Virtually Handcrafted

An Investigation of Immersive Architectural Design Processes

by

Daniel Innes

A 120-point thesis submitted to the Victoria University of Wellington
in partial fulfilment of the requirements for the
degree of Master of Architecture (Professional)

Victoria University of Wellington
School of Architecture

2018

acknowledgements

Many thanks to my parents for their relentless support,
to my supervisors for their encouragement,
to my friends for keeping me sane,
and to the staff of Archaus Architects for their patience.

I could not have completed this journey without you all.

abstract

Architects use media such as drawings and models to test and better understand their designs. These media are frequently scaled for convenience and reduced to two dimensions for clarity; however, in relying on these methods, the direct and visceral experience of inhabiting space is neglected. Phenomenologists such as Juhani Pallasmaa point out that this problem is exacerbated by the picture plane. The flat page or screen acts as an impenetrable window, excluding the viewer from a truly embodied appreciation of the designed spatial qualities.

This research investigates the use of virtual reality (VR) as a tool for conceiving architecture without alienating the designer from the user's perspective. It is suggested that the holistic and subjective approach of immersive media is a necessary complement to the more abstracted and objective views of architectural tradition: plan, section, and elevation. The recent availability of consumer-grade VR allows the testing of this opportunity without many of the technological limitations of research done in the 1990's. This research aims to describe tendencies of VR design and thus guide the incorporation of immersive technologies into contemporary practice.

To study the impact of VR, a real-time engine is used to develop an interactive program which allows the modelling of conceptual designs while immersed within them. Its efficacy is studied with three groups (architecture students, architects, and members of the public) from which quantitative and qualitative data is collected. By identifying the unique benefits of such tools, it is proposed how each group could make good use of the technology and extend the abilities of their existing workflows.

preface

The topic of this thesis emerged from three disparate areas of my experiences as an architecture student. Firstly, while studying for history assignments, the criticism of modern architectural representation was a thematic recurrence, usually in texts from authors such as Juhani Pallasmaa. Secondly, I began to make similar conclusions from my personal experiences observing classmates who frequently designed directly within a digital environment without reflecting on the influence that the software had on their work. Finally, the problem was made clear when my parents, while evaluating the design of their own house, failed to fully comprehend its scale, composition, and lighting qualities. The conventions that architects use to communicate and design might be efficient for some processes but, for my parents at least, they were non-intuitive and incomplete.

glossary

Experience	In this document, 'experience' denotes the term as a phenomenologist would define it; it is the culmination of bodily sensations processed by the mind to form a holistic sense of the environment.
Representation	In this document, a representation describes an artificial depiction of a real or imagined environment through the use of some medium.
Virtual Reality	Virtual reality is an immersive technology which, when in use, gives the illusion of being in a different location. Usually the scene is digitally fabricated and then displayed with a system of position-tracking devices and screens.
Immersive	The extent to which the user vividly experiences a virtual environment as if they were truly within it.
Architectural Media	The materials and techniques that architects employ to create representations of their work.

“Perspectival space leaves us as outside observers,

whereas multi-perspectival and atmospheric space and peripheral vision enclose and enfold us in their embrace”

- Juhani Pallasmaa (2014, p. 243)

Contents

1. introduction

Introduction

The media that architects use to convey their ideas is a subtle and yet ever-present variable in the equation of good design practice. Despite being often considered as merely the material or object which communicates the ideas, choice of medium has a profound influence on how those ideas are relayed and received. Just as the meaning of a piece of art is transmuted by its physical manifestation, architectural design ideas contained within a drawing can be limited or liberated through the means by which it is depicted. Ultimately, this has a "strong bearing on the built environment we create and inhabit" (Whyte, 2002, p. vii).

Problem Statement

While conventional drawing techniques such as plan, section, and elevation have been successfully employed for centuries, they remain bound to a flat surface and detach the viewer from understanding the proposal as an environment (Lockard, 1982, p. 72; Pallasmaa, 2012, p. 22). The ability of a well-layered drawing to impart objective truths about a design is not challenged; but, because of the perceptual discrepancies associated with visual abstraction and distortion, they are limited when it comes to evaluating a design's aesthetics from the perspective of an inhabitant (Bafna, 2008, p. 542). The tendencies of a representation to emphasise some parts of a design but not others is inevitable and implicit in the method used. This includes visualisations generated within software used by many professionals. Unfortunately, relying on these methods without being critical of the assumptions they make can lead to neglect of a major component of architecture's value: the embodied experience.

Research Proposition

While drawings are limited to flat surfaces, and physical models usually made at a smaller scale, virtual reality (VR) simulates full-scale, three-dimensional immersion. This allows greater understanding of the peripheral qualities of the designed experience which traditional media struggle to convey. According to William Lockard (1982), knowledge of these qualities is “absolutely basic” to the designer’s responsibility (p. 2). If the media used to design a building has an impact on the outcomes architects produce, virtual reality has a unique potential to add greater depth of analysis to design processes. This research explores the extent to which virtual reality provides an effective design interface, and the ways that it could be a valuable tool for architectural design. Hence, this thesis asks the question:

Q

What are the benefits of using immersive virtual reality modelling for architectural design?

Aims & Objectives

Aims

1. Mitigate the discrepancies between the embodied experience of architecture and its representation during the design process.
2. Position the role of immersive media in architectural design to aid their incorporation into practice.

Objectives

1. Investigate innovative conceptual design methods using VR.
2. Describe the limits and affordances of immersive media for spatial design.
3. Identify the target audiences of interactive VR design tools.
4. Find the relative efficacy of VR tools for each group.
5. Outline the characteristics of VR which affect design efficacy for each audience.

Research Framework

In 2003, Peter Downton proposed three approaches to design research: research *for* design, research *about* design, and research *through* design. While this project can be described as research through the design of a VR application, it is ultimately intended as research *for* design; the development of this particular software offers direct insight into how architects could interact with immersive technologies and how the technologies could be formed to aid in the architectural design process.

This thesis consists of a literature review, design development, and design testing. Each of these components was executed in parallel during the research period, informing one another throughout. The literature review forms the theoretical underpinnings of the argument, explaining the potential that VR has in the architectural discipline. The design development includes learning the skills to develop the program and the design of the tools and interface. This was interspersed with testing of the VR program, including many instances of informal testing, two formal experiments, interim reviews and subsequent reflections. The following details describe these parts and explain their contribution to the thesis methodology:

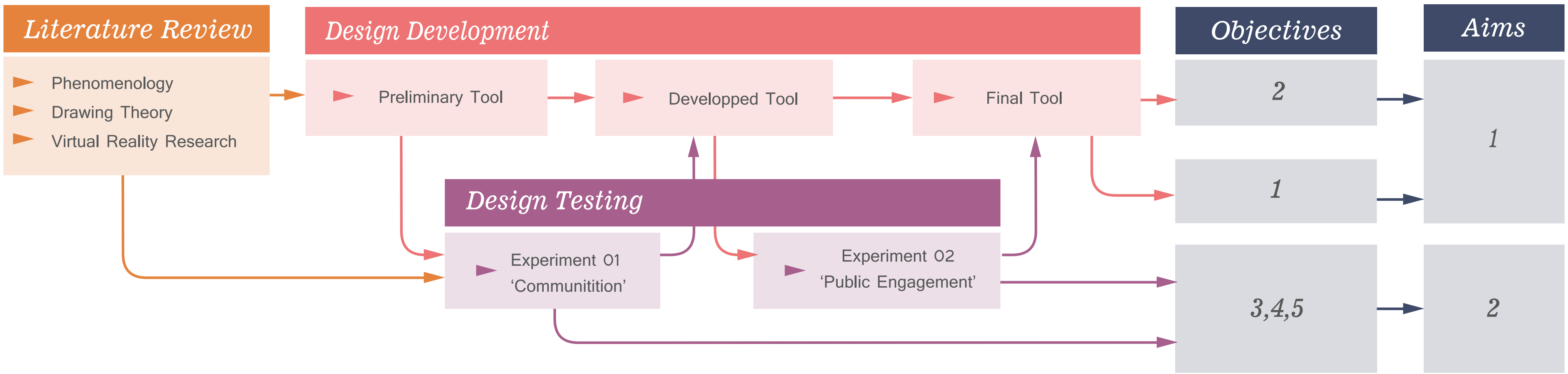


Fig. 1.1. Diagram of research methodology

Research Methods

Literature Review:

1. A theoretical basis for the need of VR in architecture is provided by phenomenological literature from authors such as Pallasmaa, Moore, and Zumthor.
2. A review of late twentieth-century to contemporary texts on architectural design representation link knowledge of perception to the discipline and its methods – namely, drawing and modelling (manual and digital).
3. An analysis of current virtual reality research and immersive software precedents identifies gaps in the literature and positions this work in an up-to-date context.

Design Development:

4. An interactive modelling application is developed for use in VR, acting as a proof of concept and, most importantly, a flexible vehicle for experimentation. The tools and interactions created are regularly reflected upon to analyse their potential usefulness and direct the research.

Design Testing:

5. The actions of designers and non-designers within the program are tested. Quantitative and qualitative data is collected and analysed between and within groups to establish efficacy. Criteria include ease of use, model comprehension, and quality of work, as rated by other participants.
6. A potential workflow is constructed through reflecting on results, highlighting the benefits and shortcomings of immersive media and what this means for its use in design practice.

Scope

Limitations of the research are described here. In some cases these negatively impact the range of explored topics, but mostly they are a result of selected research priorities and the optimum use of available resources:

- This project uses testing with virtual reality only. Although there are currently many immersive technologies being researched, including augmented reality and mixed reality (Schnabel & Xiangyu, 2009), virtual reality is more developed, more frequently written about, and also more accessible in terms of support and equipment. While this narrows the types of immersive media investigated, the testing variables are minimised, increasing research focus. Furthermore, many of the findings are applicable to all immersive technologies due to their common mode of 'natural perception'.

- Because of the lack of easily customisable VR software, the program which the research focuses on is custom-made. There is a practical limit to the functionality that can be implemented into this during the research period. This means that more advanced potential benefits of virtual reality, such as networking or fine mesh editing, are not included in the scope. Instead, these are left as an area for further exploration in the future.

- Also because of the short research period, long-term studies which track the entire arc of a design project are not feasible. Instead, this research explores early stage design, focusing on the effects of immersive technologies on the process of spatial ideation.

- Many complex psychological processes are involved in the perception of VR and there are many researchers at the cutting edge of this knowledge; however, as this is an architectural thesis, only its relevance to design is explored here.

- As virtual reality is a dynamic and interactive medium, it is impossible to fully communicate its power with static imagery. As such, it is highly recommended that this document be understood and interpreted in the context of the actual devices which it discusses. Therefore, please watch this video of the 'Sketchspace' software in action as a complement to this document: <http://bit.ly/2EWt9FG>. Assuming that this thesis is to be encompassed with pictures alone goes against its very premise.

2. literature review

When considering the value of an architect, the economical argument is the one that first comes to mind; according to Paul Laseau (2001), designing is about seeing “what could or would be achieved before investing too much time, energy, or money” (p. 39). As noted by Kendra Smith in her book, *Architects’ Drawings* (2005), “architects depend on substitute media to assist in visual thinking” because it is “economically unfeasible” to design at full scale, (p. 1). Clearly, representation is an important part of this time, energy, and money-saving process, since it allows stakeholders to anticipate issues with something they will, presumably, be investing a lot in. Over many centuries, architects have developed conventional drawing techniques which comprehensively and unambiguously describe the geometric conditions of their work. Now, as architects face an increasingly digital industry, it is necessary to reflect on their relationship with conventions and how the interface between the design realm and the physical realm influences their practice.

This research interrogates how architects’ usage of immersive representational techniques affect the way they perceive and conceive their designs. In this literature review, a framework for the ‘goals of representation’ defines the criteria for design media efficacy in terms of current and future roles of the architect. In other words, why do architects use representation and how does it help them achieve their design objectives. The framework is created from the writings of phenomenologists, such as Juhani Pallasmaa, as well as other theorists of architectural drawing. It aims to identify limitations of current media and, consequently, areas of the design process that could benefit from the incorporation of virtual reality. This includes naming the relevant stakeholders of the construction process who are likely to benefit from virtual reality design processes.

The Goals of Representation

The goals of *architecture* are described in Vitruvius’ seminal *De Architectura* as a triad of criteria: firmness, commodity, and delight (Pollio, trans. 2009). Just as architecture itself has goals, we can identify discrete goals of architectural media and use this to evaluate the suitability of VR. At the fundamental level, architects use representations to investigate or present the implications of their design decisions; however, the effects that a building has on its inhabitants are diverse. Consequently, for representations to fulfil their purpose, they must bring to light the validity of the architect’s decisions with respect to all variables of building quality. The appropriateness of the selected technique for the characteristic depicted affects the comprehension of that characteristic and its relative importance to the overall design. Put simply, architectural media must show that the depicted proposal meets all three of Vitruvius’ criteria.

Of course, the criteria of a building and its representation concern stakeholders in the design process to varying extents. According to William Lockard (1982), there are three kinds of drawing: design drawing, for generating and evaluating, drawing as art, for responding and expressing, and drawing as drafting, for describing and instructing (p.3-5). Each of these represent a different role of the architect, a different audience, and, therefore, a different purpose of the representation; the architect firstly creates sketches to aid in designing, secondly communicates the design to a client, and finally communicates the design to a contractor or builder who executes the proposal. Each process is concerned with different characteristics of the design proposal and thus has an optimum representation method.

In considering the variables described by both of these pre-existing frameworks, one can see that what a representation shows and for whom it is being shown has an importance to the method which the architect uses. Together, these variables can be summarised by categorising representational goals into four components. Each component also has a set of suitable techniques which will achieve those goals with relative efficacy:

1. Understanding Geometry

This describes representations which explain the form of a building, often diagrammatically. Examples include parti diagrams, axonometric drawings, and sometimes sections.

2. Understanding Function

Representations which explain how a building works or is used, including programmatic function. Most notably, this covers plans and occasionally axonometrics.

3. Understanding Experience

Media which relate to this category evoke the potential emotional and physical reactions from an individual in the proposed space. Usually, photographs or renders but also potentially VR.

4. Understanding Construction

This media explains how the building is put together and with which materials. Typically this describes most of the orthographic drawings in a building consent application, for example.

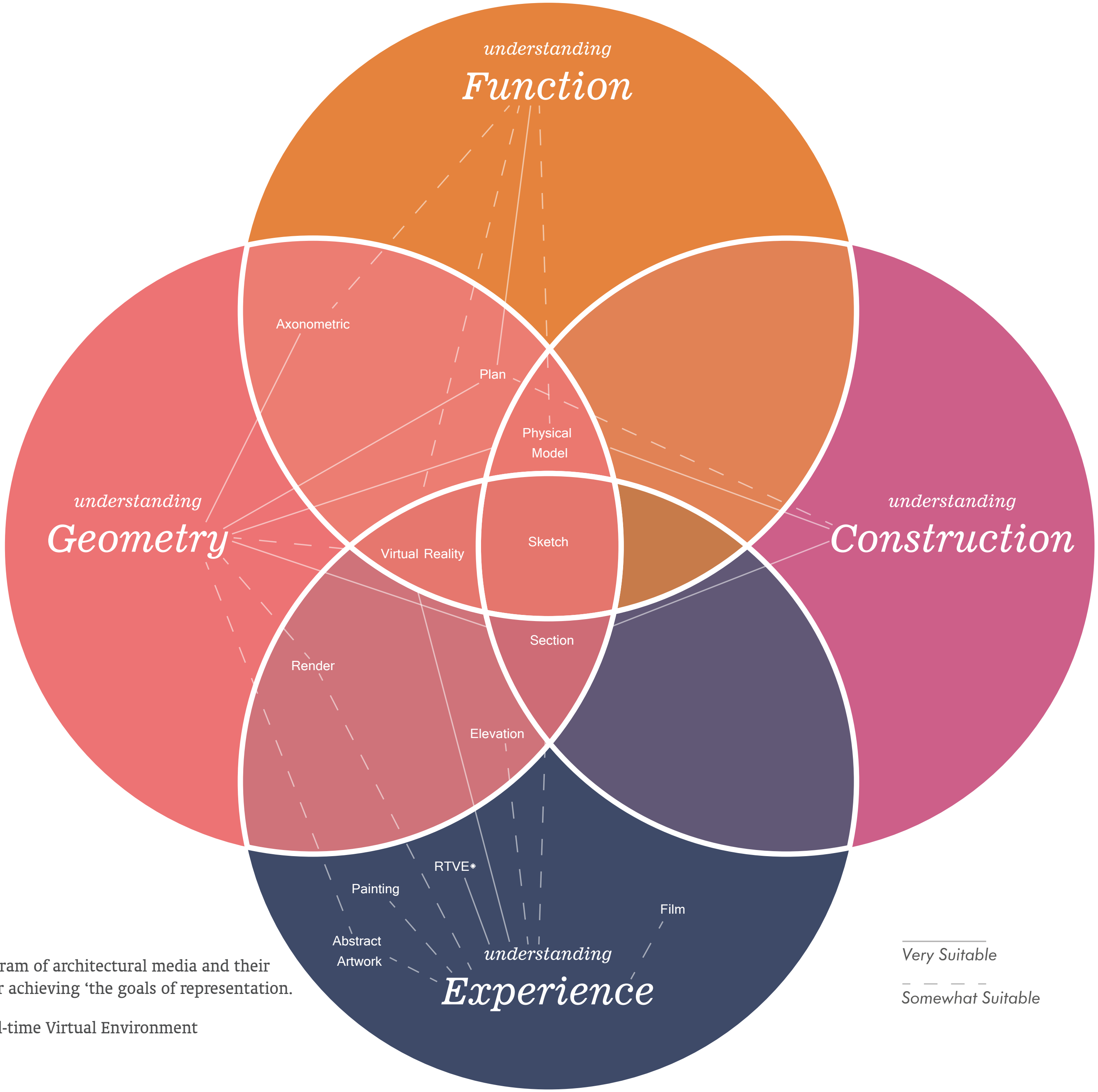


Fig. 2.1. Diagram of architectural media and their suitability for achieving 'the goals of representation.

*RTVE = Real-time Virtual Environment

Inevitably, each method of representation offers a view of the proposal which focuses on some aspects while suppressing or ignoring others; for example, orthographic drawings reduce three dimensions to two in order to "increase the clarity and focus" (Fraser and Henmi, 1994, p. 25). The architect also decides a point of view and frames the presented area, further reducing the information provided (de la Fuente Suárez, 2016, p. 51). This is "at once a hindrance and an aid to visualisation" (Fraser and Henmi, 1994, p. 26) because it shows less information but also gives the designer the control to emphasise what they consider important or worth noticing (Gibson, 1979, p. 274).

Through these processes of reduction and abstraction, the image becomes something that is distant from the object depicted. To fully comprehend a series of architectural drawings a viewer must "meld two or more drawings together in the mind" (Fraser and Henmi, 1994, p. 46). Because of this culling of information, all methods of representation have their limits. Two-dimensional drawings, for example, usually have a narrow field of view and lack spatial inclusion; Laseau (2001) writes: "we must recognize that even with the most sophisticated techniques, drawings are not a full substitute for the actual experience of an architectural environment" (p. 39). This is the discrepancy between reality and representation which could be mitigated by VR's immersive qualities.

Architects use drawings as a thinking device. Not only is it a physical manifestation of thought, it influences the thoughts of those who view it (Fraser and Henmi, 1994, p. viii). As such, it stands to reason that the medium and method of architectural representation has an important role to play in the extent to which the outcome responds to each facet of design. This influence is discussed relative to design drawings in Kendra Smith's book (2005, p. 1); however, the logic applies to all media used by architects today, including physical models, digital models, digital drafting, and, of course, virtual reality. According to Luis Alfonso de la Fuente Suárez (2016), architects tend to lack necessary critical background in topics related to representation (p. 58). Without critically evaluating why a representational method is used, whether for design drawings, CAD drafting, or presentation, an architect surrenders some control to the assumptions implicit in the technique or software. Often, these assumptions include the bias of the picture plane and the method of projection onto it, perpetuating the notion of the design as an image rather than an environment.

This research began from the position that ultimately, architecture is judged from the perspective of the users, and that " the objective of architecture is not the architectural artefact but the experience it facilitates" (Angulo & de Velasco, 2013, p. 495). This begs the question: to what extent should representation be a simulation of the human perspective? Are orthographic drawings, which abstract this experience, inappropriately used for evaluating the designed environment? Can VR provide a more comprehensive understanding of spatial design?

Embodied Experience in Representation

While Vitruvius' 'firmness' is an objectively measurable characteristic of a design, the other two criteria are, to a greater extent, human-centric and therefore rather subjective. The coexistence of the seemingly conflicting objective and subjective aims of an architect is well-known and documented; Juhani Pallasmaa describes architecture as an "impure art form" because it "has fundamentally a multiple essence" (Grabow, 2015, p. xiv).

