Step Into The Void

A Study of Spatial Perception in Virtual Reality

by

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Author’s Declaration

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

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

Abstract

The introduction of virtual reality (VR) into the architectural profession offers an unprecedented opportunity to experience unbuilt designs at full scale. The premise of the technology is that it gives users the illusion of being in another place by replacing their field of vision with a digital image. While VR technology, for the most part, can only simulate visual sensations at this point in its development, it has demonstrated in various applications that the immersiveness of the medium can elicit visceral reactions. This potential could be leveraged to expand the capacity of architects to convey the complexities of architectural space in an easily comprehensible form.

Because VR is relatively unfamiliar, especially in architecture, there is a need to identify the technology's strengths and weaknesses so that it can be appropriately utilized in practice. The goal of this thesis is to further the understanding of interior spatial perception in VR. Perception of interior space is affected by many visual factors, like the shape of the space, details, and how crowded the space is. In order to test the impact of these aspects of spatial perception in VR, a set of experiments were conducted at the School of Architecture. Participants engaged in a series of exercises where they would attempt to position the walls and ceilings of a series of rooms to match a given set of dimensions. Each room is designed slightly differently to test the aforementioned aspects of spatial perception. These exercises are completed once with orthogonal architectural drawings and once with VR.

Some results from the experiments might indicate that atmospheric design elements may be more impactful when represented in VR, but further research is required. In most cases, participants were more accurate when using orthogonal drawings to complete the exercises. However, participants created rooms that were more similar to each other when completing the exercises in VR, which suggests that VR might be more effective than orthogonal drawings in imparting a common understanding of space to different people, an encouraging sign that VR is an effective medium for communication.

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INTRODUCTION

More Than Meets The Eye

What is VR?

Architects have long relied on a familiar set of tools to transform their ideas into reality, so when a newcomer arrives in the form of virtual reality (commonly referred to as VR), it has been met with equal parts excitement and trepidation. This mixed reaction can possibly be attributed to its indeterminate boundaries as a technology. An idealized form of VR has been shown many times in science fiction, depicting VR as a true alternate reality where anything can happen. The history books, on the other hand, point to the floundering of VR in the 90's when it was held back by technological limitations that made the head-mounted displays (HMD's) used for VR extremely cumbersome both physically and financially.

Even though HMDs of today have overcome many of the challenges that proved to be insurmountable in the past, having drastically reduced the cost and size of the equipment, there is still a long road ahead before it starts to bear some semblance to the fantastical versions of VR depicted in films like *The Matrix* and *Ready Player One*. A scholar in the topic, Frank Biocca, writes, "Virtual reality is not a technology; it is a destination."[1] Starting with a device that gives users the impression that they are somewhere else – which in many cases is an HMD – layers of technological innovations are added to improve the immersiveness of the experience (Fig. 0.1). With each new layer, the technology slowly moves towards the destination of simulating reality.

What VR can do quite well at the moment is trick our visual senses into seeing different environments than the one physically inhabited

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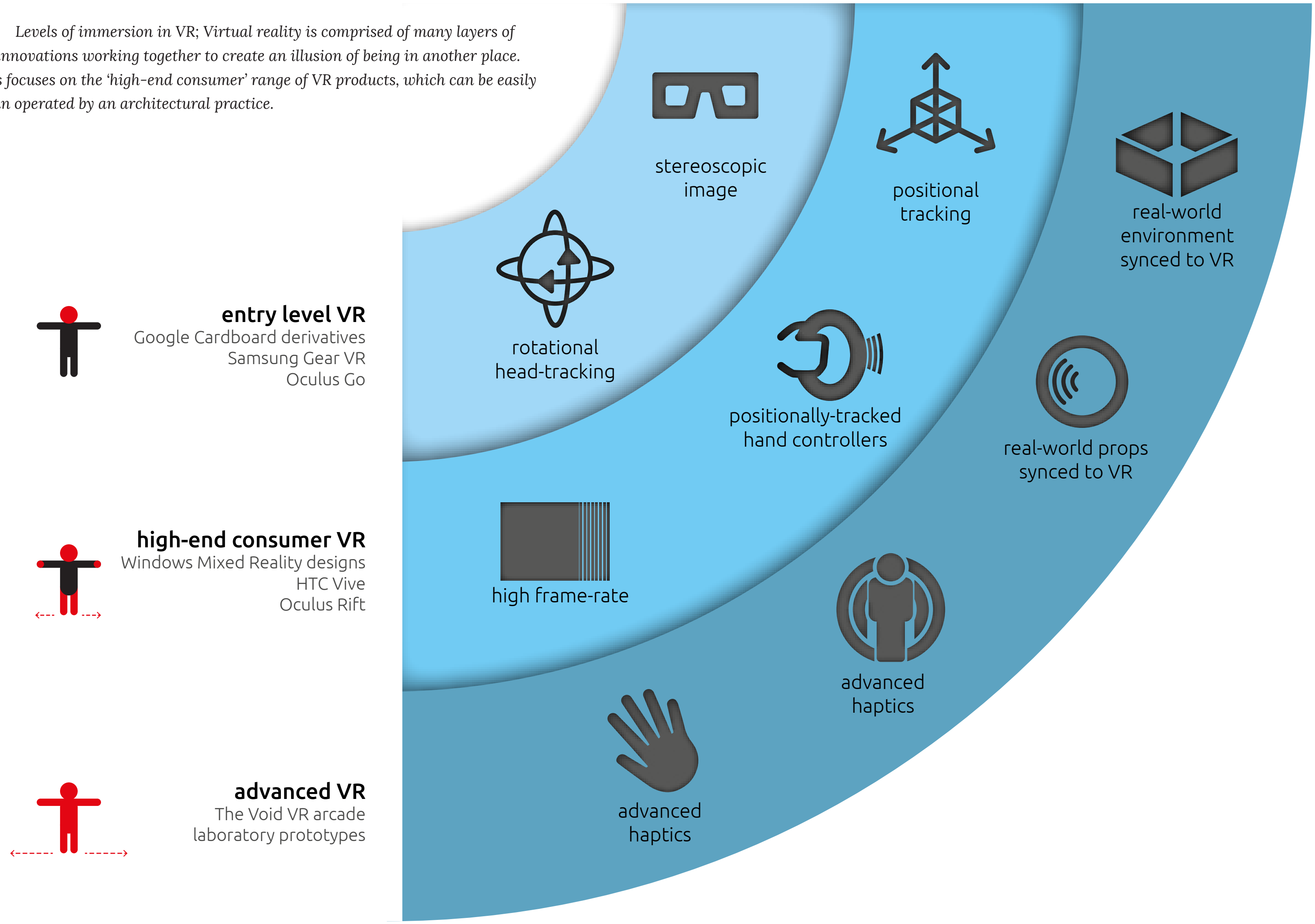
[1] Frank Biocca and Mark R. Levy, eds., *Communication in the Age of Virtual Reality*, LEA's Communication Series (Hillsdale, N.J: L. Erlbaum Associates, 1995), 16.

Figure 0.1 *Levels of immersion in VR; Virtual reality is comprised of many layers of technical innovations working together to create an illusion of being in another place. This thesis focuses on the 'high-end consumer' range of VR products, which can be easily obtained an operated by an architectural practice.*



by the user. Rotational tracking of the headset synchronizes the user's movements with the digital image on the HMD so that when they turn their heads the image responds correspondingly. High-end consumer VR headsets (Fig 0.1) have positional tracking systems so that users can move around within a small room. These higher-end headsets also have hand controllers that show a representation of where the user's hands are in space, further engaging the user's proprioceptive senses and allowing interactions that are more gestural. More sophisticated VR experiences will also have three-dimensional binaural audio, which means that users can hear where sounds are coming from and how far they are.

Beyond these senses, however, it is difficult for VR to replicate sensations of smell, taste, and touch. However, VR is still an important step towards digital representation of architecture that presents itself in a more natural way. The source of the viewpoint is centered on the viewer and their gaze can wander around the surrounding visuals focusing on whatever piques their interest, similar to the real experience of architecture. This is not the case with framed images, which have a viewpoint separate from the viewer that they cannot control, set by the artist in service of a particular narrative (Fig 0.2).

VR can be a useful addition to the architect's toolbox

The process of materializing a building from a concept puts architects in a position where they act as intermediaries between different stakeholders of a project, requiring communication of complex ideas to many people of different professions. VR's ability to represent architecture perspicuously at full scale makes it a valuable medium with which to communicate with. Prominent urban theorist and sociologist William H. Whyte advised that "the greatest barrier to communication is the illusion of it in the mind of the sender." It is important that architects present architectural ideas in ways that are more easily understood so as to avoid any miscommunication. To stakeholders who have little training in architecture, plans and sections may be difficult to piece together into a cohesive image. Also, many elements in orthographic drawings are abstracted for the sake of legibility, which can cause confusion for non-professionals. VR removes many of these barriers that might obfuscate architectural ideas.

VR presents the opportunity for architects to experience a preview of their designs at full scale, something that has been prohibitively expensive and unpractical in all but a few architectural endeavors. Although there is presently a certain level of technical expertise and investment of time and resources required to develop and operate VR architectural representations, this bar is continuing to be lowered towards a point where integration with established workflows is seamless.

