroughly. Studies on multisensory VR show that well-designed spatial audio that enhances the primary experience increases both voluntary exploration and physiological engagement.[99]

The consistent increases observed across all participants indicate that the auditory stimuli successfully enhanced them to have a comprehensive understanding and experience in the environment rather than overwhelming or confusing them. This validates the design decisions for integrating and applying sounds within the virtual environment, and this finding supports the hypothesis that spatialized sound provides meaningful improvements in architectural VR contexts.

99 *Takara E. Truong, et al.*
"Evaluating the Effect of Multi Sensory Stimulation on Startle Response Using the Virtual Reality Locomotion Interface "

7-4. Analysis on rating scale of participants' perceptions

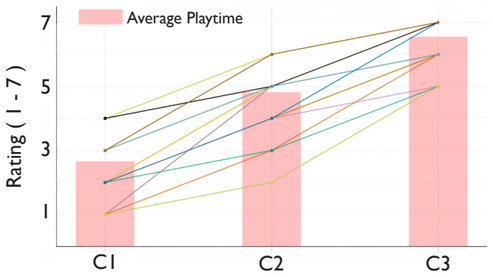


Figure 7.4 *Immersion rating across conditions (n = 38)*

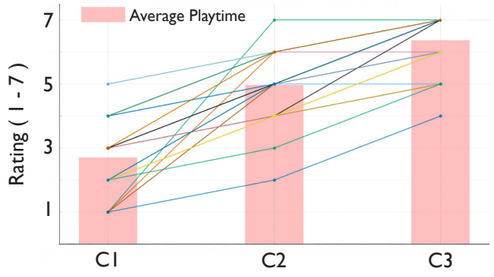


Figure 7.5 *Realism rating across conditions (n = 38)*

Ratings on immersion, realism, and emotional engagement

In addition to measuring exploration time, participants were asked to rate each condition on three key aspects using 7-point scales (1 = very low and 7 = very high):

- *Immersion*: How much they felt 'inside' the virtual space
- *Realism*: How realistic the space appeared and felt
- *Emotional Engagement*: How emotionally connected they felt to the experience

The rating patterns closely matched the playtime results and showed progressive increases across all three measures as sensory stimuli were enhanced. Condition 1 (PC) received the lowest ratings across all three categories, Condition 2 (visual-VR) showed substantial improvements, and Condition 3 (multisensory-VR) achieved the highest ratings in all areas.

Correlation between time and ratings

The strong relationship between playtime and participants' ratings was observed; therefore, this finding provides validation for both measures. When participants rated their experiences as more immersive, realistic, and emotionally engaging, they also spent more time exploring the environment. This correlation supports the interpretation in other studies, which demonstrate that increased exploration time reflects genuine engagement rather than confusion or difficulty navigating the virtual environment.[100]

100 *Jacob M. H, et al.*
"Audio's Impact on Immersive Experience in Extended Reality and Digital Games: A Systematic Review"

7-5. Statistical significance and reliability

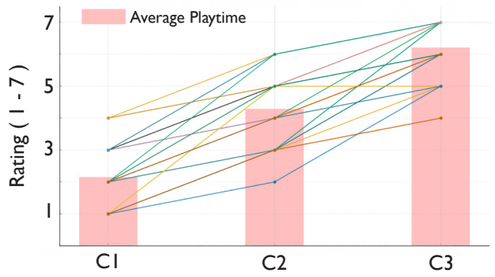


Figure 7.6 *Emotional engagement rating across conditions (n = 38)*

Confirming the results

Statistical analysis in this experiment confirmed that the differences between conditions did not occur by chance. The progressive increases in both playtime and ratings were observed consistently across participants and show that enhancing the sensory stimuli, particularly spatial sound, reliably improved the participants' experiences. The magnitude of differences between conditions suggests that these improvements would be practical in the architectural field.

Methodology strengths

The calibration procedure done in experiment phase 1 helped address potential learning effects and ensured that improvements in the later conditions reflected sensory stimuli enhancements rather than increased familiarity between conditions.

The experimental design, in which each participant experienced all three versions, provided proper control for individual differences in technological experience and spatial skills, minimizing other parameters as much as possible.