The ever-present subjectivity of architectural space is an inevitable result of the individuality of its users; As much as it is easier to make 'objective' conclusions about the quality of a space, the more complex truth is that each person is a unique agent with their own senses and experience of the designed environment. This individual experience shapes how everyday people evaluate the spaces they inhabit. Only through embodied occupation can someone gain the most visceral appreciation of architecture and its delight (Kent and Moore, 1977, p. 36; Zumthor, 1999, p. 77). In fact, in his book *The Death of Drawing*, David Scheer (2014) argues that architecture's direct impact is the "raw material" which representations draw upon (p. 218). Initially, this was one of the main tenets of this thesis because it demonstrated that VR is the most 'raw' representation we currently have.

A phenomenological understanding of how we subjectively evaluate spaces is central to this thesis and its arguments for a more critical use of media in architecture. This is because, while drawings refer to form, they are nevertheless a translation of reality and have "intrinsic limitations of reference" (Evans, 1997, p. 159). The compromises made in turning three-dimensional ideas into representation are a reflection on the priorities of the designer and, to a certain extent, their artistic intent. Selecting what information to show and what qualities to express in a representation becomes a subjective process in itself. This is in opposition to the assumption that representations show a design 'as it is'. It then follows that by designing with a medium like virtual reality, if the compromises of translating reality are minimal, one could more clearly evaluate the direct and subjective experience of a spatial design.

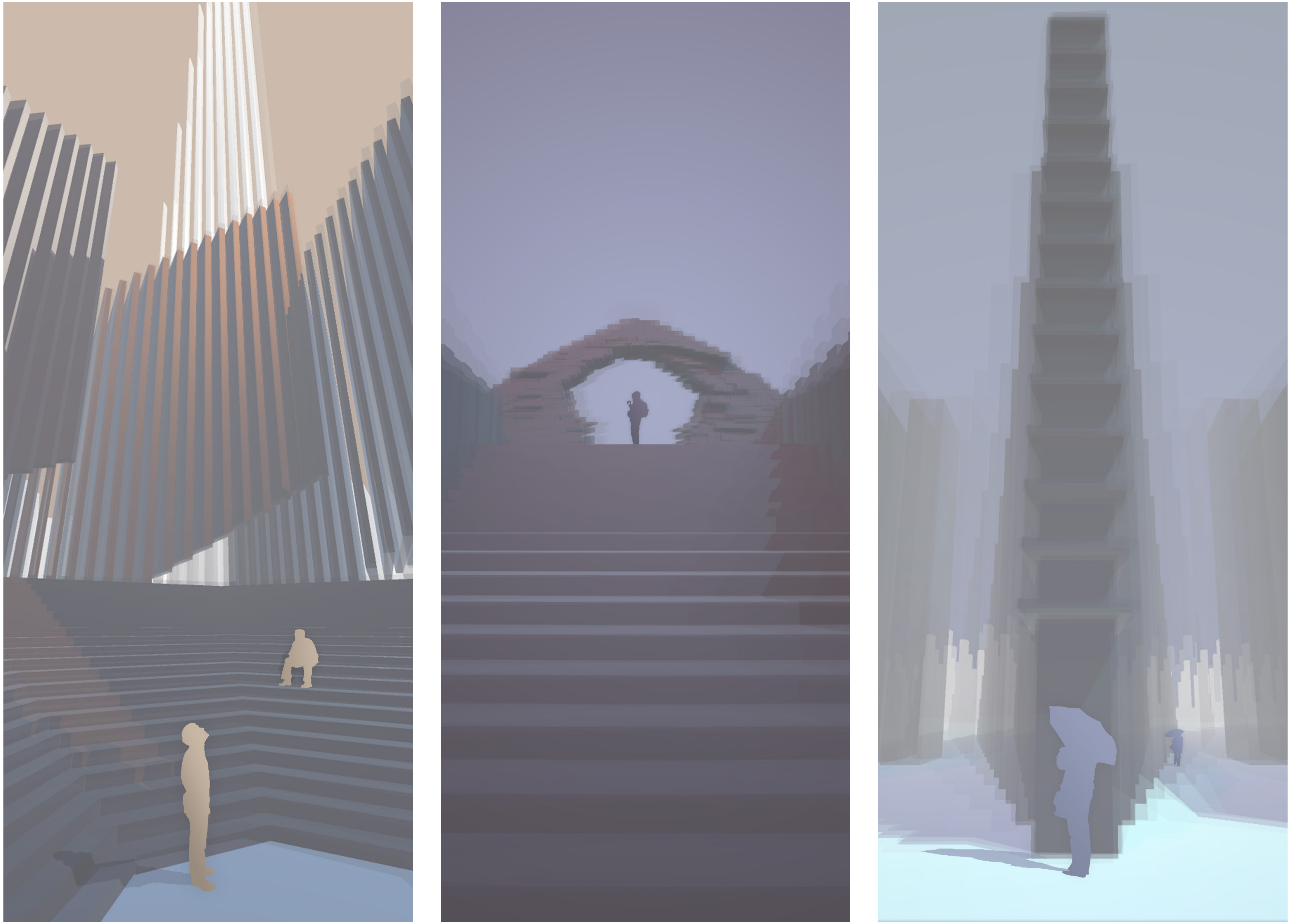


Fig. 2.2. Preliminary concept images portraying embodied experience of architecture. Models made within custom application.

Virtual Reality Research & The Knowledge Gap

As a foundation for determining the need for VR representation, this research aims to identify the limitations which hinder each representational technique from effectively achieving its goals. For example, Bafna (2008) suggests that orthographic drawings are "far less useful for formulating critical judgements about designs, than are the presentation renderings" (p. 542). Some of these limitations are identified through the investigations in this study, but many have been previously described in the literature:

Orthographic Drawings

- Highly reductive (2008, Bafna, p.25)
- No direct indication of "qualities of privacy, light, sound, or tactility" (Lockard, 1982, p. 74).
- "Weak in conveying any sense of time or movement" (Lockard, 1982, p. 74).
- Limited relationship to experience (Lockard, 1982, p. 74)
- Best suited for "uncomplicated" designs with traditional forms and limited innovation (since drafting was established long before perspective) (Lockard, 1982, p. 76).
- Pursuing depth in orthographic drawings "retarded architectural vision by keeping it restricted within the confines of particular conventions" (Evans, 1986, p.171).

Perspective Drawings

- Provides an "intense illusion of 'being there' at the expense of the convenience and uniformity of paraline drawings (Fraser and Henmi, 1994, p. 59)
- Scale is unclear (Fraser and Henmi, 1994, p. 72)
- Point of view is stationary (Aguilera, 2008)

Photographs & Renders

- Reduces architecture to "mere retinal art" (Pallasmaa, 2012, p. 33)
- Architecture appears to have no dimension of time (Pallasmaa, 2012, p. 33; Gibson, 1979, p. 293)
- Alienates vision from "emotional involvement and identification" (Pallasmaa, 2012, p. 25)
- The digital image can be seen but not felt (Smith, 2005, p. 208)
- Lacks the "peripheral and unconscious" senses of atmospheric perception: sensations of orientation, gravity, balance, stability, motion, duration, continuity, scale, and illumination. (Pallasmaa, 2014, p.231)

Because of its fundamentally different approach to simulating visual perception, virtual reality has the potential to mitigate the preceding limitations of typical architectural design processes. This potential has been investigated by many researchers since the development of the technology in the 1990's (Achten & Arthur 1999; Beckmann, 1998; Kvan & Schnabel 2003; Orzechowski et al., 2003; Slater & Wilbur 1997); yet, crude prototypes and a lack of computational power restricted simulation realism and prevented a seamless study of the tool (Bakker, 2001, p.22). During this time, "virtual worlds had become unfashionable," whereas today we are seeing that "technologies have now matured beyond this stage to become productive in practical contexts" (Kim, Wang, Love, Li, & Shih-Chung, 2013, p. 280). This is especially true with the release of mainstream VR headsets such as the Oculus Rift and HTC VIVE. Now there is a considerable amount of interest in VR within many industries including that of Architecture, Engineering, and Construction. Although research on representation is relatively scarce (de la Fuente Suárez, 2016, p. 58), excitement in the field of immersive media has been slowly increasing once more. Many authors have recently been optimistic about the potential of the medium for architectural spatial evaluation and design (Kim et al., 2013, p. 286).

There has been a lot of research to demonstrate that designers do indeed think differently about their work when using VR. In 2003, Schnabel and Kvan (2003) demonstrated that students who worked in two-dimensions were able to accurately rebuild a volume of interconnected forms, but nevertheless did not fully understand the three-dimensional arrangement (p. 442). The students' counterparts who used virtual reality to assess the arrangement had a much greater appreciation of the spatial relationships.

More recently, in 2014, Abdelhameed recorded that "some students highlighted a link between their creativity and the perception provided within the VR use," showing promise for the technology's use in the design process. This study also reinforced what Schnabel and Kvan found about the users' awareness of spaces. Interestingly, the strong effect of VR was noticed most significantly in relation to form propositions, form compositions, and most of all form exploring (Abdelhameed, 2014, p. 727). Abdelhameed's paper gives a good starting point for scoping the priorities of this research investigation.

Much of the potential benefits of VR arise from its inherent property of simulating true perception; "it is because of this 'natural' interaction between the computer-generated world and the user that VR is defined as the ultimate interface between man and machine" (Bertol, 1997, p. xv). It can be seen that VR has a profound impact on the way that we perceive and communicate a proposed design (Whyte, 2002, p. 73) and, according to Bertol (1997), "seems to be the next logical step in the path laid by CAD" (p. xv).

Precedents

Already, practices around the world have been using the technology to demonstrate their designs to clients in a highly interactive manner, like the global design firm NBBJ. However the extent of their incorporation into the design process itself is limited. As Schnabel and Kvan (2003) note, “[virtual environments] are employed successfully to study, communicate and present architectural design but are seldom used for the actual act of creation” (p. 437). Technically, VR is being used as a visualisation tool and not one for design. Real-time interaction has been an increasingly strong area of potential research (Asanowicz, 2016, p.202) and as of 2017, some VR modelling programs are becoming available for consumers. Angulo & Vásquez de Velasco have two papers which explore this: one comparing VR design processes with more traditional design processes (2013), and the other investigating the rendering and visualisation qualities which affect VR design (2015). Just as the medium of a design drawing has an impact on the design process, so too could VR change the way architects confer with representations and conceive buildings. Thus far, no modelling program has been made publicly available which specifically caters for spatial design. The programs which are available tend to be limited by either the scale model paradigm, which encourages formal rather than experiential evaluation, or a lack of manipulation tools, which makes a VR design workflow unfeasible:

Fuzor (Kalloc Studios, 2016)/ **Enscape** (Enscape 3D, 2016)

Fuzor and Enscape are Revit plug-in softwares which transfer Revit models to a VR simulated environment for users to experience. This is most useful for visualisation and limited design tasks, such as changing materials. Geometry manipulation is currently crude relative to other dedicated modelling softwares.

Rhino VR (Minddesk VR, 2017)

At the time of writing, Rhino VR is a Rhinoceros 3D plug-in, currently in development, which allows the VR controller to act as a three-dimensional mouse. Primitive shapes are created at the hand location, limiting its functionality as a full-scale architecture design tool. Like the host program, rendering is rudimentary. Furthermore, the geometric toolset is currently lacking, but will presumably grow with development.

Tilt Brush (Google, 2016)

Tilt Brush is a Google-developed VR platform for creating 3D artistic models with a sketch-like appearance. Again, the user controls the creation at the location of the hand, as if using a paint brush. It is noteworthy because of its high level of immersion despite an ‘unrealistic’ scene. The ‘palette’ interface swivels around the controller with ease and users can quickly get to the creation stages.

Gravity Sketch (Paredes Fuentes, D. S., Oluwaseyi, 2017)

Gravity Sketch is a modelling program with a greater level of control, precision, and adjustability than other software currently on the market. The inclusion of curve and symmetry tools make it suitable more for conceptual product design than architecture. This program also relies on a hand-held 'mouse' which limits the usability to hand-held model scales.

Google Blocks (Google, 2017)

With a simple and intuitive interface, Google Blocks makes VR modelling very accessible to those with minimal to no training. Models tend to be restricted to a small scale making this program less suitable for spatial design.

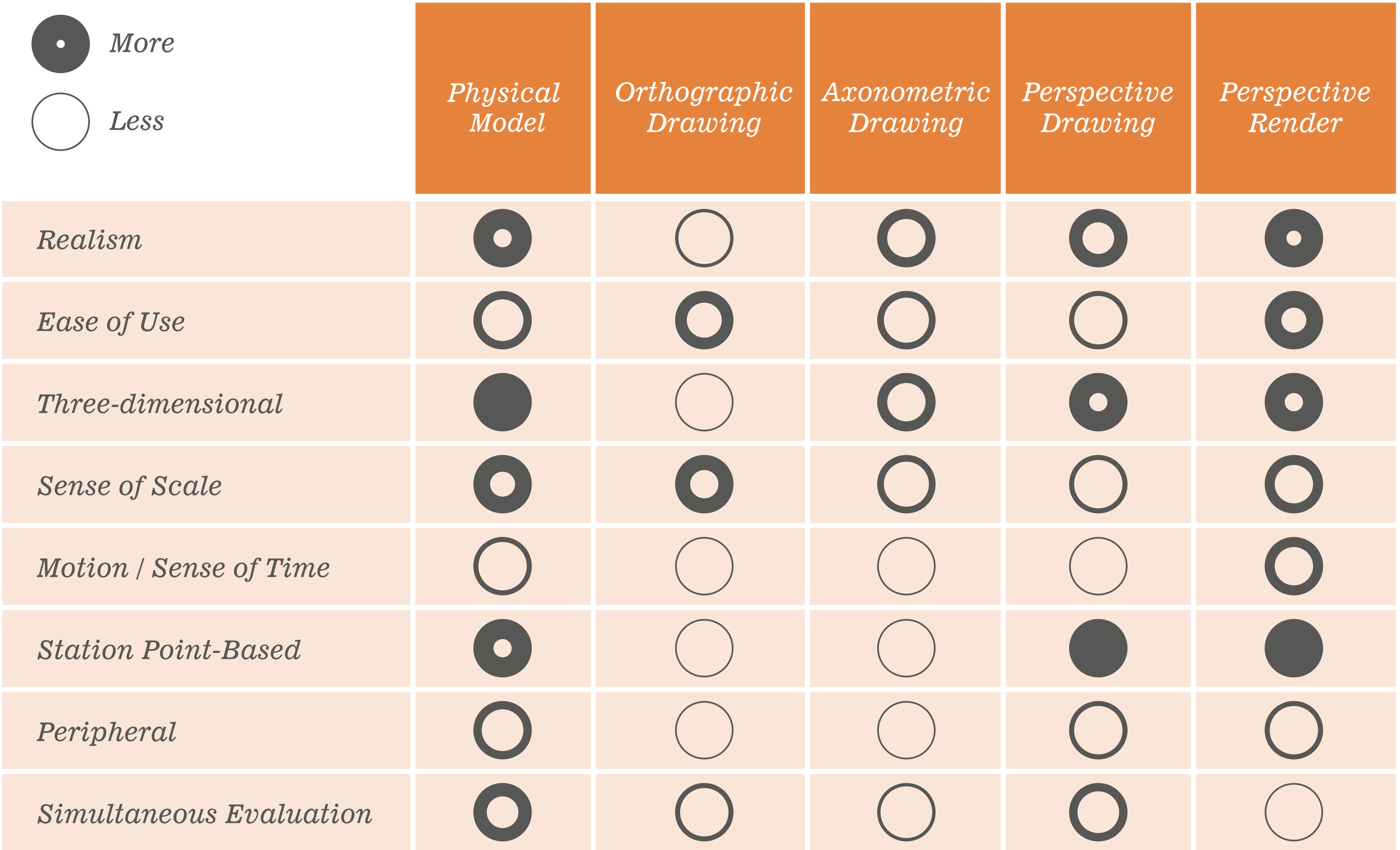


Fig. 2.3. Chart of benefits and disadvantages of VR precedents and other design media techniques.

Virtual Reality				
Fuzor/ Enscape	*Rhino VR*	*Gravity Sketch*	*Tilt Brush*	*Google Blocks*
◉	○	○	○	○
◉	○	◉	●	◉
●	●	●	●	●
◉	◉	◉	◉	○
◉	○	○	◉	○
●	●	●	●	●
○	◉	◉	○	○
○	○	○	○	○

3. a response
to the status quo

Perception and Representation

"Architects are said to possess two perspectives: a bird's eye view and a life-size, ground-based perception of space...

They are supposed to be able to move freely between the two...

The problem with architects is that too often they design with a god's-eye view, looking down!" ***- Kengo Kuma***
(Goodwin & Ursprung, 2014, p. 69)

In this excerpt, Kengo Kuma highlights an important distinction between two approaches to the representations of a design: overview and simulation. These play important roles in the design process because they have somewhat different mental outputs which complement each other for a broader understanding of the design. An overview, such as a site plan or context elevation, will give the designer a sense of the foundational logic or patterns and a conceptual understanding for the design's relationship to its surroundings. This is the objective view. In contrast, by putting themselves in the shoes of a person at ground level, architects get to know what it would be like for the users and, importantly, how the decisions made in an overview will impact the perception of an individual; the subjective view.

Lockard (1982) explains this thoroughly in his book on design drawing, describing the two approaches of 'overview and imitation' as 'quantitative and qualitative', respectively; orthographic and axonometric drawings, which show the building uniformly from an abstract viewpoint, are quantitative while perspectives are constructed according to the view of an inhabitant and are therefore qualitative (p. 72). This relates to the 'goals of representation'; media which aim to convey form, function, or construction methods do not necessitate the perspective of an individual and are explained well with an abstract view. In fact, an immersive approach might hinder objective communication, rather than improve it. On the other hand, 'experience,' requires evocation of something at least analogous to the true feeling of architectural presence. This 'simulation' of perception, according to both Kuma and Lockard, is what should be encouraged as a part of the design process. VR's ability to do this convincingly is why it was chosen for this study.

With the explosion of computer-aided design (CAD) came a new paradigm of design-designer interaction. For many architects, perceiving a design by viewing a digital model on a computer monitor has become the predominant method of understanding a proposal (Smith, 2005, p.207). With digital technology, "the designer can interpret the vision with much more clarity than before, to the benefit of everyone involved in the project" (Aspelund, 2010, p. 107). Computers are now a vital component of contemporary architectural practice and very few firms can successfully build without their use (Smith, 2005, p.207); however, the typical viewing method is limited in numerous ways, including the narrow field of view of virtual cameras (Aguilera, 2008), the lack of a consistent scale (Aspelund, 2010, p. 108), and even the disconnect between the motion of the hand and the model itself (Smith, 2005, p. 208). Most significantly for this thesis, displaying a three-dimensional model on a two-dimensional screen separates the viewer from the experience of the building since peripheral vision is cropped out of the experience. Thus, when evaluating the design on a screen, architects tend to see the building as an image rather than an embodied experience.

The lack of peripheral vision is one of the main aspects of flat representational media that limits its use in conveying architectural experiences (Pallasmaa, 2014, p.243). Luis Alfonso de la Fuente Suárez emphasises this in his article Towards Experiential Representation (2016), describing two-dimensional images as "an inflexible guide in our vicarious experience of the architectural object" (p. 52).

Nevertheless, such criticisms must acknowledge that drawings are only insufficient insofar as they attempt to encompass the peripheral qualities of an embodied spatial experience.

One could argue that it is the job of the architect to imagine the periphery and make judgements based on that. With training and practice, a good architect will be able to infer some sense of a proposed environment from a flat drawing (Lockard, 1982, 33), however this is subject to error, incompleteness and bias (Asanowicz, 2016, p.202; Bafna, 2008, p. 542; Smith, 2005, p. 1). As such, while drawings are valuable for the quantitative communication of a design project, they are unable to fully address issues pertaining to its qualitative perception.

Furthermore, drawings that ostensibly explain the building form are frequently embellished through graphical means, be it through artistic liberties or even digitally-manipulated overlays. These additions are suitable for eye-candy but, again, do not evoke a real-world architectural experience. The distinction must be made clear. Idealising or even romanticising an image diverts attention from the true nature of the building, becoming unproductive in the long run. Grounding the viewer in a reality which they can expect to get from the proposed building provides a foundation for honest representation (de la Fuente Suárez, 2016, p. 53; Zumthor, 1999, p. 66).