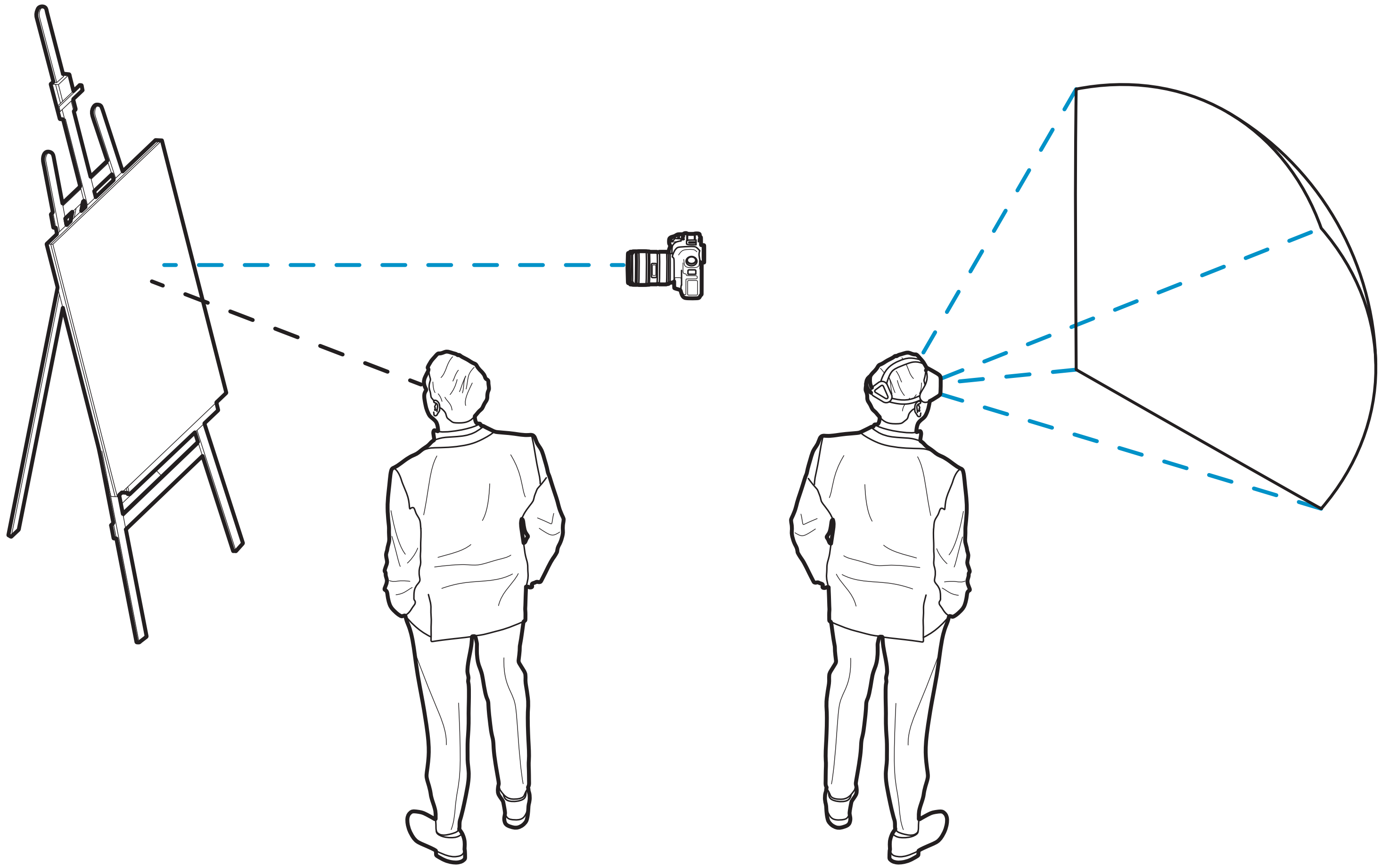


Figure 0.2 *Perspectival images have pre-determined viewpoints that do not necessarily align with the viewer's. However, VR places the viewer at the center of the experience, giving them control over what to look at.*

Scope of thesis

There are a variety of VR applications that architects can choose from to use in different stages of the design process. When doing research for a project, VR can be used to explore a site through Google Earth or Street View (Fig. 0.3).[2] In the early stages of design, digital sculpting or painting in VR can be used to produce rapid and expressive sketches that can be explored in three-dimensional space, reducing the chance for misinterpretations from unclear perspectives (Fig. 0.4).[3] As the design is being developed in CAD, there are programs that allow designers to preview their models in VR with just a few clicks, the only downside being that the graphics are less polished (Fig. 0.5). Simulations of different aspects like materials, weather, and lighting can also be experienced in VR to gain an inside perspective of the space and its relation to the simulated dataset.[4] In the latter stages of design, VR can also be used to understand the construction of buildings by showing tectonic details at full scale (Fig. 0.6).[5]

The list of ways to use VR in architecture continues to expand, especially in this relatively early period of its growth. Developers of VR content are continually learning what makes sense to be made in VR and what would be better served in other mediums. Before taking a deep dive into using VR in specialized architectural uses, there is a need to take a step back and evaluate immersive VR as a medium and identify where it holds advantages over other forms of representation. Therefore, the topic of investigation is a more elemental aspect of the medium of VR: how the understanding of spatial volumes in VR differs from the reading of architectural drawings. By exploring this fundamental aspect of VR, this thesis may be able to serve as a foundation for other investigations into how VR can be utilized effectively in architecture.

2 “Google Earth VR,” Google, https://vr.google.com/earth.
3 “Tiltbrush,” Google, https://www.tiltbrush.com.
4 “Prospect,” IrisVR, https://irisvr.com/prospect.
5 Sarah Downey, “VR and AR Could Revolutionize Construction, But There Are Still Big Challenges,” UploadVR, November 22, 2016, https://uploadvr.com/vr-and-ar-in-construction.

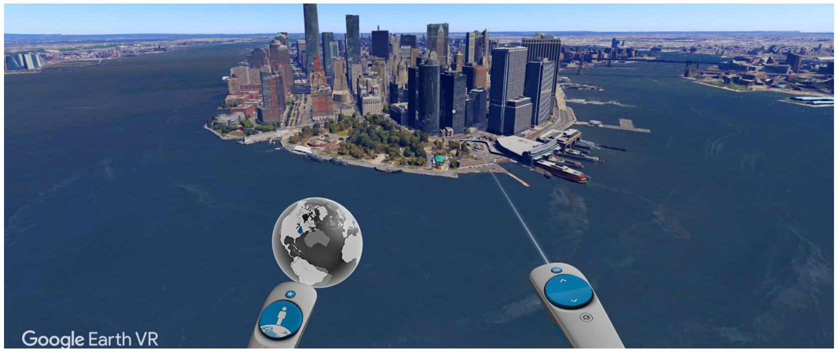


Figure 0.4 *The experience of using Google Earth VR is like viewing different locations around the world as though they were miniature scale models.*

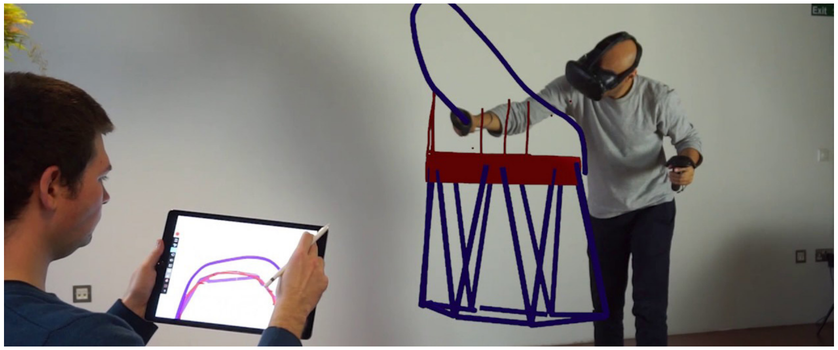


Figure 0.3 *Gravity Sketch VR is one of many programs that enables users to sketch in 3D space. One of the advantages of such software is that sketches can be easily exported into CAD software for further refinement.*

Figure 0.5 *With software like IrisVR, architects can take a 3D model and view it in VR within a matter of seconds.*

Figure 0.6 *AR technology for AEC helps users see exactly how the building comes together.*

Figure 0.7 *Spinning tunnel optical illusion at the Brisbane Science Centre.*

Even when vision is the only sense being tricked, the results are surprisingly powerful

As mentioned previously, VR is currently only capable of engaging mainly the visual sense, and to a lesser extent audial, proprioceptive, and haptic senses. While it is certainly true that the visual sense is not the only sense that is important in the experience of architecture, it is a powerful and influential one.

In the spinning tunnel illusion (opposite, Fig 0.7), the visual impact of the illusion is such that it completely unbalances the vestibular system that is telling the brain to brace for a shift in balance that never ensues.[6] Similarly, in Julian Hoeber's installation *Demon Hills*, the artist puts viewer's visual and vestibular senses at odds by tilting an otherwise ordinary room on an axis. As viewers step into the room, their visual sense tells them that they are standing in a flat, rectangular room. However, gravity forces their bodies to adjust. This cognitive dissonance can cause severe discomfort or nausea which viewers are warned about before they enter the exhibit. Although the installation is completely transparent in letting people know beforehand that the room is tipped on its side, the strength of the visual illusion is such that the discomfort of the cognitive dissonance is "not something you can just logic your way out of", as Hoeber puts it.[7]

What Hoeber is alluding to is that visceral reactions to our surrounding environment precede a logical understanding of it. In other

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6 F. Bonato and A. Bubka, "Visual/Vestibular Conflict, Illusory Self-Motion, and Motion Sickness," *Journal of Vision* 4, no. 8 (August 1, 2004): 798–798, https://doi.org/10.1167/4.8.798.

7 Flora Lichtman, "Step Into an Optical Illusion," Science Friday, October 12, 2012, https://www.sciencefriday.com/videos/step-into-an-optical-illusion-2.

words, the subconscious mind plays an important role in how a space is perceived. In the experience of architecture, the separation of the conscious and subconscious can be looked at in terms of the difference between perception and cognition. Spatial perception and spatial cognition are terms that are closely related and can sometimes be mistaken for each other, but serve different purposes in the experience of architectural space. While perception is the initial input of sensory information to the nervous system, cognition happens afterwards when the brain processes the information. Many of the initial reactions we have towards things happen between the two stages, often without our knowledge. This has led to some environmental psychology theories like the cathedral effect, prospect-refuge theory, and chromotherapy. The difference between what is subconsciously perceived and what is consciously processed is important when discussing architectural VR experiences.

Similar to the aforementioned illusions, VR has also proven to be effective in tapping into the subconscious part of the mind. By tricking the senses into perceiving something that is not there, VR is able to elicit primordial responses that can be difficult to suppress because they happen subconsciously. When looking at architectural drawings and perspectival images, what we perceive are drawings on a sheet of paper or on a digital screen. It is difficult to determine if subconscious reactions to the design result from the design of the architecture or the interpretation of the drawings. VR has proven in many different applications to be quite capable of tapping into the subconscious.

Stanford University has been using VR to train their players to read

Figure 0.8 *Julian Hoeber's* Demon Hill *installation; exterior view (above), interior view (below)*

a game of football and make adjustments accordingly. In the first season of trying to implement VR into practice, Stanford's quarterback saw his passing completion numbers go from 64% to 76%, and the offense as a whole improved as well. Although the coach, David Shaw, is quick to admit that correlation does not equal causation, he believes that VR played a significant role in helping their quarterback understand the field better and anticipate how plays would develop.[8] In a game where every little advantage counts, VR provided Stanford with a much needed edge. While designing architecture may not be anywhere near as fast-paced as a game of football, a convincing case could be made that the stakes are extremely high. Buildings are expensive and time-consuming endeavors. Having an immersive perspective on a design could prove to be valuable to the stakeholders in an architectural project.