Results

Discussion

Current limitation of visual-only approaches

The results of the experiment highlight a limitation in contemporary architectural VR implementation. While the precedents examined in Chapter 2 demonstrate successful applications of VR technology across various types of projects and scales, architects consistently tend to focus on visual presentation for better delivering their design intent.[101] The quantitative findings of the experiment show that this approach is effective but also represent only partial utilization of the potential of VR technology for enhancing spatial understanding and users' engagement.

The 84.5s increase from Condition 1 (PC-based) to Condition 2 (visual-only VR) proves why the current architectural industry focuses on immersive visualization in VR. However, the additional 111.2s increase from Condition 2 (visual-only VR) to Condition 3 (multisensory VR) shows that the limited implementations of visual-only experiences are missing significant opportunities that are achievable with the implementation of auditory effects.

101 Nikitha Sunil, "How AR and VR Are Transforming Client Experience in Architecture"

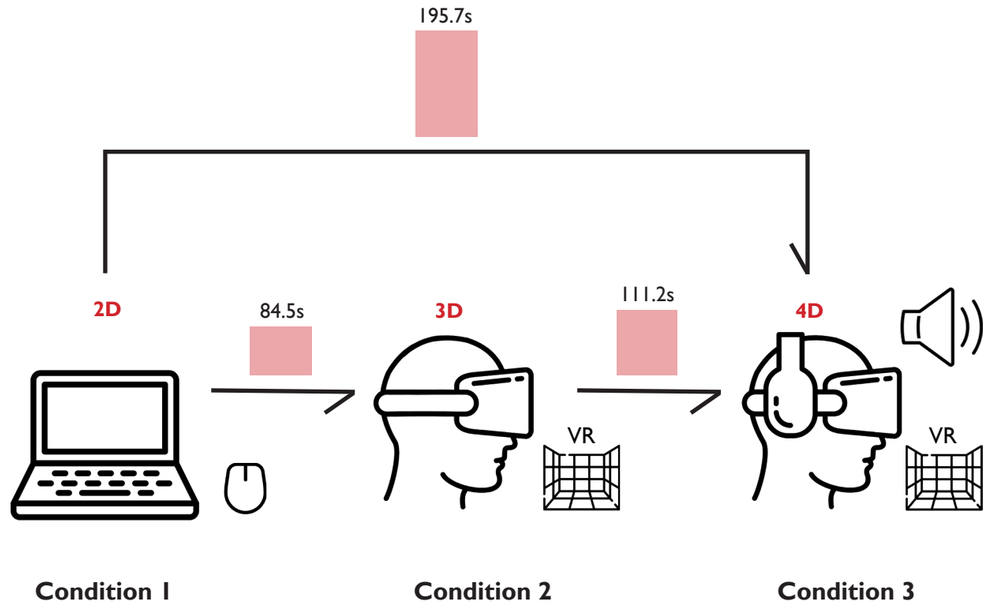


Figure 8.1 *Diagram showing increase rate of voluntary playtime between conditions*

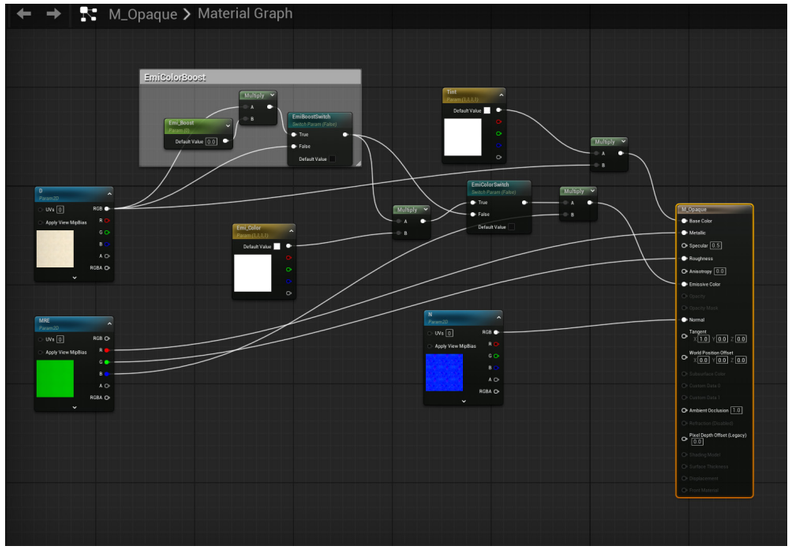


Figure 8.2 *Screenshot of material blueprint in Unreal Engine*

Implication

1. Implication for architectural VR design

The substantial increase in voluntary engagement observed during the participants' playtime supports the theoretical foundation established in PART 2 regarding multisensory implementation in spatial cognition. The 111.2s increase in the average playtime between Condition 2 (visual-only VR) and Condition 3 (multisensory VR) illustrates that the auditory effects provide immediate and measurable advantages beyond visual-only effects in VR.