Virtual Reality as a Design Representation Tool

For a large proportion of architectural history, the drawing has held sway as the primary means of communicating architecture and its hegemony had "never really been challenged" (Evans, 1986, 165). Today, however, new technologies are providing an alternative to the assumed design media of tradition. As such, this thesis considers the suitability of VR as an interface for design. Since the medium is already being used for visualisation of complete proposals (Whyte, 2002, p. 132), this research looks into its applicability as a simultaneous visualising and modelling tool during the conceptual design stages. This has been identified as an area which remains relatively untouched by the computer (Smith, 2005, p. 207).

In 1982, William Lockard argued for the use of perspective drawings as a means to understand and improve a designed environment as an experience; to him, perspective drawings are simulations. This thesis takes Lockard's argument a step further by recontextualising it in the age of immersive media; if we think of virtual reality as an interactive, high-fidelity perspective drawing, we can see the similarity of their benefits in terms of conveying experiential qualities and thus improving the ability to judge that experience.

The hypothesis is that VR has potential because it reproduces the natural perception of a mobile human being, at least in the visual sense. In *An Ecological Approach to Perception*, James J. Gibson (1979) identifies this as a combination of 'ambient vision' (visual perception by turning the head) and 'ambulatory vision' (visual perception from walking around) (p. 1). The technological shift of VR pushes representation towards ambient and ambulant perception that can be understood by anyone with vision. This is in contrast to the sometimes esoteric abstraction of orthogonal drawings, which requires a degree of training or three-dimensional cognition. VR's advantage of total visual interactivity makes it a unique form of representation which has clear parallels to the typical perception of architecture.

Gibson (1979) describes media like pictures as 'mediated' because they are controlled by artist who guides the perception (p. 147). VR can be considered a less mediated mode of representation because the viewer is able to change their perspective at will. This poses numerous problems for designers who want to direct the focus of a client, say; immersive environments require more involved and innovative methods of attention-directing to achieve the clarity of narrative that a still picture does. Those exploring the use of technology in film are discovering similar issues with conveying artistic intent in such a free medium. It is a difference of the medium which requires critical consideration on the part of the presenter. In the field of architecture, however, the presenter must consider whether it is appropriate to direct the viewer's attention artificially when this does not occur within real world built environments. Presentation style could depend on the taste of the designer, yet this thesis suggests that displaying a building with the freedom to explore it is the more realistic and accurate way to investigate an inhabitant's response. Emphasising this concept would encourage designers to think more holistically about inhabitation and perception of entire spaces rather than individual views.

Although VR headsets create a vivid illusion of presence, it is nevertheless an illusion. Just like perspective drawings, it attempts to trick our eyes into seeing objects that do not exist and, like most illusions, VR is incomplete; at the current stage, sight and sound are the only senses that are accounted for in a typical VR setup. Others might become possible with further research, but this research explores only sight as it is the often a user's most immediate method of spatial evaluation. There are also currently technological limitations regarding the angle of view and the resolution of VR's head-mounted displays (Bakker, 2001).

Despite its shortcomings, VR is a step towards true experiential reproduction which resolves many of the limitations of the media that is typically used in architecture:

- It represents the entire modelled scene continuously
- It is able to convey time and movement
- It can communicate complicated three-dimensional designs at once
- It encourages designs with depth
- It is able to represent designs at any scale
- It allows the point of view to be changed
- It can evoke emotional involvement and identification
- It includes a wide angle of peripheral vision and atmospheric perception
- It involves the whole body

The benefits of VR as an interactive viewing device become valuable during the architectural design process. In the same way that sketches are "substitutions for mental impressions" (Smith, 2005, p. 3), VR is an easy way to externalise and interact with three-dimensional ideas.

Conclusions about Perception & Representation

The communication of architectural space is a necessary part of architects' value to the users for whom they design. As the profession relies more heavily on digital interfaces, it is possible for VR to become a method for quickly displaying digital information. However, while VR has its advantages over more restrictive, traditional media, its ability to entirely replace the simplicity of pen or pencil on paper is doubtful. Not only is there a romanticism attached to the traditional, but the limitations that orthographic techniques impose could be helpful for the mental processing of imagined objects (Evans, 1997). Immersive technologies, it is suggested, can instead be used as a subjective complement to the more abstracted and objective techniques of plan, section, and elevation (Whyte, 2002, p. 50).

4. research methods

Relationship of Methods to Aims & Objectives

This research tests the practicality and efficacy of VR as a design tool through the creation of a novel VR program. The program is self-made to allow greater flexibility and analysis capabilities. During its development, it is tested with various groups including architectural designers, architecture students, and members of the public. In getting feedback while simultaneously building on its complexity, the research is able to identify which additions have the greatest impact on the user's ability to express design ideas. Moreover, tendencies of the tools are observed and critically analysed to assess their usefulness in potential VR applications. Controlled experiments also give greater credibility to the outcomes of VR modelling, an important step towards their successful use in the future (Kim et al., 2013, p. 296).

Aims:

1. **Mitigate the discrepancies between the embodied experience of architecture and its representation during the design process:**

In creating the custom application, the research endeavours to create a design interface which portrays spaces as they would be experienced. It is a proof-of-concept which demonstrates the possibility of a fully immersive modelling program, justifying the adoption of VR as a architectural design tool and backing up the cutting-edge research in the field.

2. **Position the role of immersive media relative to other architectural design tools to aid their incorporation into practice.**

Through the literature review, the theoretical relationship between drawing and VR is explored. In addition, experimentally comparing VR with typical, monitor-based modelling programs sheds light on the similarities and differences between the two. Reflection on the application's development finds the possible improvements and failures of VR technologies which affect its value as an alternative to other media.

Objectives:

1. **Investigate innovative concept design methods using VR.**

Because of the dissatisfactory supply of architecture-focused VR modelling programs, the designed software is made to be distinct from others available on the market. This inevitably produces some new, unanticipated effects, leading to novel approaches to spatial digital interfaces.

2. **Describe the limits and affordances of immersive media for spatial design.**

As with all media, virtual reality implicitly encourages some methods and discourages others. Through the process of designing and testing with a VR application, these tendencies will become apparent. This objective seeks to answer how they can affect the design process, what parts are advantageous or not, and how these tendencies can complement existing design methods.

3. **Identify the target audiences of interactive VR tools**

&

4. **Find the relative efficacy of VR tools for each group**

By conducting experiments and tests with various groups, the research intends to observe any patterns in user efficacy. Assumptions about who the technology will benefit are verified and suggestions are made about potential markets for future softwares.

5. **Outline the characteristics of VR which affect design efficacy for each audience.**

Differences between the groups and their interactions with the tool are expected and will inform the conclusions made about the reasons for the tool's successes and failures.

Description of Work

Code, Design, & Experiments

Built with Unity 3D, a real-time virtual engine, the program is able to dynamically generate rectilinear geometries and interactively manipulate their position, size, and rotation in virtual space. These tools are developed to perform in a manner similar to the mainstream modelling programs frequently used by both students and practising architects such as Rhinoceros 3D (Robert McNeel & Associates, 1994) or SketchUp (Trimble Navigation., 2000). Such a program, which can "stretch the shapes and then allow them to be viewed from the numerous perspectives" has been suggested as a valuable tool for architects (Smith, 2005, p. 208). Interactivity is now a necessary part of design drawing and design communication software and this VR program is one example of how it can be pushed further for more seamless feedback.

The application is built from many of the basic building blocks for a modelling program, including geometry memory and manipulation, rendering processes, and hardware interactions. From these basic elements, the rest of the software is coded and implemented for use. Doing this in-house gives an appreciation of the built-in assumptions which all design softwares impart to the architects who use it. It also gave an in-depth understanding of the otherwise hidden mechanics behind such VR systems.

In order to allow for the simultaneous assessment and manipulation of the design, the interaction is based on a 'laser pointer' which can create and control geometries at any distance from the user. This feature is in response to the VR precedents which are limited by their reliance on interaction at the hand and a lack of full-scale modelling. The full capabilities of the HTC VIVE's handheld controller is explored and many functions incorporated into the software. The goal is an intuitive spatial modelling interface which intuitively integrates three-dimensional visualisation and interaction in a continuous VR experience.

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

public struct LaserEventArgs
{
    public uint controllerIndex;
    public uint flags;
    public float distance;
    public Transform target;
}

public delegate void
LaserEventHandler(object sender,
LaserEventArgs e);

public class
TemplateLaserPointer :
MonoBehaviour
{
    public enum mode { Null =
-1, Add, Delete, Move, Copy,
Rotate, Radial, PushPull, Scale,
Group, Ungroup };
    public mode modeCurrent =
mode.Null;

    public bool active = true;
    public bool visibleRest =
true;
    public bool visibleActive
= true;
    public Color colorHighlight;
    public Color colorDefault;
    public bool customMats =
false;
    public Material matRest;
    public Material matActive;
    public Material
highlightMat;
    public float thickness =
0.002f;
    public bool thicken = true;
    bool isActive = false;
    public int pressedIndex;
    public bool pressed;
    public bool gripped;
    public bool addRigidBody =
true;
    public bool pickUp = false;
    public bool highlight =
false;
    public bool destroy = false;
    public float reach = 100f;
    Vector3 previousObjPos;
    public float speed;
    public List<string> tags =
new List<string>();

    public RaycastHit hit;
    public Vector3 hitSpot;
    public GameObject otherObj;
    GameObject newObj;
    Transform otherTransform;
    Transform otherParent;
    Renderer otherRend;
    Material otherMat;
    Rigidbody otherRB;
    public bool otherGrav;
    public Vector3 otherVel;
    public Vector3 otherVector;
    Vector3 otherScale;
    Quaternion otherRot;
    Vector3 otherPosition;
    Vector3 projectX;
    Vector3 projectY;
    Vector3 projectZ;

    GameObject pointer;
    public Material pointerMat;
    public Renderer pointerRend;
    Vector3 axis;
    GameObject axisDisplay;

    SteamVR_TrackedObject
trackedObj;
    SteamVR_TrackedController
trackedCon;
    SteamVR_Controller.Device
device;
    TemplateHapticFeedback
haptic;
    UISettings settings;
    NetworkMethods netMeth;

    Vector3 posCurrent;
    //Vector3 dirCurrent;
    Vector3 posPrevious;
    Vector3 posDelta;
    Vector3 dirStart;
    Vector3 controlStart;
    Vector3 angleStart;
    Vector3 rotCentre;

    public float touchX;
    public float touchY;
    float touchXPrevious;
    float touchYPrevious;
    float touchXDelta;
    float touchYDelta;
    float swipeNum;

    float dist;
    public bool bHit;
    Vector3 normal;
    Vector3 hitNormal;
    float distLock;

    Prefabs prefabs;
    public GameObject plane;
    private GameObject planeNew;
    private Transform
planeParent;
    public bool selectionPlane
= true;
    GameObject selectObj;

    GameObject prefab;
    GameObject prefabNew;
    GameObject pointerPrefab;
    Transform heldObj;
    Bounds addBounds;
    GameObject boundbox;
    int shrinkMod;
    float scaleFactor;
    public GameObject Instances;
    GameObject Scenery;
    public bool modeSelected;
    public bool oSnap;
    public int arrayCount;
    float angleLast;
    int cubeID;

    List<Transform> arrayObjs =
new List<Transform>();
    List<Transform> groupObjs =
new List<Transform>();

    // Use this for
initialization
    void Zero()
    {
        posCurrent = Vector3.
zero;
        posPrevious = Vector3.
zero;
        posDelta = Vector3.zero;
        distLock = 0;
        if (axisDisplay)
        {

Destroy(axisDisplay);
            axisDisplay = null;
        }

        touchX = 0;
        touchY = 0;
        touchXPrevious = 0;
        touchYPrevious = 0;
        touchXDelta = 0;
        touchYDelta = 0;
        swipeNum = 0;

        newObj = null;
    }

    void Start()
    {
        Instances = new
GameObject("Instances");
        prefabs =
GetComponent<Prefabs>();
        settings =
GetComponent<UISettings>();
        if (settings.
multiplayerOn)
netMeth = GameObject.
Find("VRPawn(Clone)").

Component<NetworkMethods>();
        plane = prefabs.
SideHighlight;
        Scenery = prefabs.
Scenery;
        Instances.transform.
parent = Scenery.transform;
        prefab = prefabs.Shape;
        pointerPrefab = prefabs.
Pointer;
        boundbox = prefabs.
BoundingBox;
        modeCurrent = mode.Add;

        trackedCon =
GetComponent<SteamVR_
TrackedController>();
        trackedObj =
GetComponent<SteamVR_
TrackedObject>();
        haptic = GetComponent<Te
mplateHapticFeedback>();

        if (visibleRest ||
visibleActive)
        {
            pointer =
Instantiate(pointerPrefab,
transform.position, Quaternion.
identity, transform);
            pointer.
transform.localScale =
new Vector3((thickness),
(thickness), reach);
            pointer.transform.
localPosition = new Vector3(0f,
0f, 50f);
            pointer.transform.
localRotation = Quaternion.
identity;
        }

        //set initial beam
material
        Renderer
pointerRend = pointer.
GetComponent<MeshRenderer>();

        if (customMats &&
matRest)
        {
            pointerRend.material
= matRest;
        }
        else
        {
            Material pointerMat
= new Material(Shader.
Find("Unlit/Color"));
            pointerMat.
SetColor("_Color",
colorHighlight);
            pointerRend.material
= pointerMat;
        }

        if (visibleRest == true)
        {
            pointerRend.enabled
= true;
        }
        else
        {
            pointerRend.enabled
= false;
        }