In the medical field, VR has been instrumental in helping paraplegic patients to regain some sensitivity and ability to move in their lower bodies.[9] Through the use of an Oculus Rift VR headset and a brain-machine-interface, which allows virtual avatars to be moved by thinking about walking, patients were put into a VR experience where they walked across a soccer pitch. The act of thinking about walking, coupled with the illusion that they were actually walking, started to re-activate brain signals that had long become dormant. Like the spinning tunnel illusion and Julian Hoeber's *Demon Hills* installation, this is another example of how the sense of sight has a strong influence on

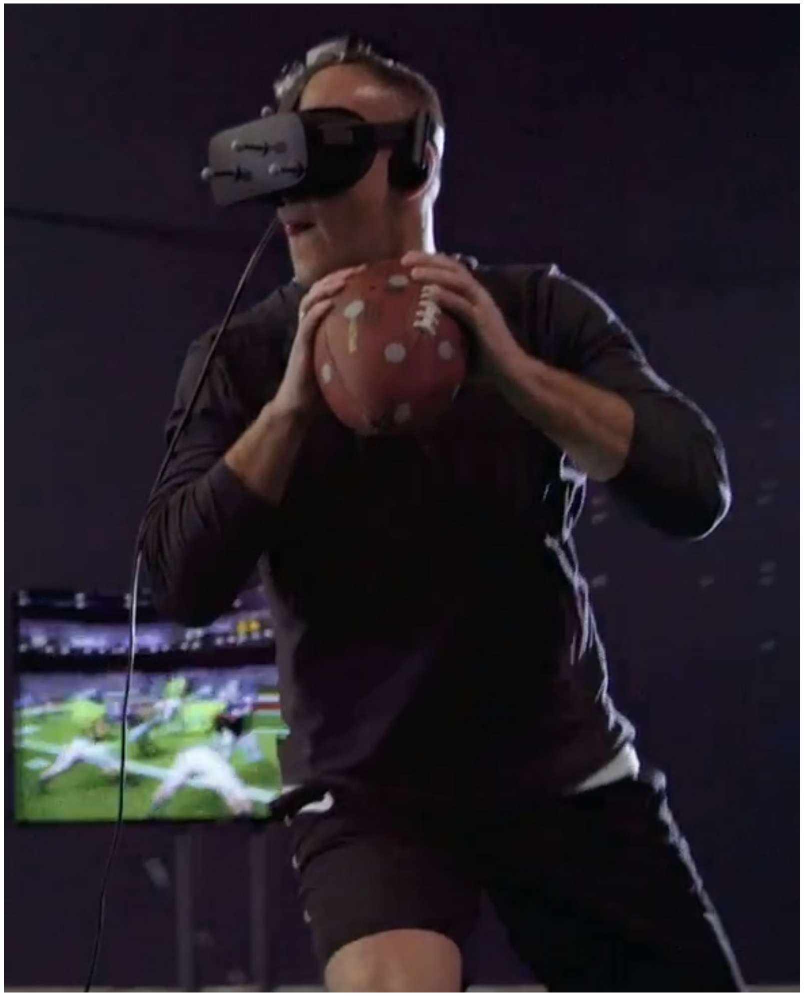

Figure 0.9 *QB Sim, a football training VR system that tracks the ball as well as the user, enabling players to practice their passing mechanics in a VR environment that is set up to mimic "game-day"intensity levels. The focus of the training is to familiarize players with different formations that the opposing team might utilize, so that they can predict what might happen based on how opposing players line up.*

8 Jeremy Bailenson, *Experience on Demand*, (New York: W. W. Norton & Company, Inc, 2018), 33.

9 Tim Radford, "'Brain Training' Technique Restores Feeling and Movement to Paraplegic Patients," The Guardian, August 11, 2016, https://www.theguardian.com/science/2016/aug/11/brain-training-technique-restores-feeling-and-movement-to-paraplegics-virtual-reality.

the rest of the body.

Other examples of how VR's illusory nature can have profound impacts on the psychology of humans will be explored in Part 1 of the thesis and form the basis of the experiments in this thesis, the design of which will be documented in Part 2. Part 3 analyzes the results of these experiments to see how VR, as a tool for simulating spatial perception, can be useful for architects.

PART ONE

CONTEXT

CHAPTER 1

Spatial Volume

A frequent topic of discussion among VR users is how to avoid bumping into obstacles around the designated use area. It is almost a rite of passage to have extended a limb too far and suffer a scrape or a bruise, in spite of the built in warning systems that headsets provide. That is because the first thing that VR does is obscure our vision of the physical surroundings and replace it with a view of another environment with different boundaries. This is a big reason why there is so much potential in VR for architects, who often need to visualize spaces of different shapes and sizes.

Some may think that the shape and size of a space is a trivial matter, that it is simply dictated by the constraints of the site and the program. However, it is one of the most fundamental elements of architecture, and sets the tone for many of the architect's subsequent design decisions. The shapes of spaces are often a key identifying feature of many well-known architects. Zaha Hadid is known for the organic flowing shapes of her designs, whereas Daniel Libeskind is known for his aggressive angular buildings. Of course, this is simplifying what makes these architects stand out, and there are excellent architects who succeed through other areas of the craft. However, shape is an aspect of architecture that can have a strong impact on how buildings leave first impressions on people.

In a study conducted by researchers at the Israel Institute of Technology, a group of architects and a group of non-experts were immersed into four different types of rooms (Fig. 1.1) in VR.[1] The sharp and angular room drew more positive comments from architects than

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[1] Avishag Shemesh, Moshe Bar, and Yasha Grobman, "Affective Response to Architecture," *Architectural Science Review* 60, no. 2 (December 21, 2016): 116–25.

non-experts, and the curvy room received more positive comments from non-experts than architects. Another difference was that when asked which of the rooms was most pleasant to them, non-experts heavily favored the square room, the safe and familiar choice, whereas architects preferred the more visually dynamic curvy angular rooms.[2] This study demonstrates how architects think about space differently than their clients. If VR can better convey spatial shapes and volumes, then it will be extremely useful in making sure that clients understand what their architects are designing for them, and that architects understand how their clients feel about their designs.

The size of spaces is often thought of as a technical matter, to be determined by manuals or precedents. An important part of an architect's job is to make sure that everything meets the standards of the building code. However, designing a space to *feel* large or small is not as straightforward; a space that is technically large in size might not necessarily feel big to its inhabitants, and likewise for small spaces. As architectural historian Geoffrey Scott writes:

> "In any building three things may be distinguished: the bigness which it actually has (mechanical measurement), the bigness which it appears to have (visual measurement), and the feeling of bigness which it gives (bodily measurement). The last two have often been confused, but it is the feeling of bigness which alone has aesthetic value."[3]

It would be difficult to argue that architectural drawings are not

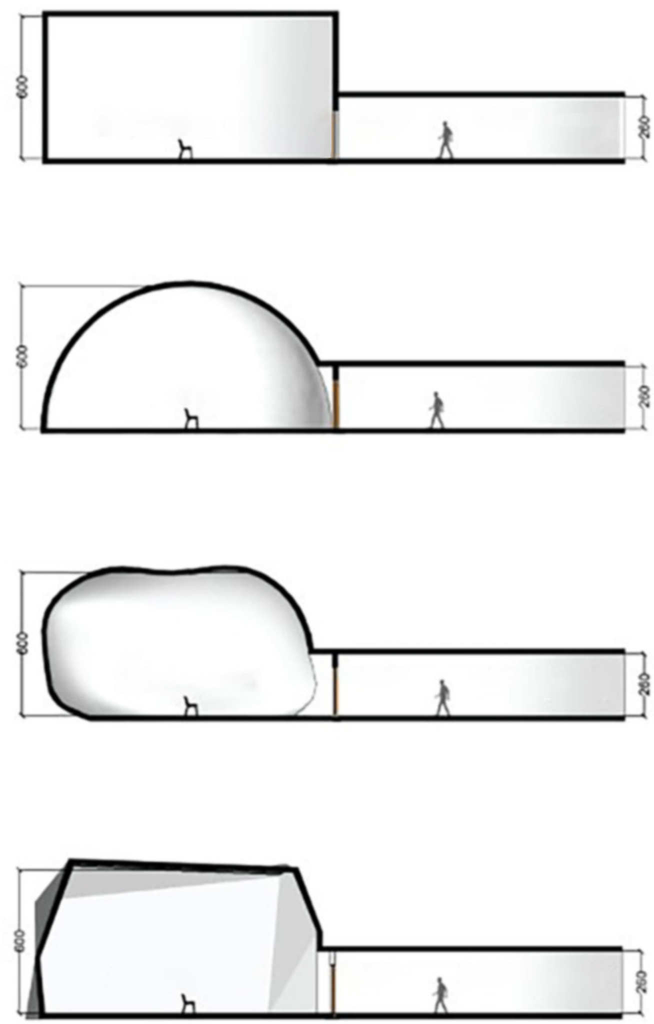

Figure 1.1 *Rooms designed for the shape preference study*

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2 Ibid, 124.
3 Geoffrey Scott, *The Architecture of Humanism: A Study in the History of Taste* (New York: W.W. Norton, 1974), 95.

well-suited to present mechanical measurements. As for visual measurements, the effectiveness of perspectival drawings in representing them is an on-going debate; some argue that architectural renderings should be expressive and artful even at the expense of realism or accuracy, while others believe that architects have a responsibility first and foremost to not conceal or deceive.[4] Conveying bodily measurement, however, is something that has been mostly left out of the discourse because traditional forms of architectural representation have to be drawn to scale, meaning that viewers must use their imaginations to mentally insert themselves into the environments that the drawings depict.[5] With VR, however, users can experience buildings at a one-to-one scale. They also have a proprioceptive sense of their height and arm-span, which they can also see if they are using room-scale VR. This helps users understand how large a space is in relation to their body, thus imparting the "feeling of bigness" that Scott believes is vital in determining aesthetic value.

Relevance to architecture

Large spaces like St. Peter's Basilica (Fig. 1.2), with its gargantuan columns and soaring ceilings, feel monumental and awe-inspiring. On the other hand, small spaces like the small wood cabin (Fig. 1.3), can feel warm and cozy. However, to some people it can feel constrictive. Frank Lloyd Wright is an example of an architect who juxtaposed spaces of different sizes to create dynamic experiences throughout his buildings.[6] A guiding principle for Wright in the shaping of spaces is how people might feel while moving through them.[7] An example of this is in his design of the Unity Temple (Fig. 1.4). Visitors enter the building into a dim lobby with low ceilings and sweeping horizontal features that usher visitors into the primary space that is the voluminous auditorium flooded with natural light.[8]

Another master in the art of manipulating space, Ludwig Mies van

4 Mario Carpo ed., Perspective, Projections and Design, 144.
5 Rainer Schützeichel, "Architecture as Bodily and Spatial Art," *Architectural Theory Review* 18, no. 3 (2013): 293–309.