The behavioral data supports the cognitive research indicating that spatial audio provides crucial cues that enhance users' ability to navigate and understand architectural environments.[102] The consistent and progressive increases observed in all participants demonstrate that the successful implementation of auditory cues validated the design approach for integrating sound within virtual environments.

102 *Takara E. Truong, et al. "Evaluating the Effect of Multi Sensory Stimulation on Startle Response Using the Virtual Reality Locomotion Interface"*

2. Practical applications and industry implications

These findings have important implications for the strategies in architectural practice and VR implementation. The significant improvements in participants' engagement suggest that the investment in multisensory VR capabilities may help architectural firms to achieve better client communication and more compelling presentations compared to visual-only approaches. Despite these significant advantages, current VR representations in the architecture industry do not fully utilize VR and auditory effects, which appears to be due to the steep learning curves and technical knowledge barriers of VR software. In particular, game engines like Unreal Engine and Unity, which enable architects to build VR environments, are complex and have many parameters, creating a barrier for beginners and requiring programming knowledge in languages such as C++ or C# for advanced use. However, software like Unreal Engine provides alternative systems such as Blueprint to help beginners and non-professionals in coding.[103] Once architects learn and become familiar with the software, only a small further step is required to control audio functionality in it; therefore, this paper strongly encourages architects to try to learn the technologies without hesitation.

The results of this paper indicate that architectural VR implementations should consider auditory cues not as an optional enhancement but as an essential component for a better VR experience. The overall improvement in the participants' playtime and scale rating from traditional PC-based presentations to multisensory VR presentations represents a significant opportunity for successful architectural representations.

103 *Oliver Carson, "Comparing Popular Game Engines"*

Limitation

The limitations identified in this study are affected by the current technical constraints of VR technologies.

First, the sensory implementation in the experiment was limited only to visual and auditory cues but excluded other sensory cues, such as tactile, olfactory, and thermal, that could enhance further comprehensive understanding in VR environments. This limitation arises from the technical constraints of current commercial VR devices, which can only provide visual and auditory output through screens and speakers. Although current VR technology has this challenge in comprehensive multisensory implementation, this study suggests further potential for more complete sensory VR representations applying not only visual and auditory cues but also other sensory modalities such as tactile, olfactory, and thermal.

Second, the auditory implementation in VR environments was constrained by the technical limitations of current VR software such as Unreal Engine and Unity, particularly regarding acoustic perception in material reflection details or geometric complexity. While current VR software provides functions for implementing direct sound, it is still limited in its ability to reproduce sophisticated acoustic phenomena, such as sound reflection and absorption on various architectural materials or the diffusion of sound on complex geometric surfaces.[104] These constraints may have caused less comprehensive implementations of more realistic auditory output in VR environments.