        switch (pressedIndex)
        {
            case 0:
                pressed = false;
                break;
            case 1:
                trackedCon.
TriggerClicked += Pressed;
                trackedCon.
TriggerUnclicked += Unpressed;
                break;
            case 2:
                trackedCon.
SteamClicked += Pressed;
                break;
            case 3:
                trackedCon.
MenuButtonClicked += Pressed;
                trackedCon.
MenuButtonUnclicked +=
Unpressed;
                break;
            case 4:
                trackedCon.
PadClicked += Pressed;
                trackedCon.
PadUnclicked += Unpressed;
                break;
            case 5:
                trackedCon.
PadTouched += Pressed;
                trackedCon.
PadUntouched += Unpressed;
                break;
            case 6:
                trackedCon.
Gripped += Pressed;
                trackedCon.
Ungripped += Unpressed;
                break;
        }
        pressed = false;
```


Fig. 4.1. Some of the C# code used to implement the custom application.

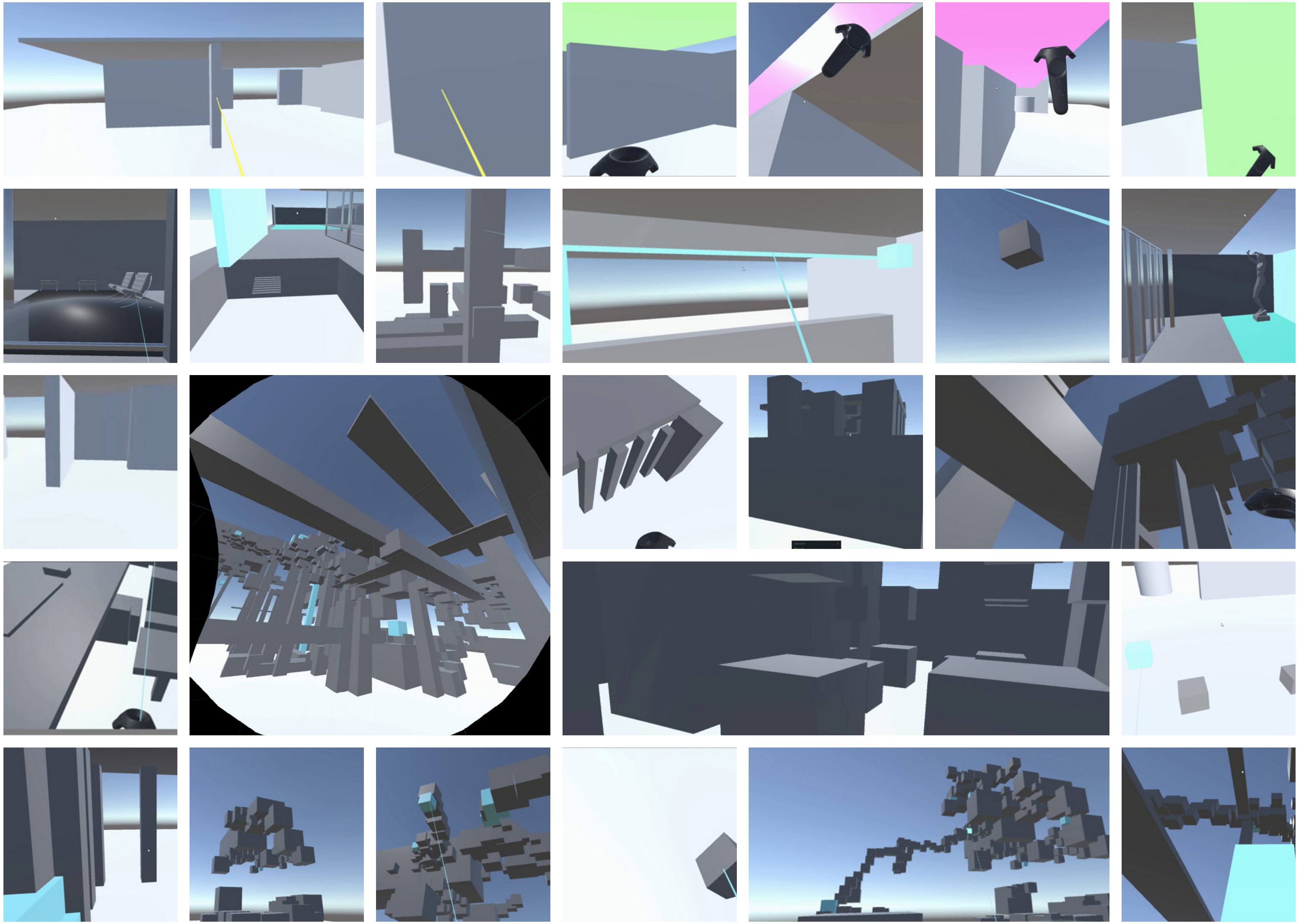


Fig. 5.1. Screenshots of initial development process of the VR application.

5. preliminary design

Tool breakdown

At the preliminary stage of the research, the VR application consisted of 9 main modelling functions: add, delete, move, copy / array, rotate, radial copy / array, push / pull, scale, group / ungroup (fig. 5.1). Within each of these, the trigger and grip buttons enabled two variations of each tool, effectively doubling the possible interactions. It should be noted some usual features of CAD software, such as snapping, dimensioning, and undoing, were not present in this version of the application. At this point, material textures were not applied to the user-made geometries; this decision was made to prioritise the study of form generation and perception.
Although room-scale VR systems such as the HTC VIVE only allow walking within the bounds of the tracking area, navigation beyond these bounds was made possible by teleporting in the digital 3D environment.

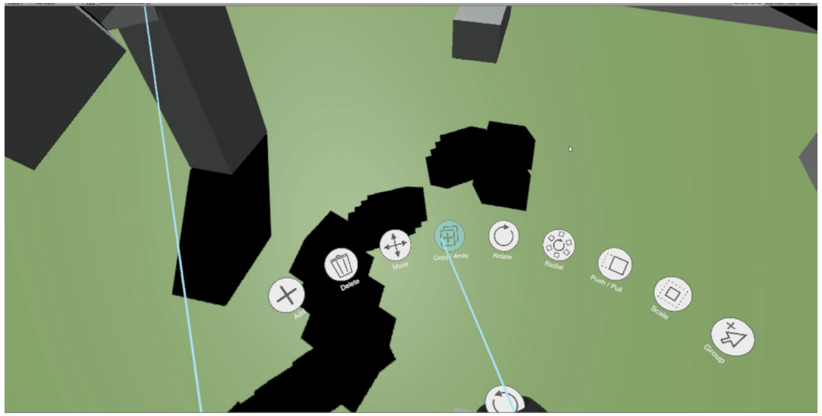


Fig.5.2. A participant selects their choice of tool from a menu in front of them

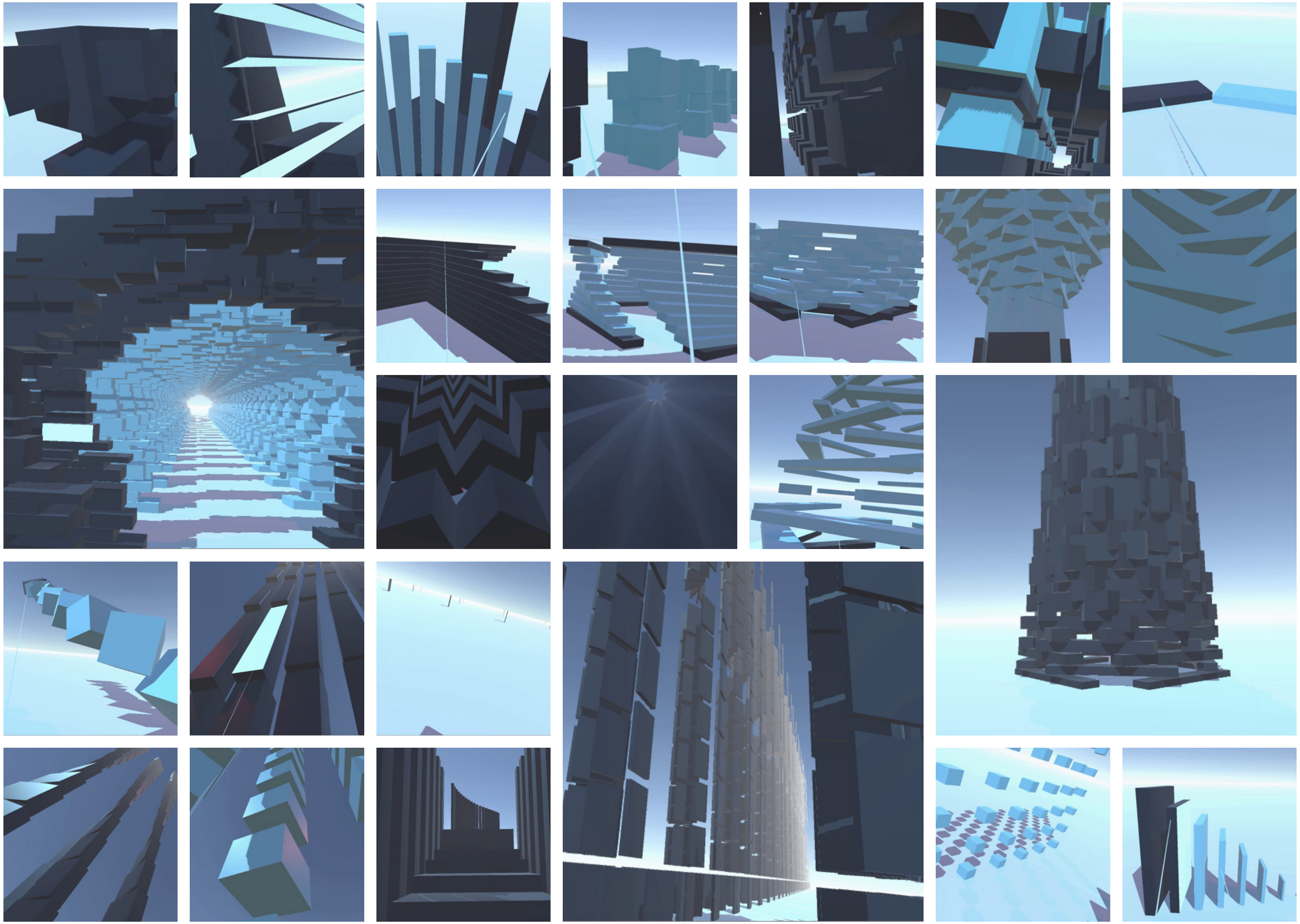
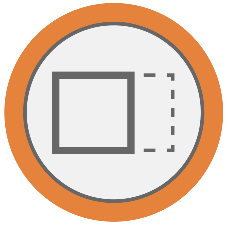


Fig. 5.3. Screenshots of VR-modelled concepts created at the preliminary stage.

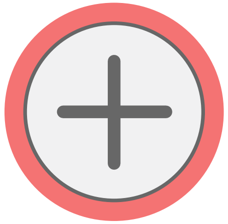
'Sketchspace' Tools

Assumptions, Limitations, and Tendencies



Push/Pull

- *Intuitive method of design*
- *Useful for adjusting sizes*
- *Tends to promote extrusion*



Add

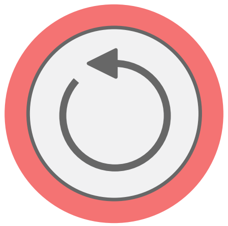
- *Initially only cubes introduced*
- *Produces a distinct aesthetic*
- *A 2-point method is chosen*

Delete

- *Assumes certainty of the designer - undo required*
- *Single click method*

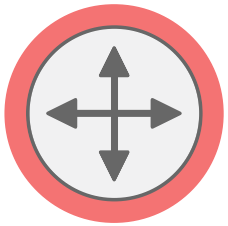
Copy

- *Copies establish pattern*
- *Repetition evokes architectural qualities*
- *Similar mechanics to 'move'*



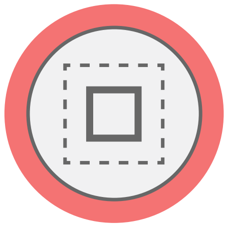
Rotate

- *Plane of rotation required*
- *Difficult to define in VR*
- *Breaks away from the grid*



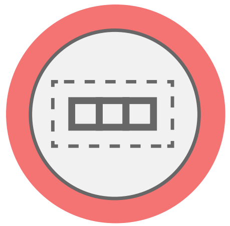
Move

- *Defaults to axial movement*
- *Pulls in direction of face*
- *Free move option lacks control*



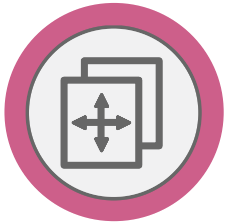
Scale

- *Has great relevance in VR*
- *Origin defaults to base*
- *Danger of over-scaling*



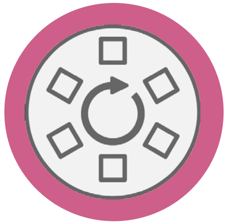
World

- *Changes world scale*
- *Later removed to encourage 1:1 modelling*



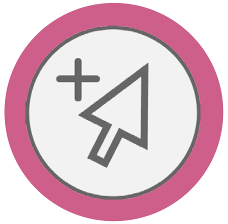
Array

- *Easily makes complex patterns (i.e. parametricism)*
- *VR gives array dimensions greater human significance*



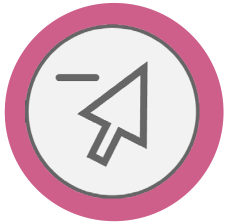
Radial

- *Rotational copy and array*
- *Tends to produce geometries with less functional purpose*
- *'Alien' appearance when not careful*



Group

- *Allows different levels of detail*
- *Nesting groups quickly increases complexity*
- *Discrete objects (e.g. furniture)*



Ungroup

- *Useful for custom manipulation of array elements*
- *Paired with 'group' tool*

Experiment 01 - The 'Communitition'

To study the differences between how designers interact with immersive media and more typical monitor-based software, an experiment was conducted using immersive (HTC VIVE VR headset) and non-immersive (screen-based) modes of the custom software. The two modes were designed to be as functionally similar as possible to control for usability. A comparative approach was chosen as it introduces elements of objective appraisal and is therefore more likely to produce reliable data than self-evaluation (Kim et al., 2013, p. 296). With the tool, designers in either mode were able to navigate through, adjust, and evaluate their architectural concepts as they saw fit.

Sites/ Briefs

For the majority of the project, the tool is tested within a mass model of Wellington. Wellington was selected because it ensured familiarity with the site and its context. Although the exact location were not critical, flat and open urban areas were preferred because of their ease of imagined development and increased ability to allow individual designs to arise. The briefs consisted of firstly, a pavilion dedicated to peace, which acted as a creative but somewhat subjective exercise deliberately lacking a program, and secondly a performance venue, which had more programmatic requirements and consequently more objective criteria.

Set up

A 'communitition,' or community-competition (Segard, Moloney, Moleta, 2013) (fig. 5.4), was used to gather qualitative data about the designs of 16 postgraduate architecture students, through self-reported questionnaires as well as a collective evaluation. Quantitative data was also collected about the dimensions of the designed geometries and the user's interaction with the program. The competition consisted of two phases; a design phase and an evaluation phase.

The Design Phase

For the design phase, participants were asked to respond to two design briefs with a simple architectural intervention in a familiar urban environment. The first brief was for a memorial park, while the second required a waterfront performance space with complex functional parameters. The participants were split into four groups, two of which used either immersive or non-immersive media (swapping for the second design) and two control groups who did not swap media. After a short period getting used to both interfaces, the participants spent 20 minutes on each design and completed a questionnaire immediately after both designs, reflecting on the work produced and their experience. Here, they rated the success of their designs in terms of functionality, aesthetics, and experiential qualities, as well as giving an overall self-rating.

The Evaluation Phase

The evaluation phase consisted of each participant viewing the other designs in a shuffled order. Some evaluated the design in immersive VR and some on-screen. To record the subjective value of the designs, the participants were asked to give ratings for each of the measures which were answered in the questionnaire.

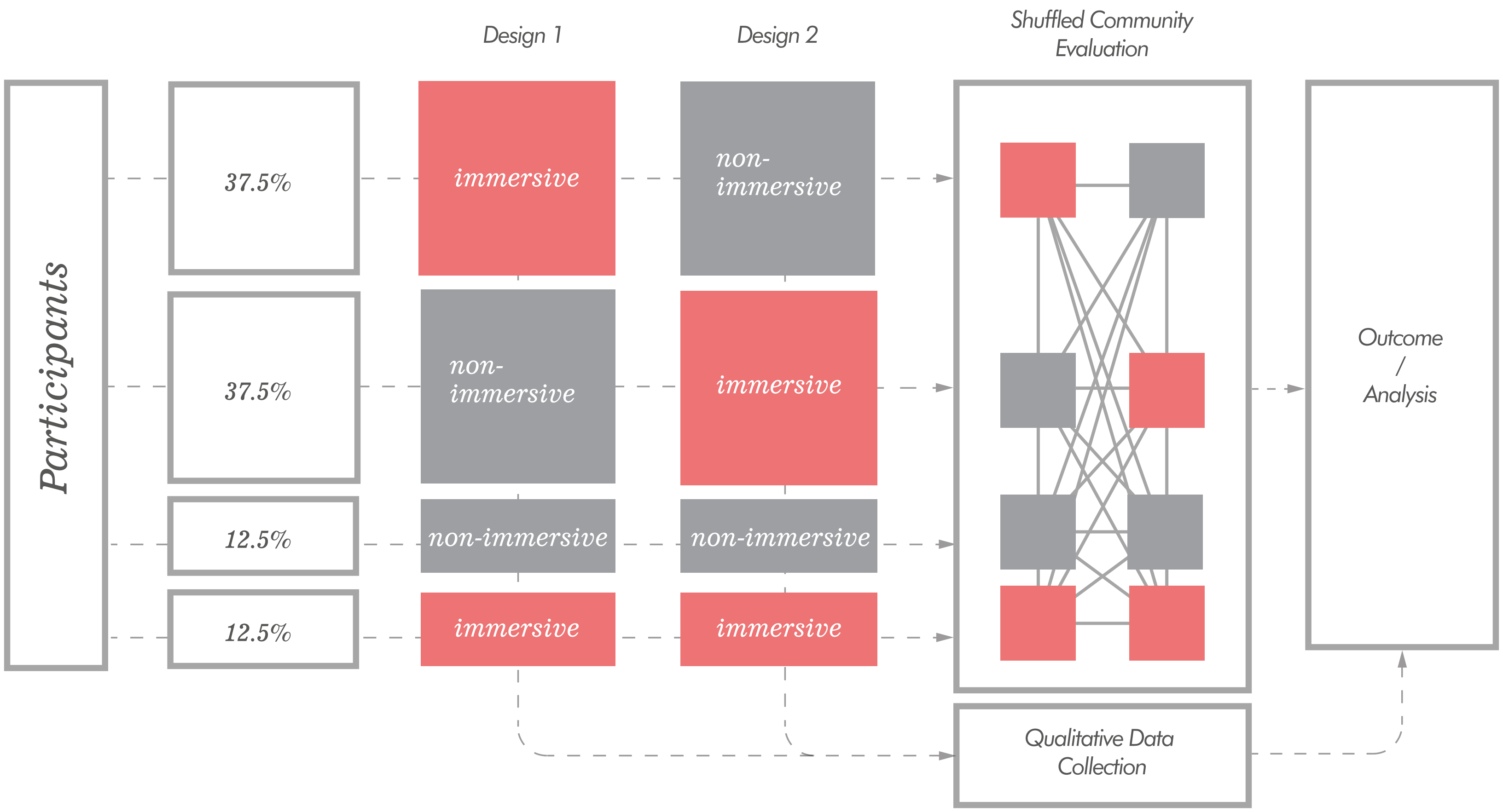


Fig. 5.4. 'Communitition' set-up diagram.

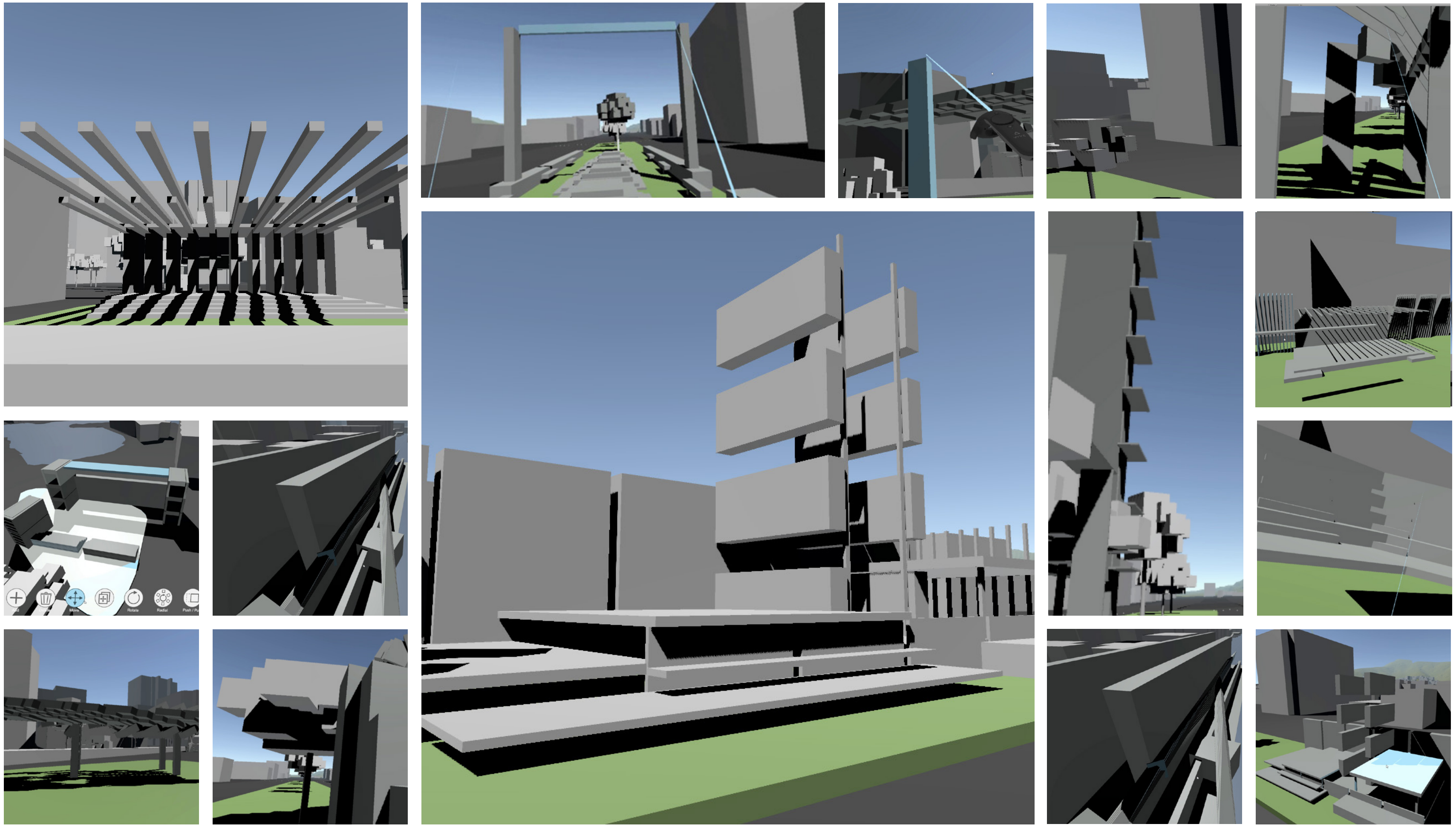


Fig. 5.5. Screenshots of resulting models from the first experiment, comparing immersive and non-immersive modelling modes.

Results

The data from the evaluation produced a highly varied survey sample which was not sufficiently homogenous to reach statistical significance. Nevertheless, some high level conclusions can be drawn from the average tendencies regarding the participants' interaction with the two media. Due to the variability of taste, these averages provide the best indication of an effect on the design quality. On the other hand, the quantitative data showed a clear decrease in completed actions within the VR application compared to the non-immersive equivalent. Together, these results give an interesting perspective on the nature of immersive design interaction.

When looking at the average rating trends (fig. 5.6, 5.7), noticeable differences between designs made with the immersive and non-immersive interfaces become apparent. For design 1, work made in the immersive environment received ratings on average 20% lower in all measures except consideration of the inhabitant, which was 15% lower. For design 2, however, the effect was reversed, and the immersively designed work was rated slightly higher on average. Because of the nature of design, and its expected variance, these differences did not reach significant levels, $F(3,12)$ $p=0.447$, although an effect between media and rating was detected. From this data, we can calculate that such an experiment would require a much less feasible number of participants (~52) to reach significant levels.

As the immersive-based control group showed the most consistent improvement from design 1 (fig. 5.9), familiarity with VR could be a factor in the difference. Further research with greater sample sizes as well as designers with more VR experience is recommended.

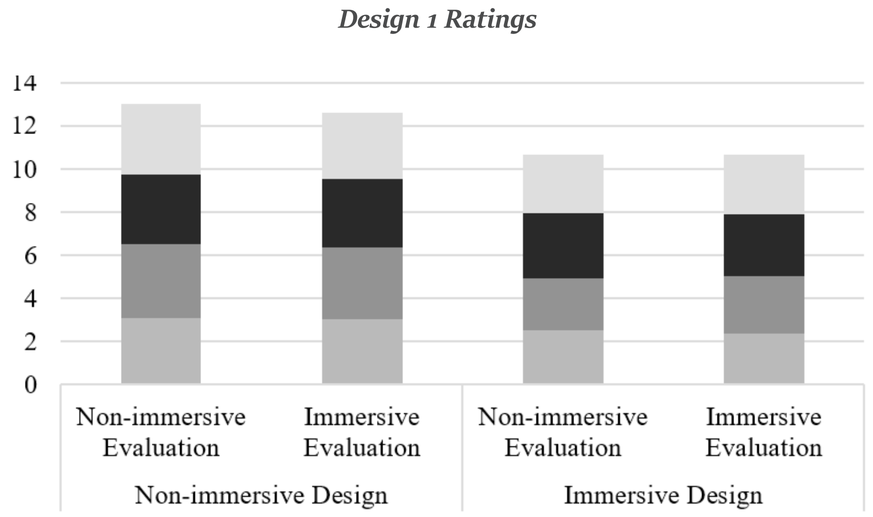


Fig.5.6. Design 1 peer-ratings in four categories

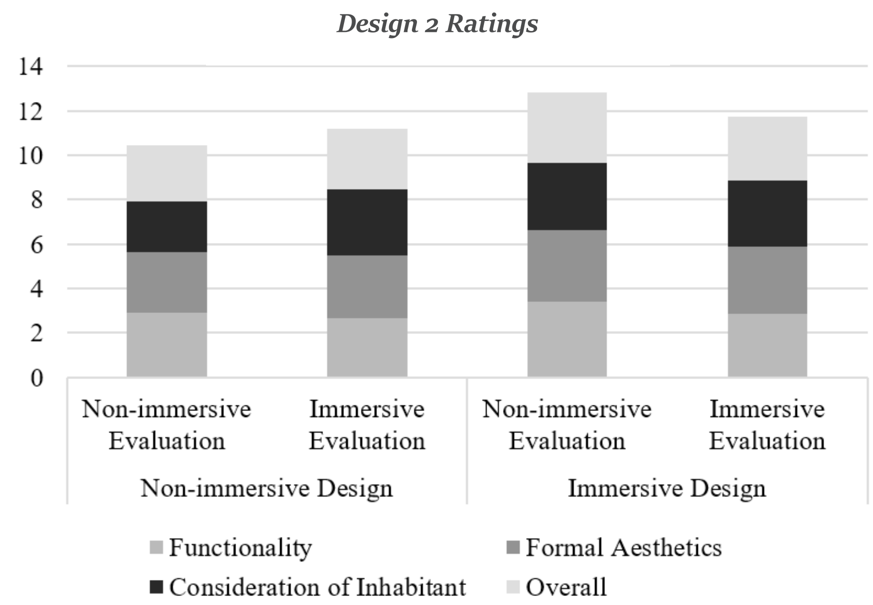


Fig. 5.7. Design 2 peer-ratings in four categories

Quantitative Data

In a more objective light, however, one can see that on average, the participants who used VR in the second design completed significantly fewer actions, F(3,12) p = 0.050 (fig. 5.8), made fewer shapes (fig. 5.9), with generally smaller volumes (fig. 5.10) than their non-immersive screen-based counterparts. The action count of 87.5% of participants in this group dropped greatly from design 1, compared with only 50% of the non-immersive group dropping at all (fig. 5.12).

When considered alongside the comparable ratings that were produced from both media (fig. 5.11), this means that the participants who used VR designed to a similar quality in a more efficient manner. This is compelling evidence for the negative effect that separation of body and space has on a designer's ability to relate themselves to the scale of the object they are creating. It suggests that the 1:1 modelling environment is an effective way to reinforce the visceral understanding of human scale. Of course, as is typical with the creative process, this effect does not easily mitigate outliers;

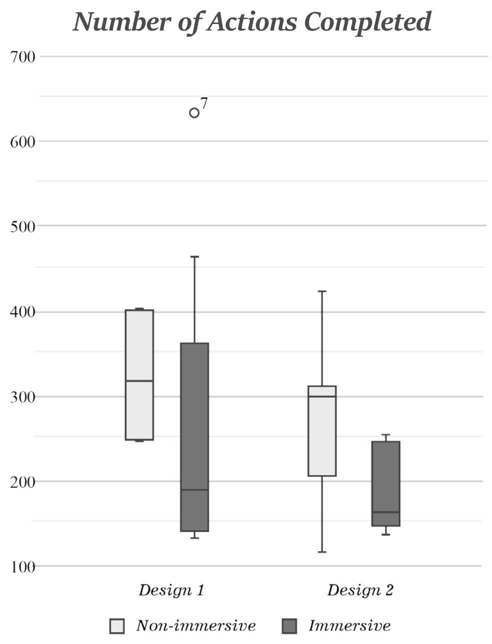


Fig. 5.8. Number of actions (clicks) made in immersive and non-immersive modes.

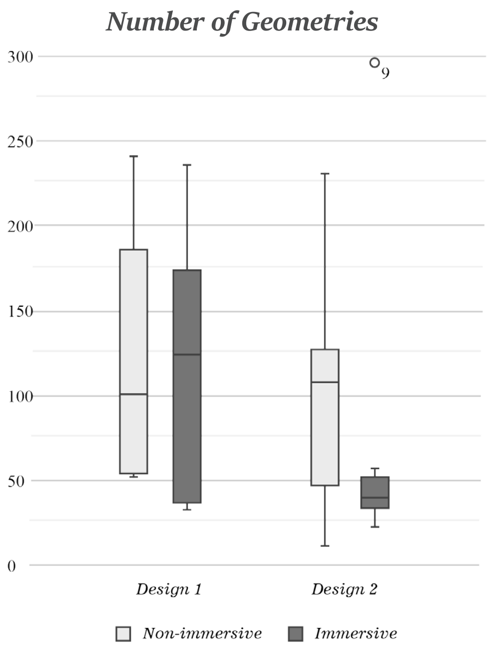


Fig. 5.9. Total geometry count of designs between each group

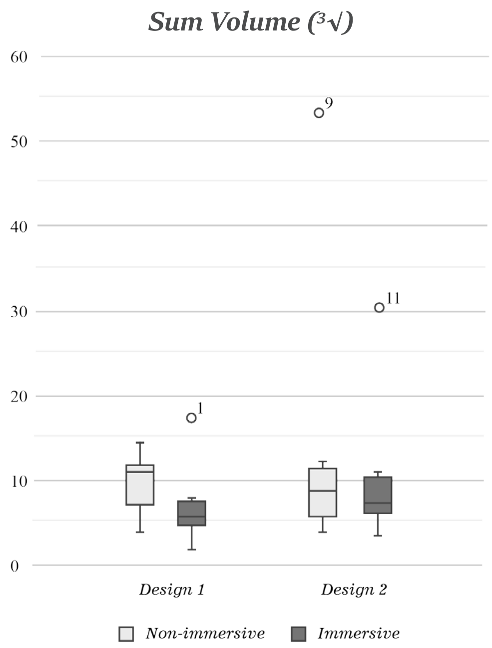


Fig. 5.10. Total volume sum (cubed root) of designed geometry between each group.

essentially, while the medium appears to be strong a factor in the tendencies of the designer, it only encourages certain thinking rather than demanding it.

Self-reported Questionnaire

Several participants of the study reported experiencing a difference in the way that they thought about developing their design while using immersive and non-immersive media. Many noted that they would habitually view their work from above, for a better overview, and this lent itself to conceiving the architecture as an object. Conversely, viewing the design from the human perspective was found to be generally easier, with a greater sense of the intervention's true scale, especially at the detailed level.

Also, for some, the novelty of the immersive environment distracted from the design task. This is consistent with the observation that the participants in the immersive control group improved the ratings of their design for the second brief, at which point their focus would have returned to the work.