6 Robert McCarter, "The Integrated Ideal," in *Frank Lloyd Wright: A Primer on Architectural Principles* (New York, NY: Princeton Architectural Press, 1991), 263.
7 Ibid, 254.
8 Jonathan Lipman, "Consecrated Space," in *Frank Lloyd Wright: A Primer on Architectural Principles*, ed. Robert McCarter (New York, NY: Princeton Architectural Press, 1991), 198.

Figure 1.2 *St. Peter's Basilica*

Figure 1.3 *Small woodland cabin*

Figure 1.4 *Unity Temple*

der Rohe, is one of the most imitated architects of the modern era. Mies' international style, true to its name, can be found around the world. The minimalistic aesthetic of this type of architecture may have been the most impactful part of Mies' legacy, but what many imitators struggle to fully grasp is his immaculate sense of scale and proportion. When the edges of a space are so clean and crisp, imbalances in the space become that much more apparent. Students of Mies began their education by mastering how to draw lines before moving on to anything else.[9] Not only how to draw precise and parallel lines, but also what different line-weights mean on the page. Students spend an excruciating amount of time mastering the art of drawing lines before moving on to learn how to form planes and volumes.[10]

The impact of the size and scale of a space lasts beyond the first impression, according to psychologists. An experiment conducted by Joan Meyers-Levy at the Carlton School of Management found that rooms with tall ceilings encouraged abstract, relational thought, which is generally considered to be important for creativity. Conversely, rooms with low ceilings encouraged a more item-specific line of thinking, which helps with work that requires detailed precision.[11] The goal of Meyers-Levy's research was to find out how different ceiling heights can be used to "prime" customers towards a favorable mindset. A clothing store, for example, may want customers to think abstractly, while a hardware store may want customers to think concretely.

9 Rolf Achilles, Kevin Harrington, and Charlotte Myhrum, eds., *Mies van Der Rohe: Architect as Educator* (Chicago: Illinois Institute of Technology, 1986), 47.

10 Ibid., 48.

11 Joan Meyers-Levy and Juliet Zhu, "The Influence of Ceiling Height: The Effect of Priming on the Type of Processing that People Use." *Journal of Consumer Research,* vol. 34, no. 2, 2007, 174-186.

Karen Finlay, a professor at the University of Guelph who studies the behavior of gamblers, conducted a study to see how different casino designs affect the amount of time and money people spend gambling. Finlay's study shows that larger spaces prime visitors to feel more comfortable and mentally "restored", reducing stress and loosening purse-strings.[12]

Of course, designing architecture is not a simple matter of prescribing dimensions to obtain a desired outcome. Both Meyers-Levy and Finlay caution against using their research as an all-encompassing manual. There are always a multitude of options to any given design problem. VR offers a vessel for architects to experiment with spatial volumes. With that being said, VR is not a replacement for an architectural education; it will not teach students the precise sensibility of Mies van der Rohe, or how to juxtapose spatial volumes like Frank Lloyd Wright. It can, however, help architects understand how the lines on their drawings translate into a volumetric space, and what it feels like to inhabit it.

State of VR in the field

While it is true that orthogonal and perspective drawings have been serviceable apparatuses for conveying volumes of space, there is reason to believe that they might not have the same affective potential as VR. Therapists of anxiety disorders that are relevant to spatial perception like claustrophobia and acrophobia have found that VR, with its

12 Karen Finlay et al., "Trait and State Emotion Congruence in Simulated Casinos," *Journal of Environmental Psychology* 27, no. 2 (June 2007): 166–75.

encompassing and immersive nature, is often a stronger stimulus than videos or photographs.[13] Similar to architects, therapists use images to help clients imagine themselves in another location, particularly when *in vivo* (real life) exposure therapy may be difficult to access.

A double-blind study conducted by professor Daniel Freeman at Oxford University found that going through a series of activities in VR that involved going up to high places helped people with acrophobia.[14] The activities are set inside a large 10-storey virtual atrium (Fig. 1.5) and included walking across a rope bridge, playing a xylophone on the edge of the floor looking onto the atrium, climbing up a tree to rescue a cat (Fig. 1.6), among others. The equipment used was an HTC Vive, which allows participants to walk around, and includes spatially tracked hand-controllers that allow participants to engage in the activities using natural motions. During the activities, participants are listening to a virtual coach, voice-acted and animated ahead of time, who appears as a human avatar giving reassuring words. At the same time, the virtual coach is also asking participants to test the limits of their fear. Before embarking on an activity, participants are asked to rate their fear on a scale of 1 to 10. The idea behind the treatment is that the simulated activity will then prove to the patient that it is safe, gradually dispelling their fear of heights. According to Freeman, the tests are not designed to be exposure therapy exercises but are designed to be behavioural experiment tests. This means that patients are not merely thrown into anxiety-inducing situations until they become acclimatized to them; the coaching is designed to encourage patients to engage with heights of their own free will.

After six 30-minute sessions over the course of two weeks, the group that was administered this experimental VR treatment was given a Heights Interpretation Questionnaire (HIQ) and scored much higher

13 Brenda K. Wiederhold and Stephane Bouchard, *Advances in Virtual Reality and Anxiety Disorders* (New York, NY: Springer, 2014), 4.

14 Daniel Freeman et al., "Automated Psychological Therapy Using Immersive Virtual Reality for Treatment of Fear of Heights," *The Lancet* 5, no. 8 (August 2018): 625–32.

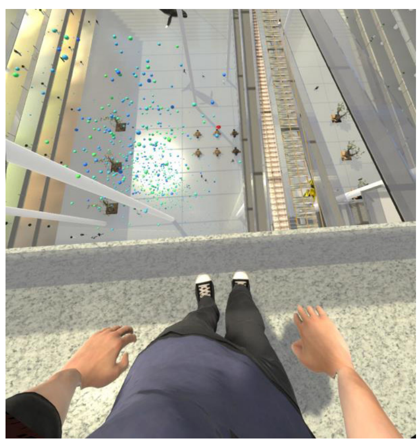

Figure 1.5 *Patients choose which floor of the atrium they would like to be on to conduct the exercises, which helps to track their progress between sessions.*

Figure 1.6 *Tasks like rescuing the cat engage patients with the environment*

than the control group, which was given no treatment.[15] At the time of writing, the researchers have yet to compare the VR treatment to the traditional methods of treatment with a therapist. However, when compared to the methods that therapists had been using before, VR is proving itself to be more capable of drawing out visceral reactions to spatial configurations.

VR in the lab

There have been several research studies that illustrate how drawings might not engage our brains in a similar fashion to spatial navigation in the real world. A seminal study conducted by Eleanor Maguire found that taxi drivers in London have much more grey matter in their hippocampi than people in other professions. In fact, more experienced drivers have more developed hippocampi than new taxi drivers, and more developed than bus drivers, who follow predetermined routes. A follow-up study found that these navigational skills begin to deteriorate after retirement from taxi-driving, so it is a part of the brain that needs regular exercise.[16] Similarly, another study found that people who are given turn-by-turn instructions have their hippocampi switched off, meaning that drivers who depend on their GPS are less likely to commit the route to memory and do not remember as many details along the way as people who use visual cues in the environment to navigate.[17] This would appear to support research that found that people with impaired hippocampi are still able to perform map-reading tasks.[18]

Spatial processing in VR can be seen in an experiment devised by Tim McNamara and students at Vanderbilt University where they are testing their hypothesis that grid cells may be involved in the understanding of spatial distances. While wearing a VR headset, participants of the study are put into a virtual field enclosed by four walls arranged in a rectangular shape. Participants are asked to walk towards a red posts and then towards several green posts. Once they have reached the last green post, the environment disappears, and participants are asked to return to where the red post was using their memory. In the control group, the environment is not modified at any point and participants return to roughly where the red post was. In the experimental group, the walls enclosing the field are subtly expanded or compressed as the participants are following the green posts. In cases where the enclosure is expanded, participants tend to underestimate the distance to return to their starting point. When the enclosure is compressed, the opposite happens and participants overestimate the distance. This could be a result of participants judging the distance between the posts in relation to the size of the enclosure. Researchers noted that the patterns of overshooting and undershooting the distances were consistent with experiments done with rats. McNamara is quick to concede that this is only a small step in proving that humans navigate with a grid cell system like the ones observed in animals, but believes that the exper-

15 Ibid.

16 Katherine Woollett et al. "Talent in the Taxi: A Model System for Exploring Expertise." *Philosophical Transactions B*, vol. 364, no. 1522, 2009, 1407-1416.

17 Amir-Homayoun Javadi et al., "Hippocampal and Prefrontal Processing of Network Topology to Simulate the Future," *Nature Communications* 8 (March 21, 2017): 14652, https://doi.org/10.1038/ncomms14652.

18 Zhisen Urgolites et al., "Map Reading, Navigating from Maps, and the Medial Temporal Lobe," *Proceedings of the National Academy of Sciences of the USA* 113, no. 50 (December 13, 2016), https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5167206.

iment provides circumstantial evidence grid cells form a part of our navigational system.[19] Although VR was not the topic of investigation in this experiment at Vanderbilt, it was an important asset in its process. By using the technology, the researchers were able to obtain valuable information that they deemed to be analogous to other research results, which is a promising sign that we navigate in VR similar to how we would in the real world.