104 *"Acoustic Virtual Reality – Methods and Challenges"*

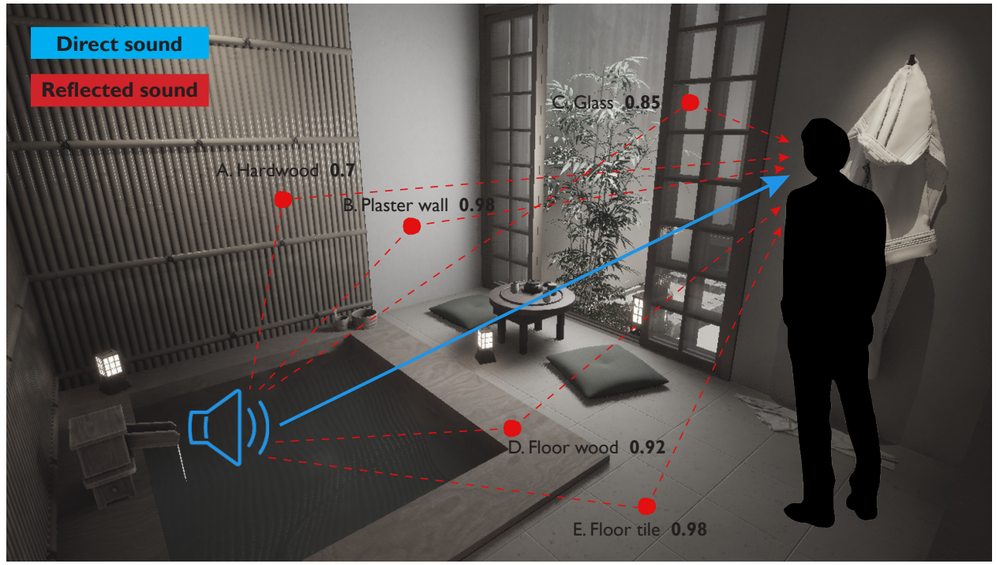


Figure 8.3 *Illustration of sound reflection rate by materials in a scene*

Material	Sound Absorption Coefficient [1] - α -
Acoustic belt, 12 mm	0.5
Acoustic tiles	0.4 - 0.8
Asbestos, sprayed 25 mm	0.6 - 0.7
Brickwork, painted	0.01 - 0.02
Brickwork, unpainted	0.02 - 0.05
Carpet, heavy on concrete	0.3 - 0.6
Carpe, heavy on foam rubber	0.5 - 0.7
Concrete block, coarse	0.3 - 0.4
Concrete block, painted	0.05 - 0.07
Cork sheet, 6 mm	0.1 - 0.2
Fiberboard on battens, 12 mm	0.3 - 0.4
Floor, concrete or terrazzo	0.02
Floor, linoleum, asphalt, rubber or cork tiles on concrete	0.03
Floor, wood	0.06 - 0.1
Hardwood	0.3
Glass, large panes heavy plate	0.03 - 0.05
Glass, ordinary windows	0.1 - 0.2
Gypsum board, 12 mm	0.04 - 0.07
Mineral wool, 100 mm	0.65
Persons, each	0.2 - 0.5
Plaster walls	0.01 - 0.03
Plywood panel, 3 mm	0.01 - 0.02
Polystyrene, expanded on 50mm battens	0.35
Polystyrene, expanded rigid backing	0.15
Polyurethane foam, flexible	0.95
Rubber sheet, 6 mm porous	0.1 - 0.2
Slag wool or glass silk, 50 mm	0.8 - 0.9
Snow	0.75
Wood wool cement on battens, 25 mm	0.6 - 0.07

Sound Absorption Coefficient rate = 1 - Reflection rate

E. Floor tile **0.98**

D. Floor wood **0.92**
A. Hardwood **0.7**

C. Glass **0.85**

B. Plaster wall **0.98**

Figure 8.4 *Table of sound absorption coefficient rate by selected materials*

Outlook

This study's implications and limitations suggest several potential directions for future research in architectural VR. First, future studies could observe even greater improvements in more advanced VR technologies including devices and platforms that incorporate integrated sensory cues beyond just visual and auditory ones. Second, further studies investigating how to implement more detailed acoustic effects by applying material reflection or geometric complexity in advanced VR software could enable architects to build more sophisticated VR environments. Lastly, future studies examining the deeper impact of multisensory VR on specific users' responses such as spatial navigation, perception of scale and distance, and design evaluation could provide more solid evidence for architects looking for practical benefits.

Future studies should broaden the experimental context beyond a single pavilion to include a range of more typical architectural spaces so the impact of auditory cues on spatial perception can be evaluated across varied conditions. A revised study could compare spatial conditions that differ in scale (small rooms and double-height halls), enclosure (open court and corridors), and material diversity (hard, reflective finishes and soft, absorptive ones). By the experiment with this broadened context, researchers could figure out how specific auditory properties, such as attenuation, overlapping sound layers, and diffraction around partitions, interact with geometric and material variables to affect presence, depth perception, wayfinding confidence, and memory for layout. This sort of further detailed research is expected to influence more generalizable practice in the architectural field.