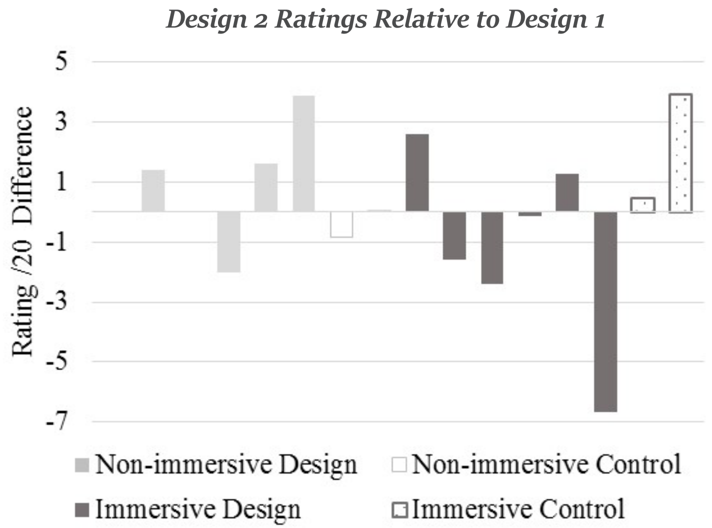


Fig. 5.11. Design 1 peer-ratings of each participant in four categories

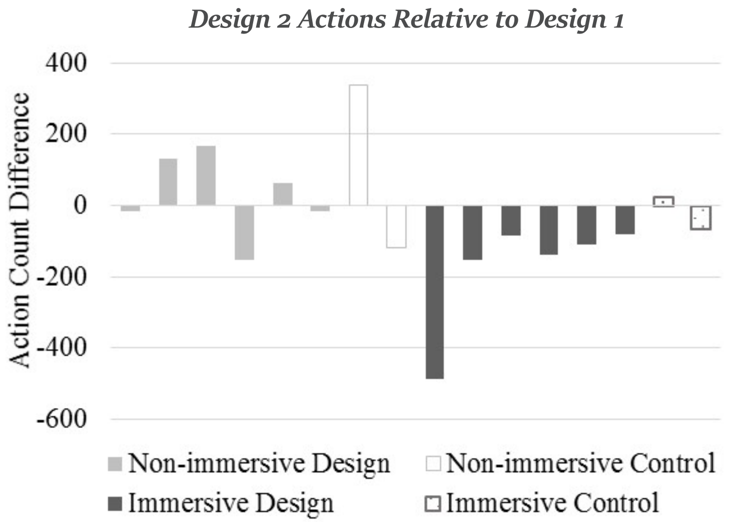


Fig. 5.12. Design 1 action count of each participant in four categories

Experiment 01 - Conclusions & Reflections

There was a great amount of diversity in responses to both briefs and in the subsequent ratings, even across the different media and within each participant. The difficulties in extracting tenable conclusions from these results appear to be a result of the sample size as well as the nature of design creativity itself.

While the qualitative results of the experiment were too varied to gain significant conclusions about the quality of the designed experience, the quantitative data show a clear difference in the way that students modelled with each method. Despite the immersively designed models being rated, on average, slightly higher in design two, the number of actions completed was significantly lower in almost all immersive cases. This suggests that the decisions made within VR are either more individually effective, perhaps because of the increased awareness of their impact on the overall spatial quality, or that they are better considered, since immersive environments reduce the need for the "discontinuous switching" of views to establish one's location and find information (Bakker, 2001, p. 2). This full-body interaction is an improvement over a mouse and keyboard for 3D navigation; the use of the head and legs for viewing and both hands for interaction mean that many parts of the program can be controlled simultaneously. In other words, the dynamic and fluent perception of a modelled object makes for a faster modelling process. This sense of efficiency was also reported by some participants.

An overall trend of improvement was observed for the participants who spent the longest in the immersive mode, whereas for those who only used it once, the lack of familiarity with VR was detrimental. This sort of learning effect is expected and indicates that more rigorous training is required to enable the true potential of the medium. As designers become more experienced with the technology, their use of it and the benefits they get from it my change drastically (Whyte, 2002, p. 29). A larger study with more points of measurement could confirm this.

Likewise, the lack of a fully-developed immersive modelling software limits the degree to which the immersive methods can be compared to existing ones. However, as these kinds of programs reach the level of usability of other CAD software, they may well become more efficient and intuitive alternatives to current digital design methods for the reasons stated above.

While the qualitative and quantitative results produced are interesting individually, they are most compelling when analysed together. The participants using virtual reality objectively tended to do less overall, but reached similar outcomes in terms of subjective evaluation. Donald Schön's The Reflective Practitioner offers a framework to explain this process (1995). If the design process is conceived as a cycle of action and reflection, then the students are constantly making design changes and then considering their overall implications. If virtual reality is able to simultaneously create geometry and offer immersive evaluation of the creation, one could speed up the cycle by minimising the switching between modes of work (fig. 5.13).

From this and self-reported responses, the research indicates that VR can be an efficient decision-making device, provided the decisions involve the future users directly. Immersive methods of visualising and modelling appear to be equally, if not more, capable of producing responsive architectural concepts. Importantly, VR applications which can be used throughout the modelling process, rather than solely after the fact, are shown to be feasible and have novel implications for how designers think about the process. The technology's potential to cause a significant shift in the culture of architectural representation and design is grounded in its natural mode of perception. The intuitive interface means that VR could be suitable for the participation of users who are untrained in reading orthographic drawings, such as clients or members of the public, which is tested in the second experiment.

Unfortunately, the research was limited by the novelty of the technology and, consequently, students' experience with it; yet, as the number of people who are familiar with VR increases, and the software becomes further refined, the opportunities for gaining clearer insights into its efficacy in architectural design will grow. Equally, more research areas will become available as novel applications of VR in architecture are found.

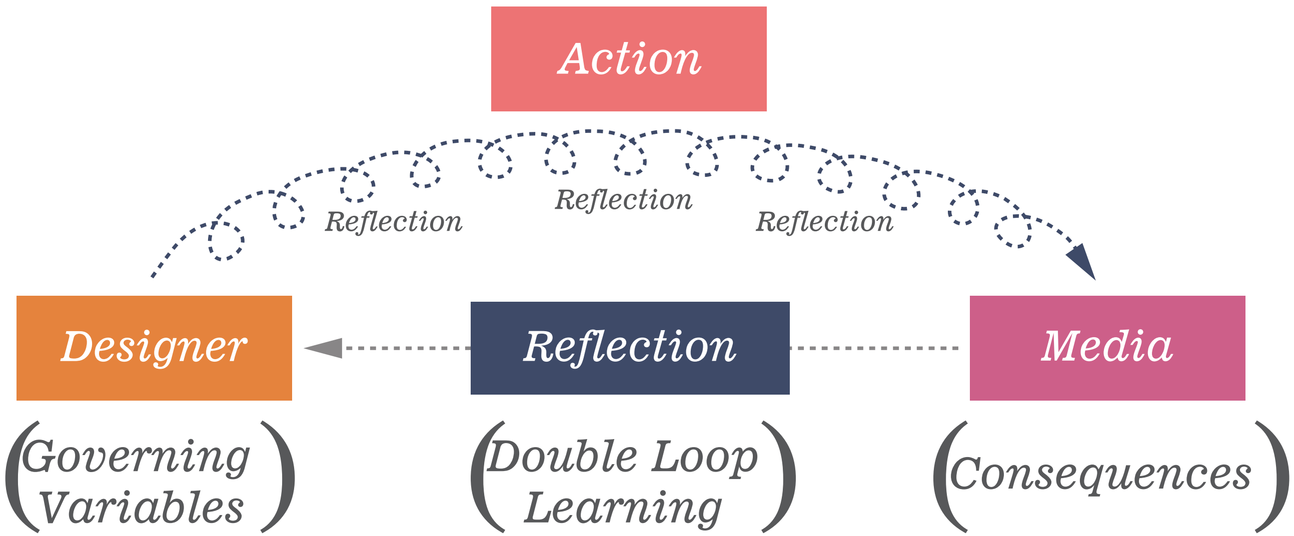


Fig. 5.13. An adaptation of Donald Schön's The Reflective Practitioner in the context of VR design.

Reflection on Design Tendencies

One of the key things that became apparent from this exercise is the importance of ambiguity in the representation, especially when the design is undeveloped. Many texts document the phenomenon, although mostly in an inconclusive or anecdotal fashion (Aspelund, 2010, p. 107; Bafna, 2008, p. 542; de la Fuente Suárez, 2016, p. 48; Pallasmaa, 2014, p. 235; Scheer, 2014, p. 217; Smith, 2005, p. 3, p. 208; Whyte, 2002, p. 30, Zumthor, 1999, p. 12-13). In fact, according to these sources, taking advantage of ambiguity in the medium leaves room for imagination, flexibility, and creativity as the mind fills in the 'gaps in the representation'. This is particularly troublesome for computational representation in design as there is an "inherent conflict between precision and imprecision" (Smith, 2005, p. 208). Similarly, because VR softwares are inclined to produce photorealistic renderings, subverting this takes a conscious decision on the developer's part. Incorporating this principle into VR design is an area in which further research would provide useful insights.

Each mode of representation has different levels of abstraction and portrays different amounts of information. These variables can greatly affect the way the design is read, influencing its conception and reception within the minds of those engaged. For example, if a designer attempts to include more information in the representation than is designed, the representation falls short of its goals and feels hollow. This paradigm is hinted at in Smith's book (2005) where James Gibson is quoted: "a picture cannot at the same time possess high fidelity for something concrete and high univocality for something abstract" (p. 208). The extent to which architects should employ realism in their design drawings depends on the narrowness of their desired representational focus (abstraction) and the development of their design (information). In the future, exploring more representations in the 'less information' and 'less abstract' corner of the representation chart could be fruitful in finding new methods of spatial ideation with greater ambiguity (fig 5.14).

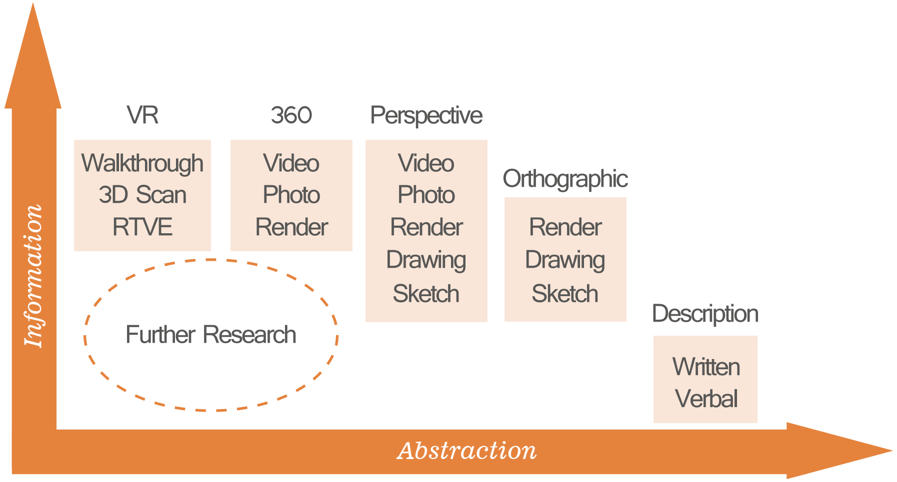


Fig. 5.14. Diagram of the relationship between abstraction and information in architectural media.

Some of the resulting designs were stifled by the limited available geometries for use; despite the tools often producing great complexity, failure to think beyond the software's limits leaves the designer falling back on the default. It is this point where the software has a strong influence on the outcome of the design. When something is done because it is easy to do in the modelling environment, the designer substitutes complacency for creativity. The existence of buildings which appear to be 'Revit' architecture or 'Grasshopper' architecture highlight this issue. Future VR modelling software must avoid these replacements for thorough design wherever possible.

Exploring modes of geometry creation was a topic that came up in the preliminary review of the research. In subsequent iterations, creation tools which pushed beyond those of unit-based geometries, including the voxel and draw tool, became a focus of the development. This attempted to solve some issues of designs being excessively influenced by the software's default.

One manifestation of this problem, ironically, is the VR application's reliance on the body as the cursor. When picking up and copying objects with the free-move tool, the objects remain at a fixed distance from the hand, resulting in shapes which tend to be placed equidistant from the body, in a spherical formation. The centrality of the body is at once a blessing for VR design and a curse since it makes the perceiver the focus of the design, but also subverts the logical structure of a more orthogonal design, say. This is inherently rooted in Kengo Kuma's dichotomy of viewing methods - the overview and the simulation - which suggests that designing solely within an immersive environment has conceptual limitations.

Some participants reported that they naturally wanted to view their designs from above, as if from a plan view, reinforcing the idea that VR is suitable for some aspects of the design process, but falls short in others. This is assuming that these participants felt this way because they understood such a view to be helpful for their design, rather than out of habit. If this is the case, and VR is to be used in such situations, it would necessarily be used in combination with other media or at least various viewing modes within the headset. A similar conclusion was made in the 2016 paper by de la Fuente Suárez who suggested that "the combination of both kinds of [pre- and post-experiential] representation in an architectural project would complement their strengths" (p. 58).

6. developed design

Tool Breakdown

At the developed stage, the custom application contained 15 functions:
add, delete, group/ ungroup, change material, move, copy/ array, rotate, radial copy, measure, push/pull, scale, morph, voxels, draw. The interface also included a settings menu with five options:
Snaps, visibility, shading, haptic feedback, and swipe to extend laser.

Fig.6.1. Screenshot of the menu of available tools in the developed stage, as seen through the VR headset.

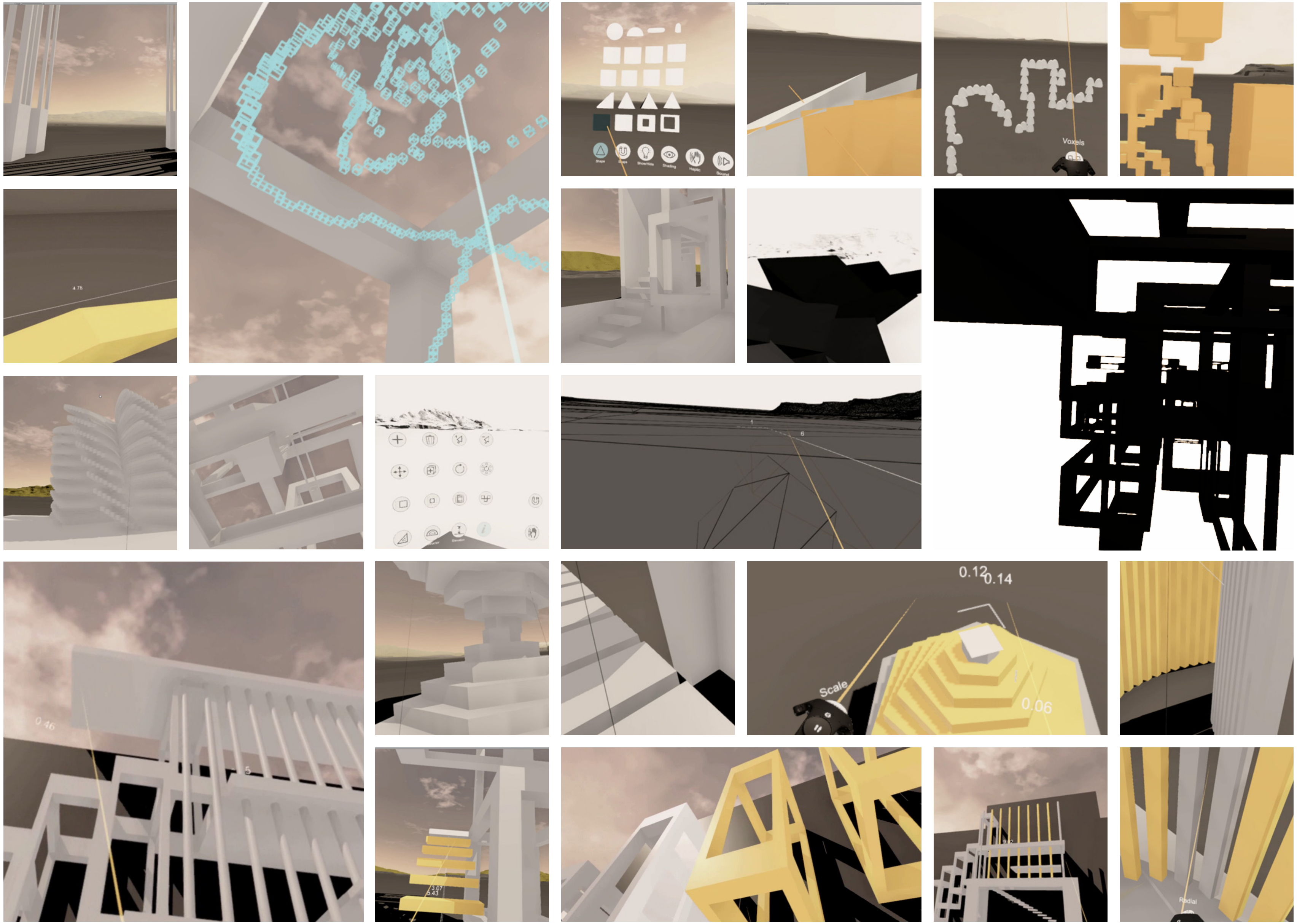


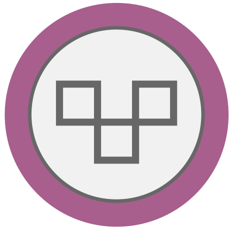
Fig.6.2. Screenshots of testing at the developed stage, showing the voxel tool, dimensioning, and shading settings.

'Sketchspace' Tools

Assumptions, Limitations, and Tendencies

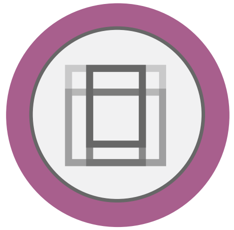
Shapes

- *Allows more diverse geometries*
- *Tends to prompt the design*
- *Unusual results when combined with the 2-point creation method*



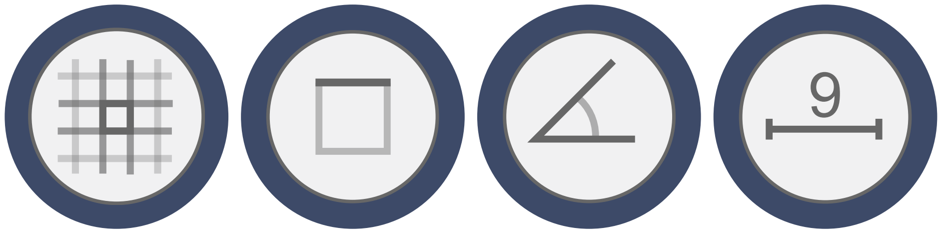
Voxels

- *(A.k.a 3D pixels)*
- *Acts as a drawing tool*
- *Becomes an effective volumetric massing tool at larger sizes*



Morph

- *Random scaling of a group of objects*
- *Shuffles shape size for inspiration*
- *Not useful for more detailed design*

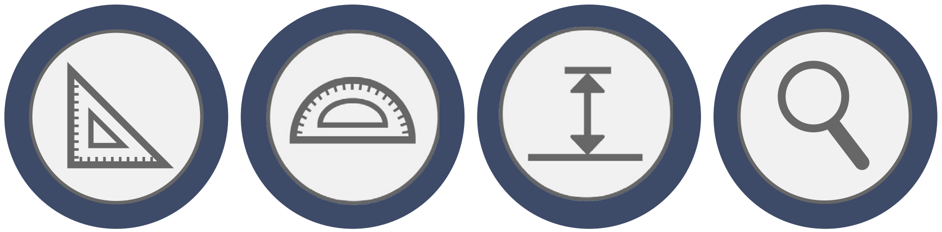


Snap Settings

- *Very powerful settings for a more controlled design experience*
- *Allows the precise alignment and organisation of objects*
- *Important for anticipating construction requirements later*

Visibility Settings

- Control over the interface is standard in industry, however it was under-utilised in the context of the concept design environment.
- Typically not used when creating in a playful and unfocused way
- Contrast of views is important for deeper understanding, yet users tended to stick with the default.



Evaluation Tools

- Useful for intuitively evaluating site properties