Outlook

While it may be true that VR can help us visualize spaces of different shapes and sizes better than flat forms of representation, an area that VR struggles with is simulating movement through spaces that are larger than the walkable area available to the user. With room-scale VR (such as the Oculus Rift and HTC Vive), areas of movement are typically 6-10 square feet.[20] This means that for most use cases in an architectural practice, VR users will have to depend on alternative forms of locomotion. Unlike traditional virtual walkthroughs on monitors, VR users cannot simply use a joystick to move around because the feeling of walking with just a slight flick of the thumb creates too much cognitive dissonance, quickly causing nausea.[21]

To circumvent this physical limitation, game designers have tried

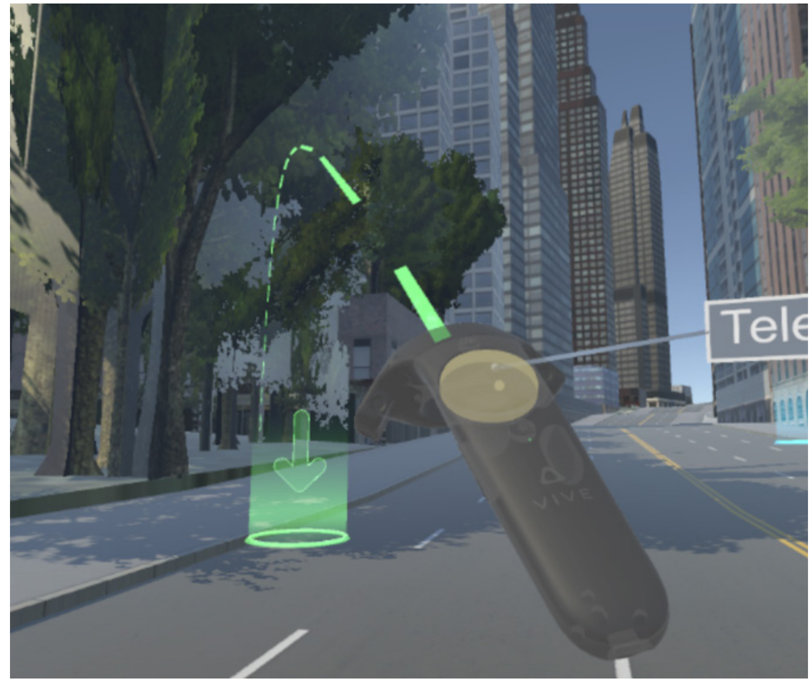

Figure 1.7 *VR teleportation, one of the many methods for articial locomotion in VR.*

many different methods to give users a means of locomotion. Another method is to use swinging arm motions to propel forward, similar to using trekking poles to walk.[22] This method might be effective if the size of the virtual space is moderately larger than the physical space, but over a long period of time this method can still cause nausea, not to mention fatigue from actively moving the arms. A third and less

19 Qiliang He and Timothy McNamara, “Environmental and Idiothetic Cues to Reference Frame Selection in Path Integration,” in *Spatial Cognition X: 13th Biennial Conference* (New York, NY: Springer Berlin Heidelberg, 2017), 137–56.

20 Oculus VR, “Roomscale Revisited: Getting the Most Out of Your Rift”, *Oculus* Blog, 5 Jan 2018, https://www.oculus.com/blog/roomscale-revisited-getting-the-most-out-of-your-rift/ (Accessed 12 Apr 2018).

21 Oculus. “Solving for Locomotion in VR.” YouTube video, 42:54. Posted Oct 2017. https://youtu.be/PMSpHIHeaR0.

22 Kevin Carbotte, “Do the Locomotion,” Tom’s Hardware, March 10, 2018, https://www.tomshardware.co.uk/picturestory/230-virtual-reality-games-locomotion-methods.html.

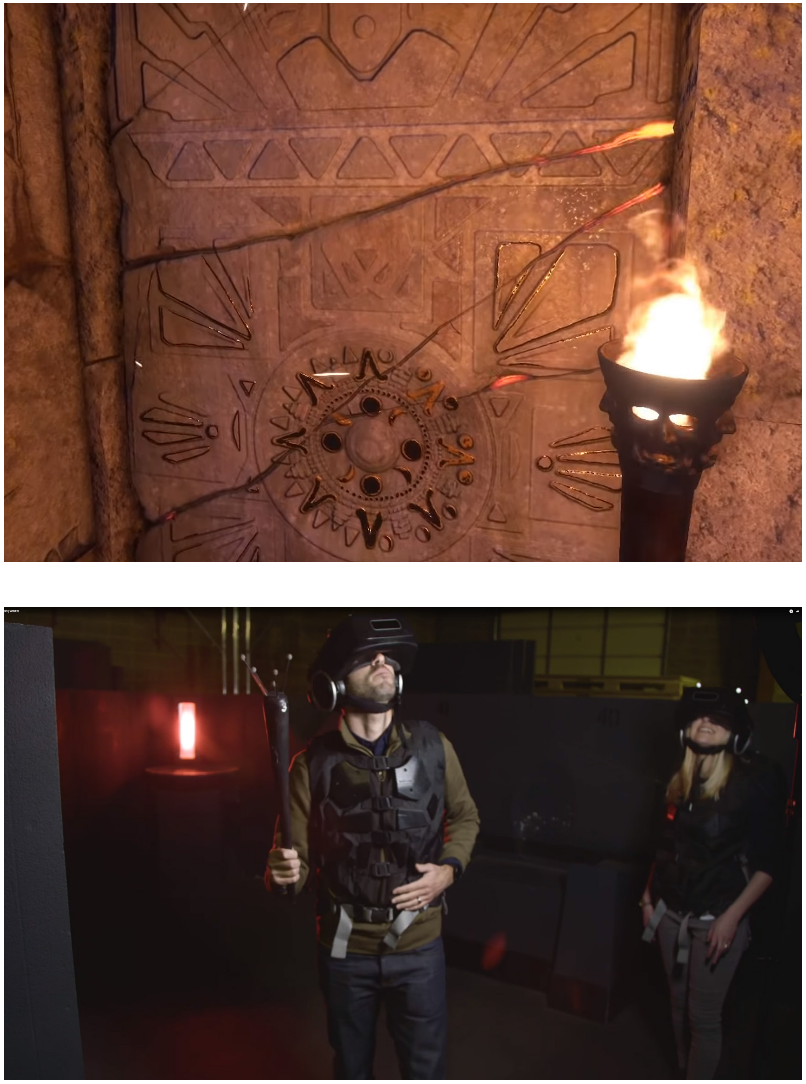

Figure 1.8 *The Void is VR experience that syncs up the visual component of VR (above) with a physical set (below) that users can freely walk through and interact with.*

common method is “Superman” locomotion, for lack of a better word. In this method, the user leans forward and extends both arms forwards like the fictional superhero.[23] While this method is surprisingly not nausea-inducing, it is again quite unnatural and may be tiring to use for extended periods of time. One of the most commonly-used methods is teleportation (Fig. 1.7), where users point to a spot that they want to move to with the hand-controllers.[24] A marker will appear at the location letting users adjust before finalizing the move. Teleportation is generally considered the most balanced solution at the moment. While it does not provide an experience that is similar to movement in the real world, it is the most comfortable method of locomotion and allows users to quickly traverse through large amounts of space. In scenarios where the walking experience through a sizable distance is being evaluated, teleportation might not be ideal. However, in most other situations for architectural designers, teleportation should be sufficient for moving around to evaluate different areas of the virtual environment.

There are locomotion methods at the time of writing that are both comfortable and natural, but these tend to come at a cost. One solution, sometimes referred to as “warehouse-scale”, is to map the virtual environment onto a one-to-one model of the space (Fig. 1.8). Users wear VR headset that either has an integrated computer or is connected to a backpack computer, which allows them to walk freely through an environment that they can physically touch and feel. Visual

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23 Ibid.

24 Sean Buckley, “Why ‘Teleportation’ Makes Sense in Virtual Reality,” *Engadget*, October 7, 2016, https://www.engadget.com/2016/10/07/why-teleportation-makes-sense-in-virtual-reality/.

effects like textures and lighting are simulated in the VR headset.[25] This might be the most natural feeling type of VR available at the moment. However, it is also one of the most expensive and most labor-intensive because it takes considerable effort to build the physical environment and set-up tracking cameras to align the built environment with the virtual environment. A solution that is more economically and physically more feasible is the omnidirectional treadmill (Fig. 1.9), which allows users to walk endlessly in any direction.[26] However, this technology is still early in its development.

The problem of simulating movement through large spaces is a tricky but important hurdle to overcome, but would be of particular interest to architects. Once VR is able to simulate locomotion in a natural way, users can roam through the largest of spaces from the confines of a small room.

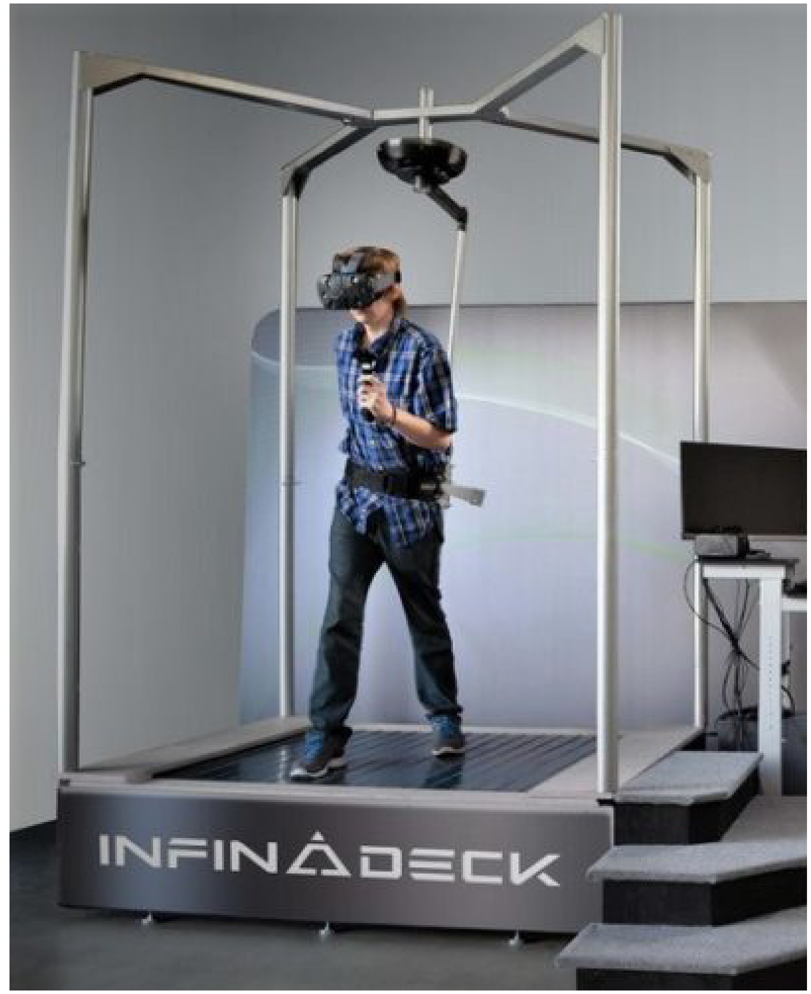

Figure 1.9 *Infinadeck omni-directional treadmill*

25 Charles LaCalle, "Enter The Void: Physical Virtual Reality," Medium, March 10, 2016, https://medium.com/@charleslacalle/enter-the-void-physical-virtual-reality-9e5deea30b28.

26 Juanita Leatham, "VR Omnidirectional Treadmills Making Gains Towards Full Immersion and Cardio," VR Fitness Insider, April 5, 2018, https://www.vrfitnessinsider.com/vr-omnidirectional-treadmills-making-gains-towards-full-immersion-and-cardio.