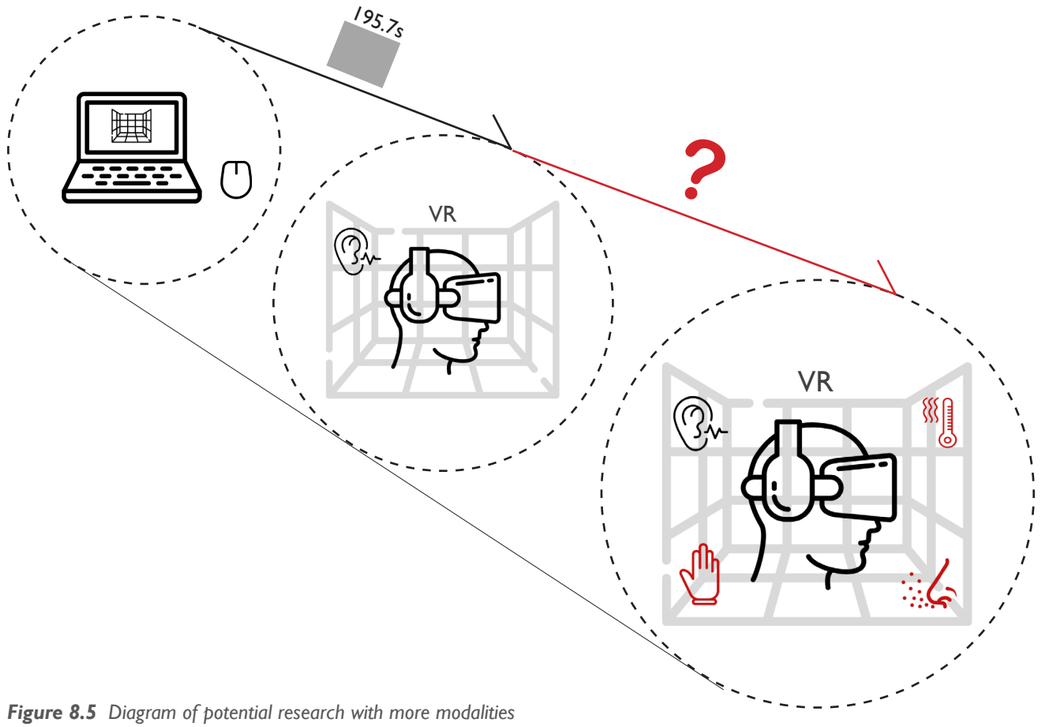


Figure 8.5 *Diagram of potential research with more modalities*

Conclusion

In the experiment, a single C-shaped vacation villa with a courtyard, tearoom, and spa room was selected as the VR environmental design. It was chosen for its simplicity, to clearly isolate and demonstrate the perceived benefit of adding audio to the VR environment. Five distinct auditory cues were placed at different locations in the environment, and these auditory stimuli created spatialized auditory effects, such as attenuation with distance, overlapping from simultaneous sources, and diffraction through door gaps and around openings, providing the participants a better sense of space and scale, spatial relationships, and an increased sense of immersion and voluntary engagement.

The results from the experiment provide strong evidence that multisensory cues applying both visual and auditory effects significantly enhance users' engagement in architectural VR environments. The dramatic improvement in voluntary exploration time from traditional PC-based presentation to multisensory VR presentation demonstrates significant potential for enhancing effective design communication achieved by multisensory VR environments.

These findings have an important message that the current architectural industry focuses primarily on visual VR presentation and underutilizes the full potential of VR technologies that attract more engagement and spatial understanding from clients and stakeholders. This study supports both theoretical evidence emphasizing the importance of multisensory cues in spatial cognition and practical evidence for the value of incorporating auditory properties in architectural VR presentations.

The current applications of VR in the architecture industry are primarily limited to selling features to convince clients. Instead of being utilized in the early design stages, VR is employed in the final stages to create a more realistic design. From this perspective, VR applications in architectural projects remain an 'extra' rather than an 'essential' task. Therefore, it may take some time before it becomes widely utilized in the architectural field, considering the limitations in project cost and available technicians.

The shift from visual-only VR to multisensory VR that applies auditory cues in architectural representations resembles the historical shift from silent films to sound films: once audio was introduced in films, it rapidly became mainstream for storytelling and audience engagement.[105] In a similar way, architectural VR representations utilizing auditory cues can also move from novelty to norm, becoming a familiar and expected method of presentation for both architects and clients.

However, a technical limitation was identified during the experiment: these software are limited in their ability to incorporate accurate acoustic properties for materials, while they readily provide preset visual parameters, such as surface reflection and lighting, for materials and textures.