- Not frequently used, possibly due to the perceived lack of a need to be precise during the concept design stage

Experiment 02 - Public Engagement

After feedback from the second review, it was identified that the VR application, because of its intuitive interface, could have a greater use for public engagement. Theoretically, those who have a limited understanding of architectural conventions could more effectively engage with design projects from simple immersive representations and intuitive modelling tools. An experiment was conducted to test this, involving the residents of Karori in the design of their urban environment. Karori was selected because it has been identified by the Wellington City Council as a suburb designated for further urban development and densification. People in the local library were asked to participate in an immersive exercise; a detailed model of the town centre was offered as a platform for the participants to express their visions for how their neighbourhood could be improved upon. A project like this engages the residents with the urban design process and gives the locals a chance to consider and influence the shape of their future township.

Brief & Set up

The task given to the participants was left quite open ended, but focused on the development of their main street and its appeal as a public space. The users were asked to identify an issue with the environment and directly edit the model to express any creative solutions which they wanted to try. Possible solutions included placemaking, higher-density development, or infrastructure adjustments. Throughout the exercise, they verbally evaluated the success of their intervention.

The participants were allowed to spend as much time as they felt appropriate for expressing their thoughts. Similarly to the first experiment, quantitative data was collected about their models, including the number and size of the geometries, actions taken, and time taken. This is complemented by qualitative data which was gathered through a self-reported questionnaire completed immediately after the experience. From these sources, the study attempted to gather information about their ability to assess and create indicators of desired spatial quality. This process has the potential to open up discussion about architecture and urban design to the wider public and make their involvement feel personal and direct rather than auxiliary.

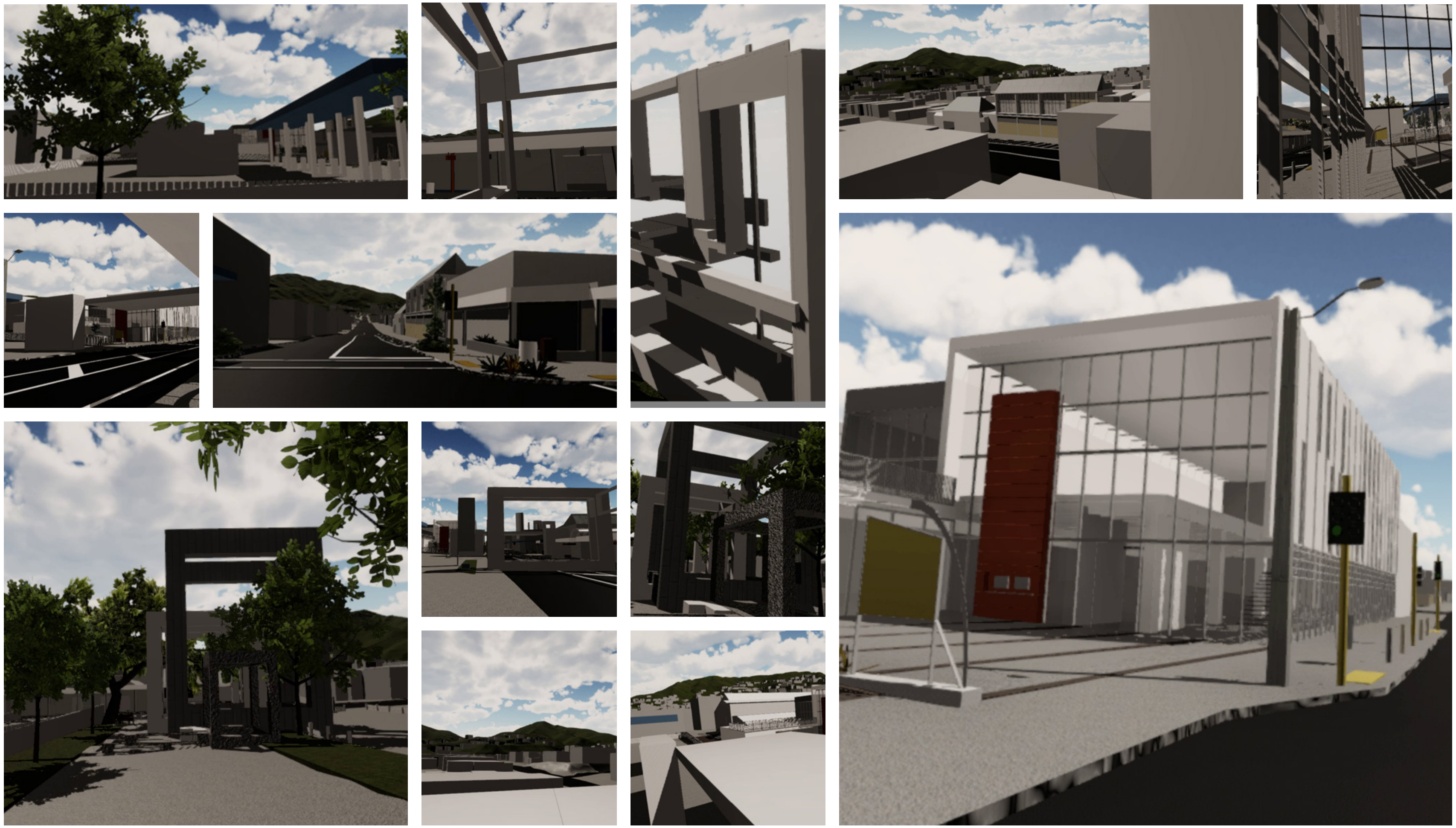


Fig.6.3. Screenshots from the second experiment's Karori model and the public-generated interventions.

Results

In total, the results from eight participants was recorded. Quantitatively, the public created significantly fewer geometries than the students of the first experiment because they spent on average just under half the time, a median of 8 minutes. However, with an average of 33 executed actions (clicks), their average rate of creation at 3.4 actions per minute was comparable to that of the architecture students' 3.2 actions per minute from the first experiment. This seemingly low rate includes the time taken to navigate and evaluate the model.

The second experiment was much simpler than the first because access to the participants was limited. The participants had no minimum time and no prescribed goal and therefore seemed to lack creative direction in their activity. Data showed that the default tool, 'Add', was used significantly more than other tools, suggesting that they had less interest in trying more nuanced approaches to the application's use. Combined with a lack of training in thinking creatively and three-dimensionally, these factors meant the participants demonstrated little promise in exploring the medium's potential. Comments about what they could do if they had more training or invested more time into it were commonly reported, which indicate that with greater exposure these results could reverse; however, further experimentation is required to determine the point at which this might occur.

Qualitatively, feedback regarding the understandability of the model (fig 6.4), ease of creative expression, and evaluation was neutral, while the ease of ideation was marginally positive. Although perfectly capable of understanding the urban model from its high level of detail, some participants struggled to get used to the interface and their interaction was not as seamless as predicted. This weakness is most likely because of their inexperience with 3D modelling tools.

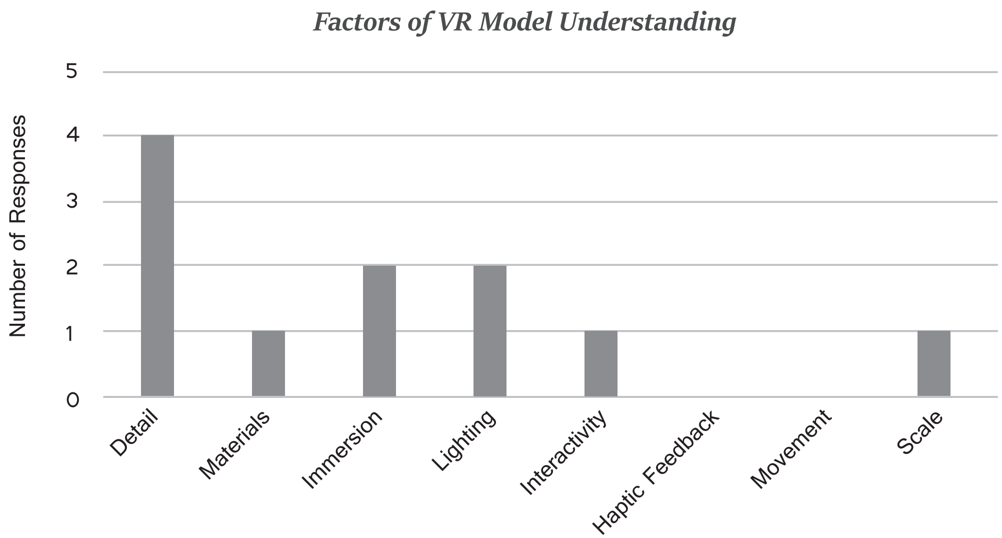


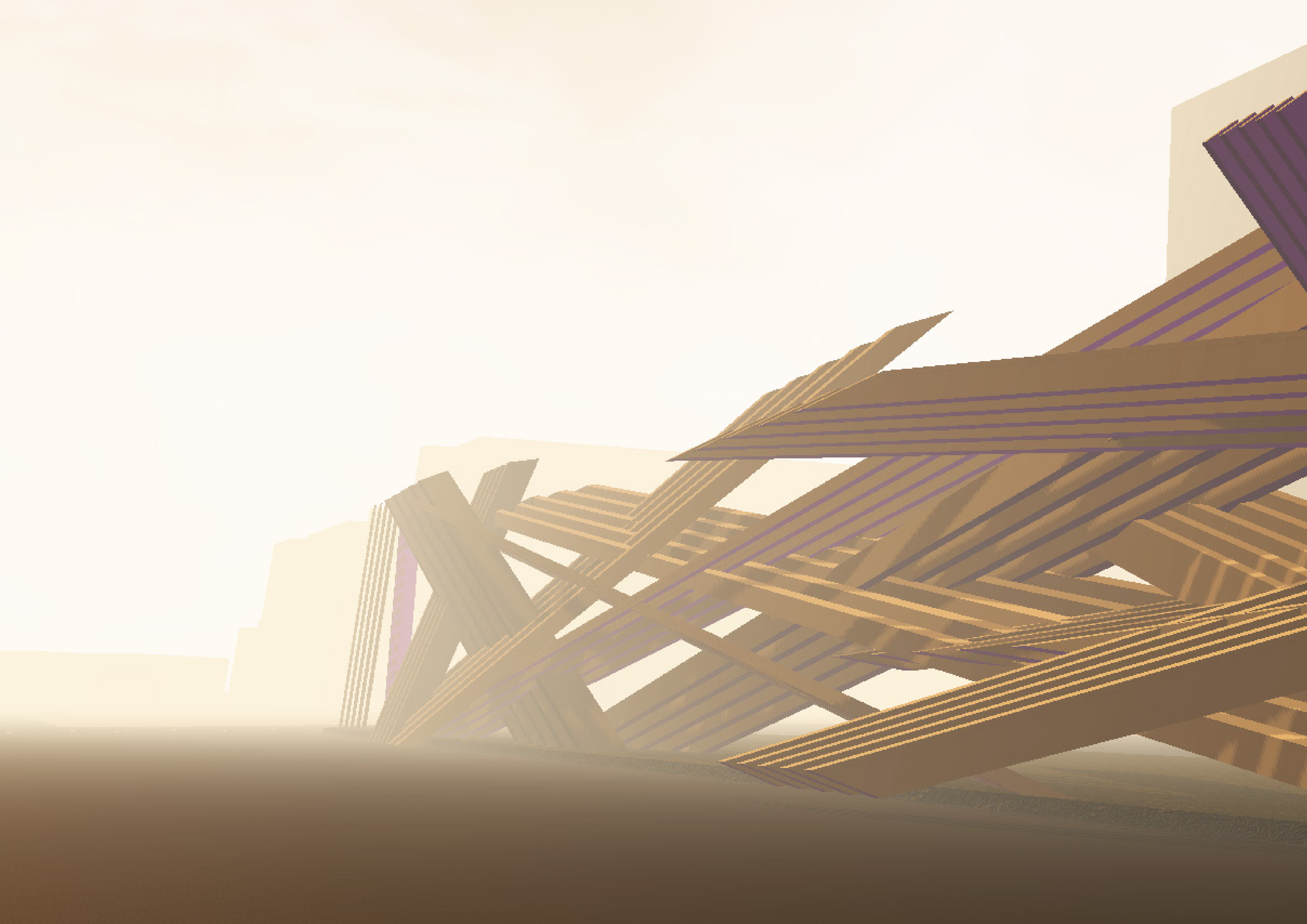
Fig. 6.4. Chart of the factors which were reported to have the most significant impact on model comprehension.

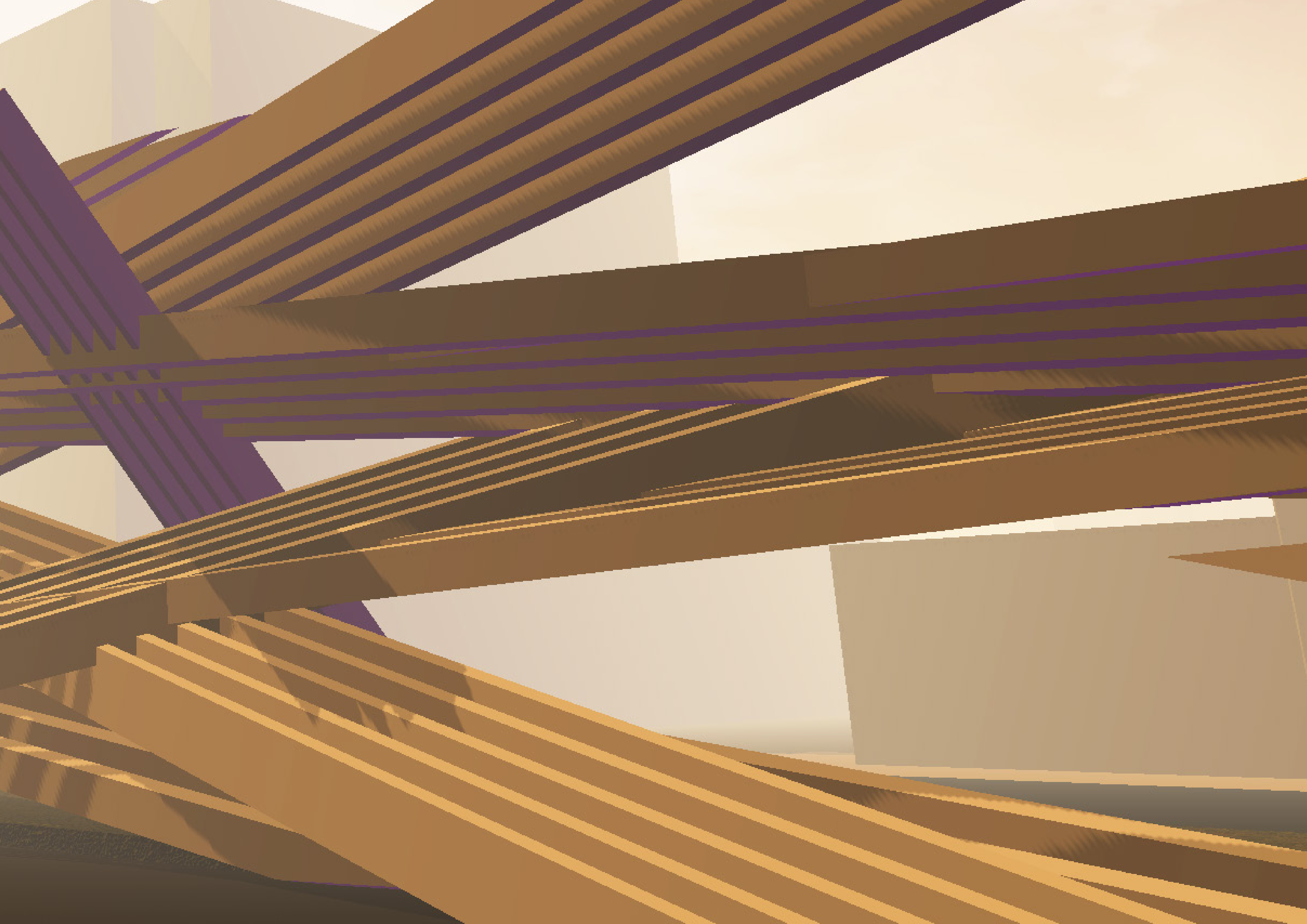
Conclusions & Reflections

Unfortunately, due to the small sample size, more definitive and statistically significant results were unable to be gathered. Nevertheless, the role of members of the public in urban design cannot be discounted. Much enthusiasm was shown toward the novel method of visualisation. The engagement with the interactive process itself could be made more clear with adjustment of the testing conditions. In the future, a 'training period' to allow the user to get used to the tool and its capabilities, as was done in the first test, will likely produce more confidence in expression and therefore greater diversity in responses.

Although the participants were mostly random, the selection method was problematic for two reasons. Firstly, the participants were self-selected. Only those who had an interest in 'trying out' the technology generally took part. This meant that it is possible that people who were the most inexperienced were recorded in the study. Equally, however, it could be that those who were most creative and curious volunteered. Secondly, the demographics of Karori skewed the participants towards elderly and families, tending to bias participants towards those who are not digitally savvy. This bias was potentially exacerbated by selecting for those who would typically visit the neighbourhood library on the weekend, for example parents with smaller children.

In this developed application, the voxel and 3D draw tools, while an evocative attempt at more undefined, 'sketchy' geometries, was plagued by the same issues as the free-move tool: users tended to draw around themselves in a spherical formation, rather than inventing creative ways to break from the default constraints. If these tools are to wrest free from their biases, they need to have a greater ability to be used independently from the circular motion of a person's limbs.





7. discussion & conclusion

Proposed Workflow

As a culmination of the conclusions made throughout this research process, a hypothetical workflow (fig 7.1) demonstrating the potential uses of VR within a design process is presented. Although these suggestions indicate one medium being better suited for some tasks, one must consider them with the caveat that every architect has tendencies and skills of their own which influence which media they find comfortable to work with. The process of design is one that is impossible to define with certainty because of the divergent nature of the work. With that in mind, these habits can and should be challenged to elevate the positive impact of the work on the lives of those it concerns. As such, this result is more of an outline of areas where the current methods could be made more effective through the thoughtful implementation of immersive tools.

The diversity of media in the suggested workflow highlights a critical quality of the way architects must think: broadly. Architectural knowledge is full of details and obscurities which must be applied to a design from every angle. It must be viewed and considered in sufficiently various ways that a three-dimensional artefact can be constructed such that it has the appropriate functional and formal properties. Virtual reality has the advantage of its intuitive and natural navigation so that three-dimensional perception is effortless; however, it simultaneously tends to have an often excessive level of realism while also having limited overview capabilities.

This is an indication that even true perception is less useful in a design context than initially assumed. Our vision and other senses do not provide us with comprehensive information about a building because the information is gathered from a single point - the body. For architecture, at least, this alone is insufficient. The existence of drawing techniques which reveal the hidden, such as sections or exploded drawings are a testament to this. Not one single technique has the ability to capture all the information needed to evaluate a design; rather, many different views and viewing styles are required to ascertain the maximum amount of information. In fact, it appears that the goal is greater flexibility in transferring between representational modes so that the designer has complete control over which qualities are made salient and therefore evaluated most effectively.

Audience Efficacy

Architecture Students

By studying how post-graduate architecture students interacted with the VR application, this research found a slight effect on the creation and self-evaluation of their designs. There is promise for the medium to provide an intuitive and more efficient conceptual modelling platform. With further refinement, VR will only become faster and easier to use, eventually getting close to replicating the "creative impulses of hand sketches" (Smith, 2005, p. 208). If this is to be possible, however, further work will need to be done to push the ambiguity of the representations to reflect the partial nature of a hand-sketch. Because these experiments were short-term and limited to conceptual models, the long-term implications of this, perhaps in a pedagogical paradigm, remain inconclusive.

Architects

Although this study did not get the chance to conduct a formal experiment with architects, designers from a local firm tried the application casually and offered their feedback. Features suggested by these architects, such as the dimensions and measuring tool, were eventually implemented into the program. Tools like these mean the interfaces do not rely solely on subjective judgement, thus making it more useful for professionals. They recommend that In future versions of such VR applications, greater control over these dimensions is a necessary criterion for its professional applicability because of the abundance of standard dimensions and ergonomic constraints. Since keyboard input is no longer feasible in the case of handheld controllers, further research would need to be done to achieve the efficient and effective specification of exact quantities.

The Public

This study failed to produce definitive results about the use of VR design tools in engaging the public. However, the results that were produced gave strong indications that lay people lack the training and experience to convey their ideas effectively in an immersive modelling environment. Visualisation was the opposite, because it involves almost no prior knowledge of the interface. This would suggest that other untrained individuals would still benefit from the guidance of an architect or other design professional. Research into linking VR headsets so that both parties interact with and evaluate a model simultaneously could produce more positive outcomes.

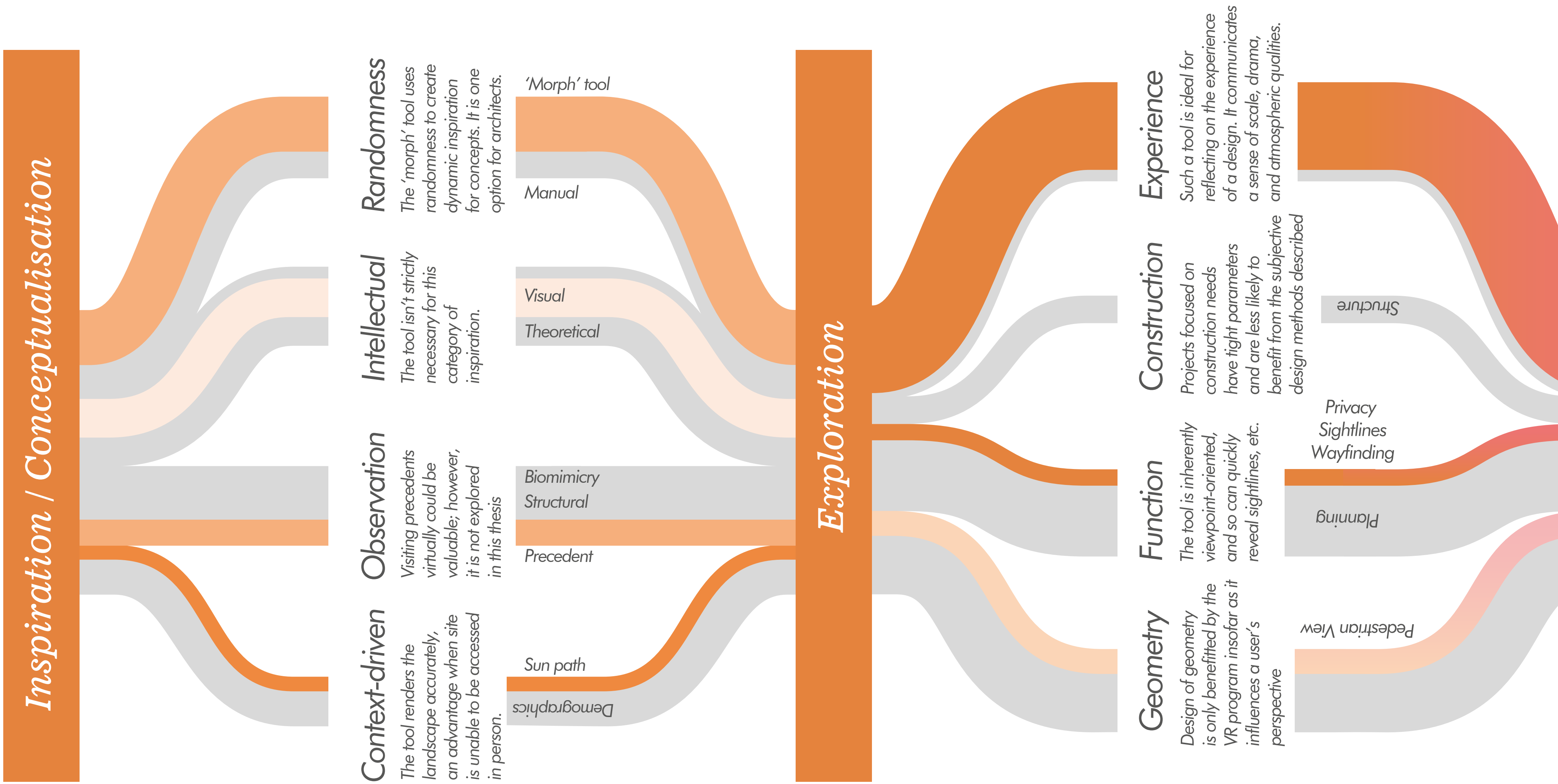
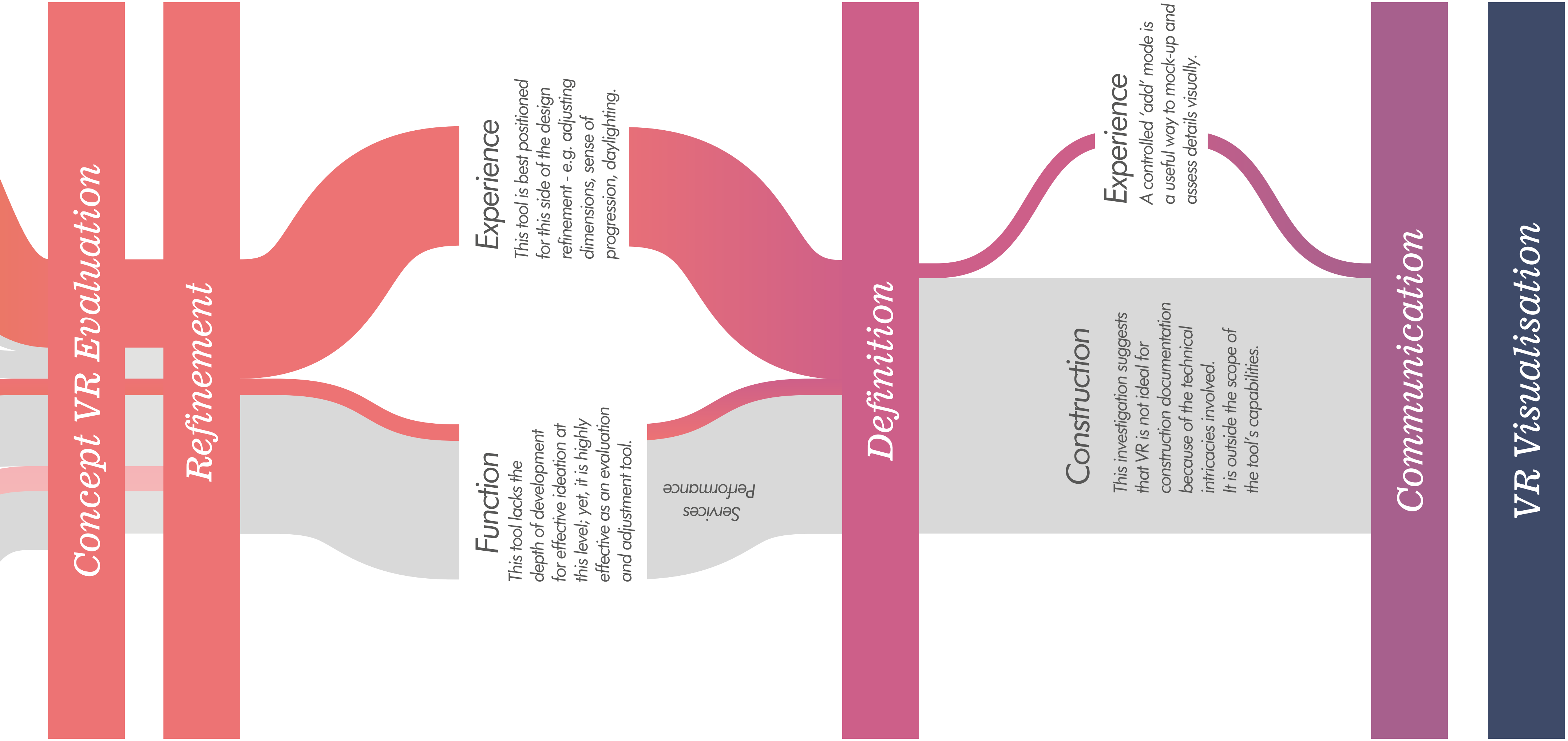


Fig.7.1. Karl Aspelund's design process (2010) and how it might integrate VR for architects.


Concept VR Evaluation
Refinement
Experience