CHAPTER 2

Spatial Complexity

One of the genres that VR has been most successful in so far has been horror. In fact, it may be too effective at scaring people; developers of VR horror games have said that they have had to practice restraint in the designs of their games. Scott Stephan, lead designer at WEVR, says that traditional horror films present “fun scares” that are abstracted by way of the screen, but VR horror bypasses the barrier of the screen and creates “survival scares” that activate a fight or flight response.[1] Similar to the spinning tunnel illusion presented in the introduction, horror experiences in VR tap into a part of the consciousness that overrides any knowledge of the fact that it is a mirage.

It is this characteristic of the human mind that has people returning to physical haunted houses. Although the focal points of haunted house experiences are usually the monsters, a lot of work must be put into making the house appear “haunted”. Claustrophobic hallways, dark and confusing sightlines, and artificially aged fixtures are just a few of the many techniques that create a spooky atmosphere.[2] While not many visitors will pay attention to these details, a strong case could be made that the set design is the most important part of the experience. After all, the costumed performers in most likelihood would not seem very intimidating at all in broad daylight.

A lot of what our senses perceive does not surface into the conscious mind; scientists have found that the vast majority of information

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1 Matthew Handrahan, “VR Devs Call for Restraint on Horror Games and Jump Scares,” gamesindustry.biz, March 14, 2016, https://www.gamesindustry.biz/articles/2016-03-14-vr-developers-advise-caution-on-horror-games-and-jump-scares.

2 Frank T. McAndrew, “What Makes a House Feel Haunted?” Psychology Today, November 2, 2015, https://www.psychologytoday.com/ca/blog/out-the-ooze/201511/what-makes-house-feel-haunted.

that we gather about our surroundings is processed subconsciously.[3] There are many aspects of the environment that may not necessarily stand out or may appear to be merely superficial features, but have a significant impact on our everyday psychology, albeit in a much less extreme fashion than theme parks and haunted houses.

Significance to architecture: What are some examples in architecture where the details or atmosphere make a huge difference?

Sally Augustin, a psychologist who specializes in person-centered design, believes that sensory stimuli in the environment has a direct impact on us. Visually, this includes: the size and shape of the room (discussed in the previous chapter), lighting, colour, patterns, and textures. Augustin believes that humans in general respond similarly, with several exceptions caused by personal experiences and cultural backgrounds.[4]

For example, greenery is known to have restorative effects and is often used in healthcare facilities (Fig. 2.1).[5] This effect has also been beneficial to business owners, who have found that the effectiveness and productivity of their employees increased when they had visual access to nature.[6] A similar effect was observed in high school students, who focused better and performed better than their peers who took classes in windowless rooms[7]. When access to exterior views is not possible, researchers have found that restorative effects can come from other pleasant distractions like potted plants and artwork.[8] On the other end of the spectrum, red has been found to be a distracting and agitating color. It is a color that interior designers advise to use in moderation, because an environment with an overwhelming amount of red has the tendency to raise blood pressure, muscular tension, and perspiration levels.[9] However, a slightly lighter shade of red – namely pink – has proven to have a dramatically different effect. An experiment

3 David Eagleman, *Incognito: The Secret Lives of the Brain*, 1st American ed (New York: Pantheon Books, 2011), 7.
4 Sally Augustin, *Place Advantage: Applied Psychology for Interior Architecture* (Hoboken, NJ: John Wiley & Sons, Inc, 2009), 6.
5 Rona Weerasuriya, Claire Henderson-Wilson, and Mardie Townsend, “A Systematic Review of Access to Green Spaces in Healthcare Facilities,” *Urban Forestry and Urban Greening*, n.d., https://doi.org/10.1016/j.ufug.2018.06.019.
6 Augustin, 169-170.

7 Dongying Li and William C. Sullivan, “Impact of Views to School Landscapes on Recovery from Stress and Mental Fatigue,” *Landscape and Urban Planning* 148 (April 2016): 149–58, https://doi.org/10.1016/j.landurbplan.2015.12.015.
8 Augustin, 32.
9 Nicholas Humphrey, *Seeing Red: A Study in Consciousness.* (Cambridge, MA: Harvard University Press, 2009).

Figure 2.1 *ICU ward in the Massachusetts General Hospital designed by NBBJ architects.*

Figure 2.2 *The so-called "drunk tank pink" that was experimented with in prison cells.*

Figure 2.3 *Football teams also experimented with the color in the visiting team's changing room, in hopes of gaining a psychological edge before games.*

conducted by Alexander Schauss in 1979 found that research participants who stared into a pink piece of cardboard would consistently perform worse in a test of strength compared to when they stared into a blue-colored piece of cardboard. Schauss recommended that the particular shade of pink be used in corrections facilities to help pacify rowdy inmates, where this particular shade of pink earned the moniker "drunk tank pink" (Fig. 2.2). With varying success, the color found its way into classrooms, nurseries, and even the visitor's rooms of some football stadia (Fig. 2.3). Although subsequent studies have found that the color's energy-sapping effect quickly wears off and repeated exposure to it lessens the effect it has on people, meaning that the color's utilization in the examples above may not be as efficacious as once thought, the initial impact of the color has not been disproved.

Contextual theory: Why might environmental details and qualities be more influential in VR?

The discussion of how architectural design affects the human experience is encapsulated in the idea of phenomenology. One of the foundational components of phenomenology is the rejection of the Cartesian dualism of mind and body,[10] the commonly-held belief that the body and mind are two distinctly separate entities. This change in thinking aligns with the argument in this thesis that representation of space should involve the body, and not be isolated in the mind. As mentioned in the introduction of the thesis, VR representations of space

10 David W. Smith, "Phenomenology," Stanford Encyclopedia of Philosophy, December 16, 2013, https://plato.stanford.edu/entries/phenomenology/.

directly engage users as active participants of a virtual world created around them. The immersiveness of VR gives users the impression that they can reach for anything around them. On the other hand, drawings and perspectives leave viewers on the outside as idle spectators.

The importance of the body in spatial perception is explored by the philosopher Maurice Merleau-Ponty, who writes that "[the] body appears to me as an attitude directed towards a certain existing or possible task. And indeed its spatiality is not, like that of external objects or like that of 'spatial sensations', a spatiality of position, but a spatiality of situation." Merleau-Ponty's words are an important reminder to architects that while it is a critical part of the job to think of space in terms of objective dimensions, the "spatiality of situation" from the subjective perspective of inhabitants should not be overlooked. He believes that spatial awareness begins from the body of the observer, who builds an awareness of their surroundings based on possible actions that can be taken.

While architects cannot anticipate every possible permutation of activities that take place in their designed spaces, it would not be remiss to suggest that architects do have a significant amount of influence in shaping how people might behave and use the spaces that they design. An important approach for architects to exert their influence on inhabitants is through affordances, a term coined by ecological psychologist James J. Gibson. Affordances are potential actions that can be taken with different objects. For example, if an architectural element like a concrete planter or a window sill is at a height that is comfortable for sitting, it affords the action of sitting even though it might not be markedly obvious or the design intention of the architect. Gibson argues that affordances are a vital part of how we understand the world around us because we must anticipate actions that are ahead of us, like maneuvering around obstacles in our path. Affordances are relative to how we understand our physical capabilities, meaning that someone skilled in parkour may see a path up a wall whereas someone who is not can only see a dead end. Affordances can also vary based on the object's location relation to the observer. When reaching for a plate on the top shelf of a cabinet, we may have to stretch our bodies upwards and use an overhand grip to grasp the plate. When the plate is on the bottom shelf close to the ground, however, the afforded action

Figure 2.4 *This installation designed by RAAAF, The End of Sitting, is an exploration into how affordances can be created through an understanding of geometry and the dimensions of the human body.*

is different, requiring us to bend down and use an underhand grip.

In his book, *The Design of Everyday Things*, Don Norman urges designers to improve the daily lives of people by making things that are intuitive to use. One example that he gives is in the case of a door (Fig. 2.5):

To operate a door, we have to find the side that opens and the part to be manipulated; in other words, we need to figure out what to do and where to do it. We expect to find some visible signal, a signifier, for the correct operation: a plate, an extension, a hollow, an indentation—something that allows the hand to touch, grasp, turn, or fit into. This tells us where to act. The next step is to figure out how: we must determine what operations are permitted, in part by using the signifiers, in part guided by constraints.[11]

Norman believes that designers should be aware of how their creations appear to the unfamiliar eye, using what he calls "signifiers" to make the intended affordances intuitive. Scientific developments have now proven that affordances do exist. Researchers found that seeing objects that can be acted upon activates neurons, now called canonical neurons, in the same part of the brain that would activate when one were to reach for the object, even if there is no intent to take action. Research has shown that canonical neurons are activated with pictures and words as well. At the moment, there have not been scientific comparisons between affordances from real objects and affordances from VR or pictures. While it appears that pictures activate a stronger reaction than words, research shows that affordances are stronger

Figure 2.5 *Handle bars on doors imply a pulling action, whereas push plates imply a pushing action. Providing clear and intuitive affordances reduces the chance that users will misinterpret how to operate the door.*

when the object is within the observer's peripersonal space. This could mean that affordances in VR would be stronger than affordances from looking at pictures because objects seen in VR are directly relatable to the observer's peripersonal space.

State of VR in the field

The previous chapter showed examples of how VR has helped therapists treat spatially-oriented anxiety disorders like claustrophobia and acrophobia. There are also anxiety disorders that have to do with environmental details and qualities, such as PTSD. Once again, VR has

[11] Donald A. Norman, *The Design of Everyday Things*, Revised and expanded edition (New York, New York: Basic Books, 2013), 132.

proven to be a helpful tool for therapists in this area as well.

Similar to other *in virtuo* types of therapy, VR treatment for PTSD involves putting patients in immersive experiences of traumatic situations while they are in a safe and controlled environment where they are being carefully monitored by a therapist. One of the main challenges in providing therapy for PTSD is that it is often difficult for patients to effectively visualize and recall traumatic experiences,[12] an important part of imaginal therapy. VR relieves patients of this difficult task and allows them to focus on mastering coping techniques that are an important step on the road to recovery. Bravemind, a VR therapy program, is designed by the University of Southern California for veterans returning home from war. Using a specially-designed interface, clinicians gradually add more and more sensory stimuli like sounds and smells into the VR scenarios, slowly easing patients into scenarios (Fig. 2.6). A meta-analysis of over a dozen studies concluded that VR therapy for anxiety and PTSD is almost as effective as *in vivo* (real-life) therapy.[13] VR's effectiveness in this type of therapy shows its ability to convey atmospheric moods, which is important for architects.