Although this study's scope is limited by current technical and methodological constraints, the results establish a solid foundation for further research investigating comprehensive approaches in multisensory VR representations. The observed improvement in the experiment and the objective data in numeric figures prove that multisensory VR representations are promising for enhancing architectural practice and client communications in the emerging virtual age.

105 *Kylie N. Groot, "From Silence to Sound: Causes and Effects of the Talkies"*

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Appendices : Survey data

Participants #	Age	Playtime (minutes : seconds)			Immersion			Realism			Emotional Engagement			Most immersive version
		Condition 1 (non-VR)	Condition 2 (visual-VR)	Condition 3 (multisensory-VR)	C1	C2	C3	C1	C2	C3	C1	C2	C3	
1	30	1:25	2:58	3:13	4	6	7	4	6	7	2	3	5	V3
2	22	1:45	3:31	5:16	4	5	7	4	5	6	4	5	6	V3
3	28	2:39	3:11	6:13	1	5	7	1	7	7	3	6	7	V3
4	23	1:56	6:41	7:36	4	5	7	5	6	7	2	4	7	V3
5	29	1:58	3:13	5:22	2	5	7	1	5	7	1	3	6	V3
6	27	1:39	3:44	6:02	3	6	7	2	5	7	1	3	4	V3
7	26	2:18	3:27	5:26	1	5	7	2	5	7	1	3	7	V3
8	37	2:19	3:38	5:21	3	5	6	4	6	7	3	5	6	V3
9	20	1:41	3:07	5:22	4	6	7	4	6	7	4	6	7	V3
10	19	1:25	1:54	4:19	4	6	7	4	5	6	4	5	7	V3
11	20	1:29	2:08	3:45	3	5	7	2	5	7	3	4	7	V3
12	26	2:11	3:54	6:48	4	6	7	3	6	7	3	6	7	V3
13	22	0:46	2:26	3:17	2	5	6	4	5	6	2	4	6	V3
14	26	0:39	2:24	3:53	3	5	6	1	5	6	1	5	7	V3
15	20	1:26	3:21	7:37	3	5	7	4	6	6	4	5	7	V3
16	28	0:52	1:16	6:17	2	4	6	2	4	6	1	3	6	V3
17	22	1:36	2:29	4:58	2	5	7	2	5	7	2	5	7	V3
18	23	1:59	2:41	3:48	2	4	7	3	5	5	1	3	7	V3
19	23	1:22	2:23	2:58	3	5	7	3	5	7	1	3	7	V3
20	24	2:10	5:21	6:10	3	5	7	2	5	7	2	3	6	V3
21	20	0:22	1:17	3:48	3	5	6	3	4	5	2	3	6	V3
22	20	0:45	1:43	4:00	2	5	7	1	6	7	1	5	7	V3
23	20	1:04	1:41	2:35	3	5	7	3	5	6	3	4	6	V3
24	20	2:01	2:34	3:36	4	5	7	3	4	7	3	6	7	V3
25	22	2:35	4:53	6:32	3	5	6	3	4	5	4	5	5	V3
26	21	1:24	1:58	2:43	3	6	7	5	6	7	3	6	7	V3
27	21	0:51	1:57	3:20	3	6	7	4	6	7	2	6	7	V3
28	19	1:31	4:38	7:21	2	5	7	2	4	6	1	5	7	V3
29	26	1:57	3:20	4:08	1	2	5	1	2	4	1	2	5	V3
30	20	2:24	3:42	6:51	1	3	6	2	5	6	1	3	4	V3
31	21	2:18	3:56	5:46	2	4	5	3	4	6	2	5	7	V3
32	24	1:12	2:59	4:42	4	5	7	3	5	7	2	4	6	V3
33	19	0:48	2:15	3:07	2	4	6	2	4	6	2	4	6	V3
34	20	1:30	2:22	4:13	3	5	6	2	5	6	2	4	5	V3
35	20	1:47	3:28	5:09	2	3	5	2	3	5	2	5	6	V3
36	24	2:07	3:02	4:43	1	2	5	2	4	6	2	4	5	V3
37	34	2:48	4:12	6:35	2	4	7	2	5	7	2	4	5	V3
38	26	1:33	2:17	3:36	3	6	7	3	6	7	2	4	6	V3
Average	23.5	1:38	3:03	4:54	2.3158	4.2632	5.8158	2.3421	4.3421	5.6579	1.8684	3.8158	5.5526	100% V3