This tool is best positioned for this side of the design refinement - e.g. adjusting dimensions, sense of progression, daylighting.
Function
This tool lacks the depth of development for effective ideation at this level; yet, it is highly effective as an evaluation and adjustment tool.
Services
Performance
Definition
Experience
A controlled 'add' mode is a useful way to mock-up and assess details visually.
Construction
This investigation suggests that VR is not ideal for construction documentation because of the technical intricacies involved.
It is outside the scope of the tool's capabilities.
Communication
VR Visualisation

Reflection

This thesis had two aims: firstly, to connect experience and representation, and secondly, to find where VR sits within the architect's toolkit. In retrospect, the first aim appears to be presumptuous because it implies that representation should reflect reality. The research indicates that this isn't necessarily true. The truth is that representational method is a choice which depends on many factors, including the time and resources available, the audience, the creative style, and of course the aim of representation itself. Defining how these factors interact is a lofty goal which is unrealistic for this research and perhaps even unnecessary. All this study can hope to do is provide frameworks and evidence for architects to make informed decisions about their own work. In this sense, the study was successful, but not in the way that was originally expected.

The second goal was perhaps more grounded. Interrogating the first aim naturally generated answers for the second, in reality. The researched and proposed frameworks used to explore how VR can be effective in spatial design also explain what it is and is not useful for. The creation of the custom application was an effective method for answering these questions because it directly confronted the boundary between the needs of the designer and how the tool caters for them. The fact that assumptions made at the beginning of its development became an integral part of the software made it difficult to compare many approaches. The sheer number of possible interactions also mean that it is not feasible to cover all with a single project. Nevertheless, what was created gave insight into the value of this permutation which is informative in itself. What is especially surprising is the diversity in responses from each audience. The skills and priorities of each group gave the technology evaluation three new perspectives which were of great importance to the study.

Future Work

Recommendations for future work have been identified throughout the research and are summarised here:

- Testing VR with greater software functionality, such as mesh editing, NURBS curve geometry, networking, or more detailed parametricism would add further depth to the research in the field and explore a wider variety of possibilities for the medium.
- Exploration of immersive tools which can integrate intuitive numerical input would give more precise control to architects when dimensioning modelled geometry.
- The study of modelling techniques which subvert the tendency of the movement and position of the body to influence the shape of the design.
- Studying the effect of ambiguity in VR design shows promise for enabling more creative ideation. This is difficult to achieve because of the tendency for VR software to render realistically.
- Further studies which include longer periods of observation, more participants, or more intensive training are suggested to improve the quality and reliability of the data.

Conclusion

Architects are in the business of anticipating the implications of their design decisions; this study suggests that virtual reality helps to do this in a way which current media are unable to. The student participants of the first study showed the developed application to be an effective alternative to conventional, monitor-based modelling softwares and performed similarly between the modes. Architects found the subjective approach less feasible for everyday modelling tasks, but could see the potential after further control mechanisms are added to the interface. Meanwhile, members of the public reported it to be a useful visualisation tool but needed more training before modelling became effective for them. Overall, while VR exceeds the capabilities of more traditional methods in some areas, traditional techniques are still the most effective method for others; the two represent two different approaches to viewing architecture, and by extension, two different approaches to thinking about architecture. A thorough design process is a balancing act of objective and subjective evaluation, reason and emotion, considering every detail while maintaining a clear view of the whole. Architects must not forget that architecture is a human-focused science as well as a human-directed art. The media used to represent architecture should reflect both of these goals and, in turn, allow designers to confer with the design in a sufficiently well-rounded manner.

Bibliography

Abdelhameed, W. A. (2013). Virtual Reality Use in Architectural Design Studios: A Case of Studying Structure and Construction. *Procedia Computer Science: International Conference on Virtual and Augmented Reality in Education* (pp. 220–230). Puerto de la Cruz: Elsevier B.V.

Abdelhameed, W. A. (2014). Creativity and VR Use. Rethinking Comprehensive Design: Speculative Counterculture. *Proceedings of the 19th International Conference on Computer-Aided Architectural Design Research in Asia* (CAADRIA) (pp. 719–728). Kyoto: Kyoto Institute of Technology.

Achten, H., Arthur, T. (1999). Virtual Reality in Early Design: The Design Studio Experiences. *Added Value of Computer Aided Architectural Design (AVOCAAD) Second International Conference* (pp. 317-326). Brussels: Hogeschool voor Wetenschap en Kunst Departement Architectuur Sint-Lucas.

Aguilera, S. (2008). *A New Perspective: A New Understanding of Perspective for all Visual Art Forms Including: Drawing, Painting, Photography, Motion Picture, and Video Game Design* (Universal ed.). El Sobrante, Calif: Artistech Books.

Angulo, A., Vásquez de Velasco, G. (2013). Immersive Simulation of Architectural Spatial Experiences. *Knowledge-based Design: 17th Conference of the Iberoamerican Society of Digital Graphics* (SIGraDi) (pp. 495-499). Valparaíso, Chile.

Angulo, A., Vásquez de Velasco, G. (2015). Virtual Sketching: Instructional Low Resolution Virtual Reality Simulations. *Proceedings of the 19th Conference of the Iberoamerican Society of Digital Graphics* (SIGraDi) (pp. 506-513). Florianópolis, Brasil.

Asanowicz, A. (2016). Digital Architectural Composition - 30 Years of Experience and Experimentation. Complexity and Simplicity: *Proceedings of the 34th International Conference on Education and Research in Computer Aided Architectural Design in Europe (eCAADe)* (pp. 195-203). Oulu, Finland.

Aspelund, K. (2010). *The Design Process*. New York, NY, Fairchild Books.

Bafna, S. (2008). How Architectural Drawings Work — and What That Implies for the Role of Representation in Architecture. *The Journal of Architecture*, 13(5), 535-564.

Bakker, N. H. (2001). *Spatial Orientation in Virtual Environments* (Unpublished PhD thesis). Design, Engineering and Production, Delft University, Delft, Netherlands.

Beckmann, J. (1998). *The Virtual Dimension: Architecture, Representation, and Crash Culture*. New York, Princeton Architectural Press.

Bloomer, K. C. & Moore, C.(1977). *Body, Memory, and Architecture*. New Haven, Yale University Press.

Ching, F. D. K. (2015). *Architectural Graphics* (4th ed.). New York: Wiley.

Downton, P. (2003). *Design Research*. Melbourne: RMIT Publishing.

Evans, R. (1997). *Translations From Drawing To Building*. Translations From Drawing To Building and Other Essays. London: Architectural Association.

Fraser, I. (1994). *Envisioning Architecture: An Analysis of Drawing*. New York: Van Nostrand Reinhold.

Fuente Suárez, L. (2016). Towards Experiential Representation in Architecture. *Journal of Architecture and Urbanism*, 40(1), 47-58.

Gibson, J. J. (1979). *The Ecological Approach to Visual Perception*. Boston: Houghton Mifflin.

Goodman, N. (1968). *Languages of Art: An Approach to a Theory of Symbols*. Indianapolis: Bobbs-Merrill Company.

Goodwin, K. & Ursprung, P. (2014). *Sensing Spaces: Architecture Reimagined*. London: Royal Academy of Arts.

Grabow, S., Spreklemeyer, K. (2015) Foreword. Pallasmaa, J., *The Architecture of Use: Aesthetics and Function in Architectural Design*. New York: Routledge.

Kim, M. J., Wang, X., Love, P. E. D., Li, H., Shih-Chung K. (2013). Virtual Reality for the Built Environment: A Critical Review of Recent Advances. *Journal of Information Technology in Construction*, 18(1), 279-305.

Kvan, T. S., Schnabel. M. A. (2003). Spatial Understanding in Immersive Virtual Environments. *International Journal of Architectural Computing*, 1(4), 435-448.

Laseau, P. (2000). *Graphic Thinking for Architects and Designers*. New York: Wiley.

Lockard, W. K. (1982). *Design drawing*. New York: Van Nostrand Reinhold Co.

Mackesy-Buckley, A. H. (2012). *Understanding Human Scale and the Importance of its Relationship with Enclosure* (Unpublished masters thesis). School of Architecture, Victoria University of Wellington.

Morris, M. (2006). *Models: Architecture and the Miniature*. Chichester, West Sussex: Wiley-Academy.

Orzechowski, M. A., de Vries, B., Timmermans, H.J.P. (2003). Virtual Reality CAD system for non-designers: Investigation of user's preferences. *7th Conference of the Iberoamerican Society of Digital Graphics (SIGraDi)* (pp. 133-137). Rosario, Argentina.

Pallasmaa, J. (2012). *The Eyes of the Skin Architecture and the Senses*. Chichester, West Sussex: Wiley.

Pallasmaa, J. (2014). Space, Place and Atmosphere: Emotion and Peripheral Perception in Architectural Experience. *Lebenswelt: Aesthetics and Philosophy of Experience*, 1(4), 230-245.

Pollio, M. V. (trans. 2009). *De Architectura* [On Architecture]. trans. Richard Schofield. New York: Penguin.

Scheer, D. R. (2014). *The Death of Drawing: Architecture in the Age of Simulation*. New York: Routledge.

Schnabel, M. A. & Wang. X. (2009). *Mixed Reality In Architecture, Design And Construction.* Dordrecht: Springer.

Schnabel, M. A., Wang, X., Seichter, H., & Kvan, T. (2007). From Virtuality to Reality and Back. *Proceedings of the International Association of Societies of Design Research (IASDR)*. Hong Kong: Hong Kong Polytechnic University.

Schon, D. A. (1995). *The Reflective Practitioner*: How Professionals Think in Action. Aldershot: Ashgate.

Segard, A., Moloney, J., Moleta, T. (2013). Open Communitition: Competitive Design in a Collaborative Virtual Environment. *Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA)* (pp. 231-240). Singapore: National University of Singapore.

Slater, M. & S. Wilbur (1997). A Framework for Immersive Virtual Environments (FIVE). *Presence: Teleoperators & Virtual Environments*, 6(6), 603-616.

Smith, K. S. (2005). *Architects' Drawings: a Selection of Sketches By World Famous Architects Through History*. Oxford: Oxford Architectural Press.

Vardehaugen (2008). Real-scale Drawings. Retrieved 15 Aug, 2017, from <vardehaugen.no/real-scale-drawings/>

Wallis, G., & Tichon, J. (2013). Predicting the efficacy of simulator-based training using a perceptual judgment task versus questionnaire-based measures of presence. *Presence: Teleoperators and Virtual Environments,* 22(1), 67-85.

Whyte, J. (2002). Virtual Reality and the Built Environment. Oxford: Architectural Press.

Zumthor, P. (2006). Thinking Architecture. Basel: Birkhäuser.