Researchers are also looking into how VR can be used to induce cravings, so that they can create a controlled environment to combat addictions like smoking and alcoholism[14]. Psychologists believe that environmental cues are an important factor to cravings. For example, warm colors like reds, oranges, and yellows help increase appetite.[15] For addicts, cues often take the form of objects that are frequently present when indulging in the addiction. It can also be in the form of sounds (e.g. music or ambient noises), or scents (e.g. a food or drinks), or a specific location. The idea behind VR therapy for addiction is that by exposing people to potential cues in VR where they cannot access the object of addiction, the conditioned behaviour of succumbing to addic-

12 Brenda K. Wiederhold and Stephane Bouchard, *Advances in Virtual Reality and Anxiety Disorders* (New York, NY: Springer, 2014), 211.

13 Emily Carl et al., "Virtual Reality Exposure Therapy for Anxiety and Related Disorders: A Meta-Analysis of Randomized Controlled Trials," *Journal of Anxiety Disorders*, August 2018, https://doi.org/10.1016/j.janxdis.2018.08.003.

14 Tracey Ledoux et al., "Using Virtual Reality to Study Food Cravings," *Appetite* 71 (December 2013): 396–402, https://doi.org/10.1016/j.appet.2013.09.006.

15 Augustin, 68.

Figure 2.6 *The dashboard adds or removes individual sensory stimuli into the VR experience, allowing granular control over the therapy session.*

tion is slowly broken down. For therapists, VR has shown that it can greatly reduce the burden of conveying complex spatial qualities and details to clients, a prospect that architects should find useful as well.

State of VR in the lab

A study conducted at the University of Vienna found that VR can be used to manipulate mood.[16] Participants were put into different VR environments that were designed to induce a specific feeling, which were joy, sadness, boredom, anger, and anxiety. Although the fact that environments in VR can affect our emotions may seem trivial, it has deeper implications on decision-making. Jeremy Bailenson, a researcher at Stanford University, has conducted many experiments to explore how VR affects human behaviour. In one of Bailenson's experiments, participants were put into a scenario where they are cutting down a tree in a forest. The first group experienced this through reading a vividly descriptive piece of writing, while the second group experienced the scenario in a first-person perspective in VR, operating a haptic device that simulated a chainsaw (Fig. 2.7). After their respective experiences, both groups replied to a survey that they

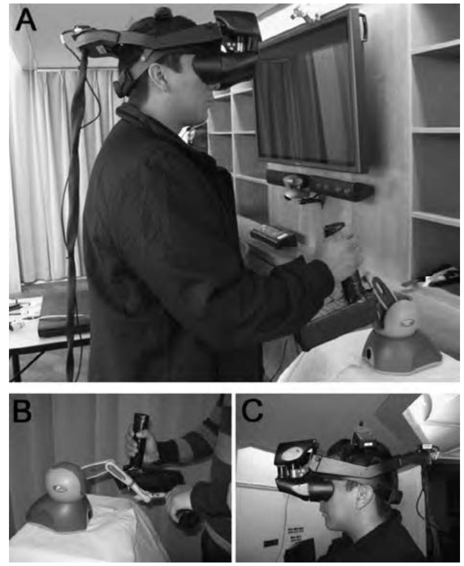

Figure 2.7 *The VR rainforest experiment by Sun Joo Ahn at Stanford University demonstrated how enacting a scenario in VR can affect attitudes and behaviours.*

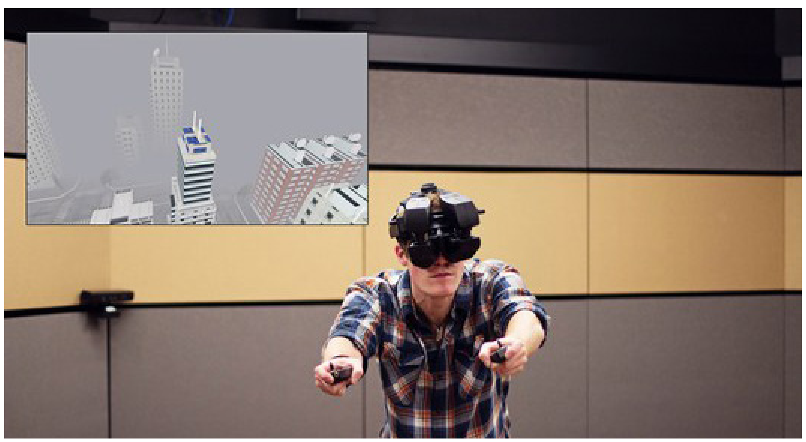

Figure 2.8 *The VR super-hero experiment by Robin Rosenberg at Stanford University demonstrated how performing the same task in VR but in a contrasting manner can affect participants differently.*

16 Anna Felnhofer et al., "Is Virtual Reality Emotionally Arousing?" *International Journal of Human-Computer Studies* 82 (October 2015): 48–56, https://doi.org/10.1016/j.ijhcs.2015.05.004.

would decrease the amount of paper that they use in their daily lives. However, when the research assistant then "accidentally" knocks over a glass of water, the VR group on average used 20% fewer napkins to clean up the mess.

In another one of Bailenson's experiments, participants fly around a virtual city looking for a missing child. Both groups experience the scenario in VR, but while one group flies around in a helicopter, the other group flies around the city like a superhero (Fig. 2.8). Like the other experiment, the research assistant "accidentally" knocks over a few pens, and the group that experienced the VR experience as a superhero were found to be more likely to help the assistant pick up the pens. The researchers believe that participants who took part in the VR experience as a superhero are mentally primed to be more proactive compared to the other group who took a more passive role. [17] For architects, Bailenson's findings are significant. Architecture is a major contributing factor in how people are mentally primed. If the VR environments are more persuasive than words or pictures, then that means VR representations of architecture could help designers understand how people feel about spaces and what they might be inclined to do in particular settings.

Outlook

In the development of VR, the simulation of senses other than sights and sounds presents a major challenge. For architects, this is certainly not ideal. Many would argue that the sense of touch is one of the most important aspects of the architectural experience. The feeling of a smooth marble floor or a plush carpet under the feet, or the feeling of a gentle breeze guided down a promenade; tactility is something that architects should not ignore. Unfortunately, it is not something VR can simulate successfully at the moment. However, the same can be said about drawings and renderings. For now, VR relies on perceived affordances to imply different sensations. Our brains tend to interpolate when given an incomplete picture.[18] Sometimes this can even involve multiple senses. Neuroscientist Jay Gottfried found that if there is a link between a picture and a scent, then the sight of the visual stimuli alone can activate brain regions associated with smell[19]. Another example is that our cheeks flush when we are close to fire as our bodies prepare to expel heat, and this physiological response can be activated by images of fire that is convincingly bright.[20]

The most complete VR experience at the moment is probably found at The Void, which was briefly mentioned at the end of the previous chapter. The Void is a "virtual reality theme park" that is similar to laser tag but with a slew of different sensory stimuli added in to increase im-

17 Robin S. Rosenberg, Shawnee L. Baughman, and Jeremy N. Bailenson, "Virtual Superheroes," ed. Attila Szolnoki, *PLoS ONE* 8, no. 1 (January 30, 2013): e55003, https://doi.org/10.1371/journal.pone.0055003.

18 Philip J Kellman and Thomas F Shipley, "A Theory of Visual Interpolation in Object Perception," *Cognitive Psychology* 23, no. 2 (April 1991): 141–221, https://doi.org/10.1016/0010-0285(91)90009-D.

19 Jay A Gottfried et al., "Remembrance of Odors Past," *Neuron* 42, no. 4 (May 2004): 687–95, https://doi.org/10.1016/S0896-6273(04)00270-3.

20 Poppy Crum, *Technology That Knows What You're Feeling* (Vancouver, Canada, 2018), https://www.ted.com/talks/poppy_crum_technology_that_knows_what_you_re_feeling.

Figure 2.9 *The Teslasuit provides users with a full-body haptic feedback system, as well as a climate control system that allows users to feel hot or cold sensations on their skin when they come into contact with virtual stimuli.*

mersion.[21] Visitors wear a VR headset that is connected to a backpack computer so that they can freely walk through a carefully constructed set that corresponds to what they see in the headset. This means that what visitors may be seeing on their headset is the interior of a spaceship, when they are actually inside a sparsely-detailed replica. The benefit of this set-up is that visitors can touch and feel their surroundings. Walls can be leaned on and chairs can be sat in, unlike a personal VR system like the Oculus Rift or HTC Vive that people purchase for their homes. In The Void's Star Wars experience, as visitors step out of their spaceship and onto the fictional volcanic planet of Mustafar, they are met with the smell of sulphur and a blast of smoldering heat.[22] The added depth of these senses go a long way to add to the immersion of the experience. From the perspective of an architect, this type of VR set-up may appear to be ideal, but it may just be too difficult and costly to justify in most scenarios. One type of designer who might be able to take advantage of this type of VR set-up is a kitchen designer, where designing interactions with appliances and cabinetry are integral parts of the job. A VR set-up where clients can physically interact with the environment and experience sounds and smells at the same time could be an enticing proposition. The modular nature of kitchen design also brings down the cost of implementation, and allows for iterations to be made rapidly.

In the design of room-scale VR experiences made for personal VR headsets like the Oculus Rift and the HTC Vive, designers have found

21 Jeremy White, "I Was a Stormtrooper for 15 Minutes and It Was Awesome," Wired, December 16, 2017, https://www.wired.co.uk/article/star-wars-vr-london-secrets-of-empire-void-experience.

22 Ibid.

that including interactions - even if they are simple and crude - help improve the feeling of immersion.[23] This could be something as simple as including a few objects that users can pick up and throw, or it could be operable mechanical parts in the environment like doors, windows, or light switches.

There are many interesting laboratory projects that have showcased the ability to simulate a limited array of sensations like heat, cold, wind, or the feeling of objects on the user's fingertips (Fig. 2.9-2.11). However, it is still early in the development of these peripheral VR accessories and it is difficult to assess the usability and efficacy of these devices. Sensations are an aspect of VR that is perhaps the most challenging, but would be a key hurdle in moving VR towards the goal of simulating reality. Nonetheless, VR's enveloping nature as a medium provides a better backdrop for reproducing spatial qualities and atmospheres. While it may not be able to recreate a complete sensorial experience, it is a big step forward from flat representations of architecture.