Software List

Enscape 3D (2016). Enscape. <www.enscape3d.com>

Google (2016). Tilt Brush. <www.tiltbrush.com>

Google (2017). Blocks. <vr.google.com/blocks/>

Kalloc Studios. (2016). Fuzor.<www.kalloctech.com>

Minddesk VR. (2017). Rhino VR. Retrieved 10 June, 2017, <www.mindeskvr.com>

Paredes Fuentes, D. S., Oluwaseyi (2017). Gravity Sketch VR. <www.gravitysketch.com>

Pixologic (2002). ZBrush.<www.pixologic.com/>

Robert McNeel & Associates (1994). Rhinoceros 3D. <www.rhino3d.com>

Trimble Navigation. (2000). SketchUp.<www.sketchup.com>

Winkler, M. (2016). Massit. Retrieved 15 Aug, 2017, from <mwvizwork.com/massit/>

Appendices

Appendix A: Experiment 01 questionnaire

	Very unsuccessful	Unsuccessful	Average	Successful	Very Successful
How would you rate the functionality of your design?	○	○	○	○	○

Explain:

How would you rate the formal aesthetics of your design? ○ ○ ○ ○ ○

Explain:

How would you rate the experience of your design? ○ ○ ○ ○ ○

Explain:

How would you rate the overall quality of your design? ○ ○ ○ ○ ○

Explain:

	Very little	Little	Neutral	Moderate	Greatly
To what extent did you consider the inhabitant of the design?	○	○	○	○	○

Explain:

Appendix B: Experiment 01 raw quantitative data

Design 1

	Non-immersive Design						Control		
Participant	Q	R	S	T	U	V	W	X	Median
Actions	634	400	338	297	247	248	52	360	317.5
Groups	9	2	8	9	9	0	28	15	9
Copies	58	47	210	35	147	58	136	134	96
Arrays	3	0	4	9	3	0	2	2	2.5
Boxes	55	55	222	52	153	69	135	243	102
Median Dimension	1.113734	0.713471	8.172886	0.817214	1.23187	0.206464	8.969486	0.400345	0.965474
Volume (Total)	84.1	138.9	144622.2	495.3	412.7	24.0	941.6	1443.7	454.0076
Volume (Cube Root of Total)	4.4	5.2	52.5	7.9	7.4	2.9	9.8	11.3	7.678688
Volume (Average)	1.5	2.5	651.5	9.5	2.7	0.3	7.0	5.9	4.319334
Volume (Median)	0.2	2.0	761.0	6.5	1.8	0.2	3.9	0.6	1.900488
Speed (Boxes/min)	2.75	2.75	11.1	2.6	7.65	3.45	6.75	12.15	5.1
Speed (Actions/min)	31.7	20	16.9	14.85	12.35	12.4	2.6	18	15.875

	Immersive Design						Control		
Participant	K	L	M	N	O	P	Y	Z	Median
Actions	221	159	139	464	361	131	123	282	190
Groups	3	7	28	5	0	30	28	3	6
Copies	89	32	108	30	155	226	51	2	70
Arrays	10	3	5	3	0	9	3	4	3.5
Boxes	186	33	142	39	164	237	108	35	125
Median Dimension	1.542587	0.531707	0.454208	0.581482	0.988343	0.25891	0.328301	1.386355	0.556594
Volume (Total)	4319.2	0.9	294.3	46.2	276.2	51.2	142.4	64.4	103.4384
Volume (Cube Root of Total)	16.3	1.0	6.7	3.6	6.5	3.7	5.2	4.0	4.615826
Volume (Average)	23.2	0.0	2.1	1.2	1.7	0.2	1.3	1.8	1.501346
Volume (Median)	0.8	0.0	0.5	0.1	0.2	0.1	0.2	0.8	0.209078
Speed (Boxes/min)	9.3	1.65	7.1	1.95	8.2	11.85	5.4	1.75	6.25
Speed (Actions/min)	11.05	7.95	6.95	23.2	18.05	6.55	6.15	14.1	9.5

Design 2

	Non-immersive Design						Control		
Participant	K	L	M	N	O	P	W	X	Median
Actions	206	290	307	312	423	116	391	241	298.5
Groups	3	0	2	38	16	12	9	0	6
Copies	88	9	46	205	110	131	110	0	99
Arrays	0	0	2	0	0	4	12	0	0
Boxes	108	12	69	232	111	144	109	27	108.5
Median Dimension	2.763349	0.50274	1.6525	1.0979	2.607706	0.523071	2.673462	2.515259	2.08388
Volume (Total)	1058.5	25.0	924.3	1394.2	2487.8	308.6	187.2	1127.7	991.4114
Volume (Cube Root of Total)	10.2	2.9	9.7	11.2	13.6	6.8	5.7	10.4	9.966209
Volume (Average)	9.8	2.1	13.4	6.0	22.4	2.1	1.7	41.8	7.905135
Volume (Median)	0.1	2.4	0.3	0.4	2.5	0.5	0.1	13.3	0.440859
Speed (Boxes/min)	5.4	0.6	3.45	11.6	5.55	7.2	5.45	1.35	5.425
Speed (Actions/min)	10.3	14.5	15.35	15.6	21.15	5.8	19.55	12.05	14.925

	Immersive Design						Control		
Participant	Q	R	S	T	U	V	Y	Z	Median
Actions	147	246	254	160	136	166	145	214	163
Groups	11	2	86	0	6	0	4	10	5
Copies	27	14	359	7	24	33	35	26	26.5
Arrays	1	0	8	0	2	0	0	3	0.5
Boxes	42	32	298	23	37	47	58	38	40
Median Dimension	0.40432	1.403654	0.555619	1.039307	1.387024	0.544128	0.820301	1.362366	0.929804
Volume (Total)	745.8	282.6	87.2	237.9	25405.2	15.5	1028.7	209.5	260.2505
Volume (Cube Root of Total)	9.1	6.6	4.4	6.2	29.4	2.5	10.1	5.9	6.37929
Volume (Average)	17.8	8.8	0.3	10.3	686.6	0.3	17.7	5.5	9.58716
Volume (Median)	3.5	1.0	0.2	4.9	12.3	0.1	7.9	3.0	3.234971
Speed (Boxes/min)	2.1	1.6	14.9	1.15	1.85	2.35	2.9	1.9	2
Speed (Actions/min)	7.35	12.3	12.7	8	6.8	8.3	7.25	10.7	8.15

Design 1	Non-immersive Design						Control		
	Q	R	S	T	U	V	W	X	Median
Functionality Ratings									
Average PC	3.2	3.9	3.0	2.7	2.8	3.8	3.5	1.5	3.1
Average VR	3.8	3.4	2.0	2.9	2.6	3.3	3.2	2.4	3.005495
Self-reported Rating	4.0	3.0	1.0	4.0	2.0	3.0	2.0	1.0	2.5
Average Expert	4.5	3.5	2.5	2.5	5.0	3.5	4.0	2.5	3.5
Average VR & PC	3.6	3.6	2.6	2.8	2.6	3.6	3.2	2.1	3.010504
Aesthetics Ratings									
Average PC	3.4	3.6	3.5	2.4	3.4	3.4	4.0	1.5	3.4
Average VR	3.4	3.0	2.3	2.6	3.7	3.3	4.2	3.4	3.366667
Self-reported Rating	5.0	4.0	3.0	5.0	3.0	3.0	3.0	2.0	3
Average Expert	4.5	4.0	2.5	2.0	4.0	1.0	4.5	2.0	3.25
Average VR & PC	3.4	3.3	3.0	2.5	3.6	3.4	4.1	2.9	3.321429
Experience of Inhabitant									
Average PC	3.2	4.1	3.5	2.7	3.0	3.3	4.3	1.8	3.225
Average VR	3.2	3.1	3.2	3.0	2.8	3.5	3.8	2.9	3.154762
Self-reported Rating	5.0	3.0	4.0	4.0	2.0	4.0	3.0	1.0	3.5
Average Expert	4.0	5.0	2.5	2.0	4.0	1.0	3.5	1.5	3
Average VR & PC	3.2	3.6	3.4	2.9	2.9	3.4	3.9	2.6	3.285714
Overall									
Average PC	6.20	7.29	6.63	5.71	6.60	6.50	7.00	3.25	6.55
Average VR	6.78	6.14	5.67	5.00	6.11	6.50	7.54	5.60	6.126984
Self-reported Rating	8.00	4.00	2.00	8.00	4.00	6.00	6.00	2.00	5
Average Expert	8.00	8.00	5.00	4.50	8.50	2.00	8.00	4.00	6.5
Average VR & PC	6.57	6.71	6.21	5.36	6.29	6.50	7.41	4.93	6.392857

Design 1

	Immersive Design						Control		
	K	L	M	N	O	P	Y	Z	Median
Functionality Ratings									
Average PC	2.2	1.9	2.4	3.2	2.2	2.4	3.2	2.5	2.3875
Average VR	2.0	1.3	2.3	2.7	2.0	2.9	4.0	2.8	2.5
Self-reported Rating	2.0	4.0	2.0	3.0	3.0	3.0	4.0	2.0	3
Average Expert	3.0	1.5	3.0	3.0	3.0	3.0	5.0	2.0	3
Average VR & PC	2.1	1.6	2.4	2.9	2.1	2.7	3.5	2.7	2.535714
Aesthetics Ratings									
Average PC	2.3	2.0	2.9	4.0	2.9	2.4	2.9	2.3	2.6375
Average VR	2.4	1.9	2.3	3.6	3.6	2.3	2.4	2.7	2.4
Self-reported Rating	3.0	3.0	2.0	4.0	2.0	4.0	3.0	3.0	3
Average Expert	3.5	1.0	3.0	2.5	2.5	3.0	4.0	2.0	2.75
Average VR & PC	2.4	1.9	2.6	3.7	3.1	2.4	2.7	2.6	2.607143
Experience of Inhabitant									
Average PC	2.6	1.9	2.8	3.4	2.6	3.2	3.1	3.0	2.875
Average VR	3.2	1.7	3.0	3.3	2.2	3.1	3.2	2.7	3.055556
Self-reported Rating	4.0	3.0	2.0	4.0	3.0	2.0	4.0	3.0	3
Average Expert	5.0	2.0	3.0	3.0	3.5	3.5	5.0	2.0	3.25
Average VR & PC	2.8	1.8	2.9	3.4	2.4	3.1	3.1	2.8	2.821429
Overall									
Average PC	4.44	3.29	5.13	6.20	5.44	5.60	5.78	5.50	5.472222
Average VR	5.40	3.43	5.33	6.33	5.20	5.00	6.20	5.40	5.366667
Self-reported Rating	4.00	6.00	2.00	6.00	4.00	6.00	6.00	6.00	6
Average Expert	7.00	2.00	5.50	4.50	7.50	4.50	4.00	5.00	4.75
Average VR & PC	4.79	3.36	5.21	6.29	5.36	5.21	5.93	5.43	5.285714

Design 2

	Non-immersive Design						Control		
	K	L	M	N	O	P	W	X	Median
Functionality Ratings									
Average PC	2.0	2.1	3.5	3.0	2.9	4.0	3.8	2.4	2.928571
Average VR	2.5	2.7	2.6	3.6	2.7	4.6	3.6	2.3	2.690476
Self-reported Rating	4.0	4.0	3.0	4.0	3.0	4.0	4.0	3.0	4
Average Expert	3.5	3.5	3.0	4.0	3.0	4.0	4.5	3.5	3.5
Average VR & PC	2.4	2.4	2.9	3.4	2.8	4.2	3.6	2.4	2.821429
Aesthetics Ratings									
Average PC	2.8	2.1	2.5	2.8	2.7	3.2	3.9	2.7	2.732143
Average VR	2.3	1.8	2.7	2.2	3.4	3.6	4.1	2.9	2.778571
Self-reported Rating	4.0	4.0	3.0	4.0	3.0	4.0	4.0	5.0	4
Average Expert	4.0	4.0	2.0	3.0	1.5	2.5	4.0	3.0	3
Average VR & PC	2.4	2.0	2.6	2.4	3.1	3.4	3.9	2.8	2.714286
Experience of Inhabitant									
Average PC	2.0	2.0	2.5	1.8	3.0	3.4	3.1	2.0	2.25
Average VR	2.7	1.7	2.5	3.1	3.0	3.8	3.1	3.0	3
Self-reported Rating	4.0	3.0	4.0	3.0	3.0	3.0	3.0	1.0	3
Average Expert	4.0	2.5	2.0	2.0	2.0	2.5	2.5	3.0	2.5
Average VR & PC	2.5	1.9	2.5	2.6	3.0	3.6	3.1	2.5	2.571429
Overall									
Average PC	4.75	4.13	5.50	4.40	6.14	6.89	7.13	4.71	5.125
Average VR	4.80	4.50	4.80	5.78	6.43	7.40	6.57	5.14	5.460317
Self-reported Rating	6.00	6.00	6.00	6.00	6.00	6.00	4.00	4.00	6
Average Expert	7.50	6.50	4.00	5.50	4.50	6.50	8.00	6.50	6.5
Average VR & PC	4.79	4.29	5.00	5.29	6.29	7.07	6.86	4.93	5.142857

Design 2

	Immersive Design						Control		
	Q	R	S	T	U	V	Y	Z	Median
Functionality Ratings									
Average PC	4.0	2.4	2.3	3.1	4.3	2.0	3.7	4.3	3.404762
Average VR	4.3	2.6	2.3	3.1	3.2	1.5	2.5	4.1	2.857143
Self-reported Rating	5.0	4.0	5.0	4.0	4.0	4.0	5.0	4.0	4
Average Expert	4.5	3.0	3.0	3.5	3.0	3.0	4.5	4.5	3.25
Average VR & PC	4.2	2.5	2.3	3.1	3.4	1.8	3.5	4.1	3.285714
Aesthetics Ratings									
Average PC	3.8	3.4	2.8	2.0	4.3	1.9	3.0	3.5	3.214286
Average VR	4.3	3.9	2.8	2.6	3.3	1.8	2.5	3.7	3.05303
Self-reported Rating	4.0	4.0	3.0	4.0	4.0	3.0	4.0	3.0	4
Average Expert	4.5	3.5	2.5	2.5	1.5	1.0	3.5	4.5	3
Average VR & PC	4.1	3.6	2.8	2.3	3.5	1.9	2.9	3.6	3.214286
Experience of Inhabitant									
Average PC	3.4	2.9	2.0	2.6	3.7	1.6	3.3	3.8	3.053571
Average VR	4.1	3.4	2.3	2.7	3.4	1.5	2.5	3.2	2.957143
Self-reported Rating	5.0	5.0	4.0	5.0	3.0	5.0	4.0	4.0	4.5
Average Expert	4.5	3.5	1.5	3.0	3.0	1.0	4.5	4.5	3.25
Average VR & PC	3.9	3.1	2.1	2.6	3.4	1.6	3.1	3.4	3.142857
Overall									
Average PC	7.00	6.00	4.75	5.29	7.67	3.13	6.58	7.75	6.291667
Average VR	8.11	6.29	5.00	5.14	5.91	3.50	5.50	6.80	5.704545
Self-reported Rating	8.00	8.00	8.00	8.00	8.00	8.00	10.00	6.00	8
Average Expert	9.50	7.00	4.50	4.50	5.00	1.50	6.00	8.00	5.5
Average VR & PC	7.71	6.14	4.86	5.21	6.29	3.29	6.43	7.07	6.214286

Please rate...

How <u>easily</u> you were able to identify issues with the design or site:

Great difficulty	Difficulty	Average	Easily	Very easily
○	○	○	○	○

Explain: [ ]

How <u>easily</u> you thought of new ideas for the space:

Great difficulty	Difficulty	Average	Easily	Very easily
○	○	○	○	○

Explain: [ ]

How <u>effectively</u> you were able to express your ideas in the model:

Not at all	Not effectively	Average	Effectively	Very effectively
○	○	○	○	○

Which tools did you find the most effective at expressing your ideas? (Tick all that apply)

☐ Add	☐ Delete	☐ Group	☐ Ungroup	☐ Material
☐ Move	☐ Copy	☐ Rotate	☐ Radial	☐ Measure
☐ Push/ Pull	☐ Scale	☐ Morph	☐ Voxels	☐ Draw

Explain: [ ]

Which factors most greatly affected your understanding of the 3D scene?
(Tick all that apply)

- ☐ Model Detail
- ☐ Virtual Materials
- ☐ Visual Immersion
- ☐ Lighting / Shadows
- ☐ Interactivity
- ☐ Controller Vibration
- ☐ Body Movement
- ☐ Other: ______

Explain:

How well you enjoyed the time spent with the model:

○ Not At All ○ A Little ○ Average ○ Well ○ Very Well

Explain:

That's everything!
Thank you for your participation!

Appendix E: Experiment 02 raw quantitative data

	A	B	C	D	E	F	G		MEDIAN
TIME	null	547.3721	780.0746	394.203	370.149	655.6271	297.9872		470.7876
MINUTES	null	9.122868	13.00124	6.57005	6.16915	10.92712	4.966453		7.846459
ACTIONS	null	106	46	29	19	36	13		32.5
SEC/ACTIONS	null	5.163888	16.95814	13.59321	19.48153	18.21186	22.92209		17.585
BOXES	null	105	17	30	19	29	14		24
SEC/BOX	null	5.213068	45.88674	13.1401	19.48153	22.60783	21.2848		20.38316
VOLUMES	null	59.82725	1596.8	29156.78	847.4579	966.3843	5138.982		1281.592
MEDIAN VOLUME	null	0.014638	10.88168	45.98607	46.88804	4.78E-02	3.20E-01		5.600803
BOXES/MINUTE	null	11.50954	1.307567	4.566175	3.079841	2.653948	2.818913		2.949377

Appendix F: Experiment 02 raw qualitative data

	A	B	C	D	E	F	G
IDENTIFY	4	2	4	3	2	4	Null
IDEATION	4	4	Null	5	4	4	Null
EXPRESSION	3	3	3	3	4	4	2
REFLECTION	4	Null	Null	4	3	5	2
ENJOYMENT	4	Null	Null	4	5	4	4

Appendix G: Experiment 02 raw qualitative data

		A	B	C	D	E	F	G
TOOLS	ADD	1		1	1		1	
	DELETE	1						
	GROUP							
	UNGROUP							
	MATERIAL						1	
	MOVE	1						
	COPY					1		
	ROTATE	1						
	RADIAL							
	MEASURE							
	PUSH PULL			1				
	SCALE							
	MORPH							
	VOXELS							
	DRAW		1					
MODEL FACTORS	DETAIL	1			1	1		1
	MATERIALS					1		
	IMMERSION	1					1	
	LIGHTING	1				1		
	INTERACTIVITY	1						
	HAPTIC							
	MOVEMENT							
	SCALE						1	