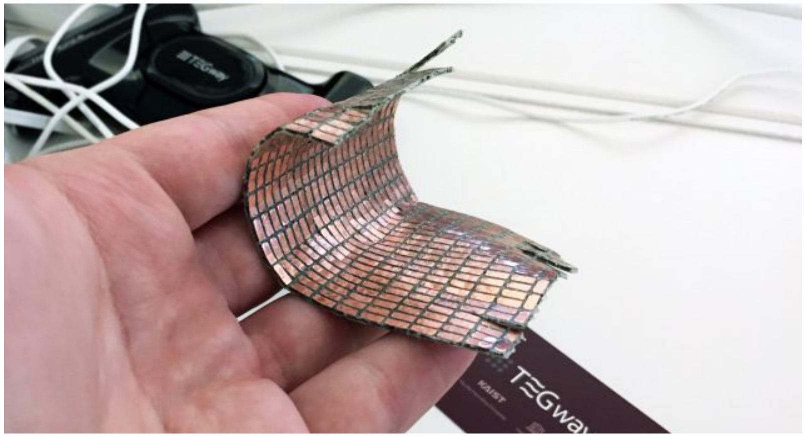

Figure 2.10 *An array of thermoelectric generators used in a prototype device (ThermoReal) that creates hot or cold sensations.*

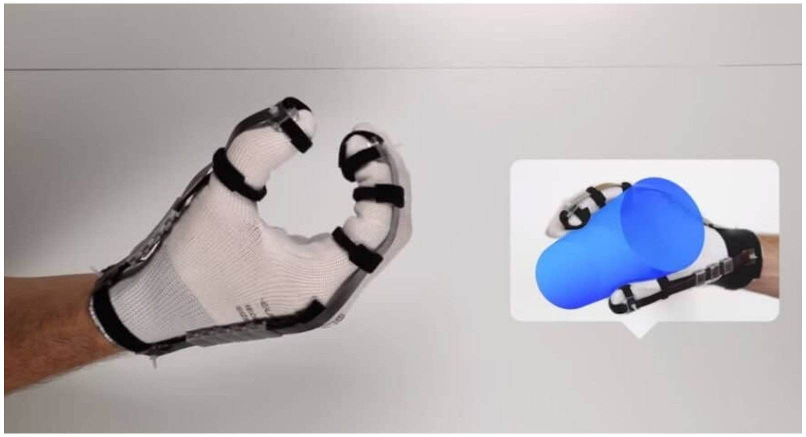

Figure 2.11 *VR gloves that prevent the fingers from bending past a certain point when the user grasps an object in VR, giving the sensation of holding a physical object.*

[23] James J. Cummings and Jeremy N. Bailenson, "How Immersive Is Enough? A Meta-Analysis of the Effect of Immersive Technology on User Presence," *Media Psychology* 19, no. 2 (April 2, 2016): 272–309, https://doi.org/10.1080/15213269.2015.1015740.

CHAPTER 3

Spatial Population

In a thought-provoking TED Talk in 2015, film-maker Chris Milk made the bold claim that VR "can create the ultimate empathy machine."[1] Speaking about *Clouds Over Sidra*, a short video that he directed to bring attention to the plight of Syrian refugees, Milk says, "When you're sitting there in [Sidra's] room, watching her, you're not watching it through a television screen, you're not watching it through a window, you're sitting there with her. When you look down, you're sitting on the same ground that she's sitting on. And because of that, you feel her humanity in a deeper way. You empathize with her in a deeper way."[2] When listening to someone in a VR experience it feels as though they are talking directly to you, and not a cameraperson who then relays the message. Milk makes the point that because it feels as though the viewer sits on the same ground as Sidra (Fig. 3.1) and is sharing the space with her, the perceived closeness forms a stronger connection between the subject and the viewer. This is something that has helped VR in the gaming industry, where players feel like the virtual characters are interacting with them directly, not through an intermediary avatar that they take control of as they watch through a window.

Although there have been many who dispute the claim that VR on its own can make people more empathetic, there are a lot of sociological and political implications for this usage of VR such as the lasting impact of VR experiences that try to motivate positive actions, or how the medium can be harnessed to cause harm as effectively as it is able

1 Chris Milk, *How Virtual Reality Can Create the Ultimate Empathy Machine* (Vancouver, Canada, 2015), https://www.ted.com/talks/chris_milk_how_virtual_reality_can_create_the_ultimate_empathy_machine.

2 Ibid.

Figure 3.1 *A scene from Chris Milk's 360° short film Clouds Over Sidra*

to do good. For this reason, the details of this discussion lie beyond the scope of this thesis. It is important to note that detractors of the idea that VR is an empathy machine do agree that the sense of perceived proximity between viewers and subjects makes VR a drastically different medium to work with.

Fortunately for architects, this may be sufficient because in most design scenarios, because the interactions between people in the public sphere are generally predictable and simple. For example, someone finding their way through a public square is usually just looking to avoid bumping into other people in their vicinity. People typically have defined thresholds of interpersonal space, a mental boundary that when encroached upon by other people, tends to cause some discomfort. The dimensions of this boundary can fluctuate from person to person, depending on a variety of factors like cultural upbringing, age, gender, and personality. Architectural factors like room size, lighting, and indoor/outdoor conditions can also affect perceptions of personal space[3]. For example, a comfortable distance between two people in an elevator would not be the same in an open field. This is where VR has a significant advantage over perspectival images; a person placed in the foreground of an image does not feel intrusive to the personal space of the viewer, it merely takes up more of the frame that is being viewed at a distance. In VR, on the other hand, viewers are not separated from other people that occupy the same virtual space, allowing a better understanding of the reciprocal relationship between architectural space and the people within it.

Significance to architecture

Sometimes the most influential aspect of the atmosphere of a space is not its design or any of its features, but the people who occupy it and their behaviours. For example, if everyone in a room is speaking in hushed whispers, then one would assume to follow suit in order to not stand out and be ridiculed. Behavioural psychologist Roger Barker referred to this phenomenon as "behaviour settings", to describe how people choose to behave in public in order to assimilate socially.[4] Even if the majority of people in a space do not directly interact with you, their presence can directly affect your experience of the space. A nightclub, for example, is a dark room mostly devoid of any décor, with a large empty space in the center, without any windows, and only illuminated by sharp colors. In any other scenario, this type of space

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3 Dak Kopec, *Environmental Psychology for Design*, 2. ed (New York: Fairchild Books, 2012), 76.

4 Ibid., 23.

Figure 3.2 *Times Square before the renovation; the lingering traffic lines and street curb create uncertainty.*

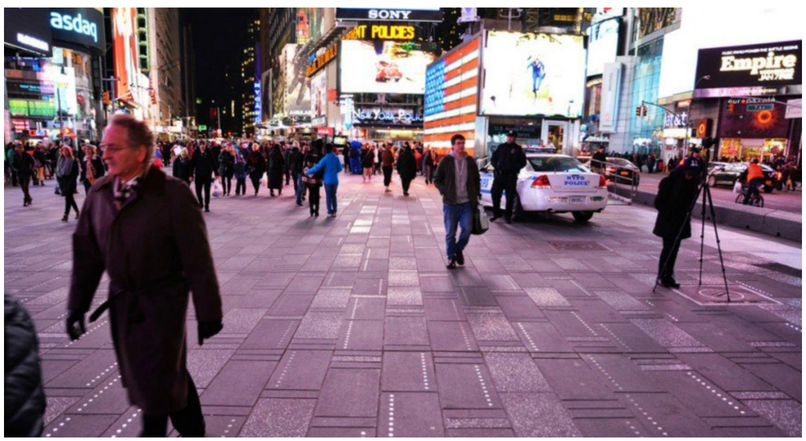

Figure 3.3 *Times Square after the renovation; areas for stopping are clearly defined from areas of movement.*

would not feel pleasant or safe. However, this all changes when it is full of people who are dancing and enjoying the company of each other. Architects may not necessarily have direct influence over how people can change the mood of a space, but it is certainly something that architects should anticipate and consider.

An example of this is New York's renowned Times Square junction. For tourists, it is a staple on the list of places to visit, but for local New Yorkers it is on the list of places to avoid.[5] When the restaurant review guide Zagat conducted a survey to find out why it seems like New Yorkers dislike Times Square so much, they found that by far the most frequent complaint about the famous landmark is that it is too crowded with tourists and that there are too many solicitors and costumed characters.[6] Locals were annoyed at how the tourists, dazzled by the bright lights and giant billboards, frequently stopped to look up and take pictures. Solicitors and costumed characters were seen as pesky and sometimes even unsettling.

In 2010, the city experimented with converting Times Square into a pedestrian-only area (Fig. 3.2), which led to a marked improvement in pedestrian safety and was a welcome change for local retailers.[7] To make the change permanent, the city held a competition for a redesign of the area, which was won by Norwegian firm Snøhetta. When asked about the intentions of the design, Craig Dykers, managing partner of

5 Joe Angio, "City Basics," Time, October 1, 2008, http://content.time.com/time/travel/cityguide/article/0,31489,1843404_1846360_1846361,00.html.

6 Zagat, "New Yorkers Actually Like Time Square, and More Surprising Results From Zagat's Survey," Huffington Post, April 30, 2015, https://www.huffingtonpost.com/zagat/new-yorkers-actually-like_b_7180808.html.

7 Michael Grynbaum, "New York Traffic Experiment Gets Permanent Run," The New York Times, February 11, 2010, https://www.nytimes.com/2010/02/12/nyregion/12broadway.html.

Snøhetta who oversaw the project, revealed that he aimed to put into practice what he learned from reading about livestock management[8]. Dykers shares a story about his friend's sheepdog who would tap at the ankles and knees of party guests, who would gradually and unknowingly gather into one corner. "As architects," Dykers says, "we have to try to be like the sheepdog at the party." Because it is impossible to account for the "weird irrationalities" asserts exist in humans and their behaviour[9], it would be beneficial for architects to refrain from attempting to micromanage or excessively dictate the use of the space.

Snøhetta's re-design of Times Square carves out different zones: "express lanes" that facilitate movement through the busy area, "chill zones" that provide seating for people to stop and take a break, and "designated activity zones" where solicitors and street performers are allowed to conduct business (Fig. 3.4). These designations are purposefully broad, and it shows in the simplicity of the design. The area is paved over with a monotonous combination of gray stone tiles, using variations in the size and direction of the tiles to subtly indicate the zones (Fig. 3.3). The only features that stand out from the ground plane are a series of monolithic benches that gradually slope to accommodate different sitting postures. As with the rest of the design, the intention is not to impose the architect's will onto users of the space, but to merely suggest.

Snøhetta's focus on the inhabitants of the space is not a new idea; throughout history there have been many types of social gathering

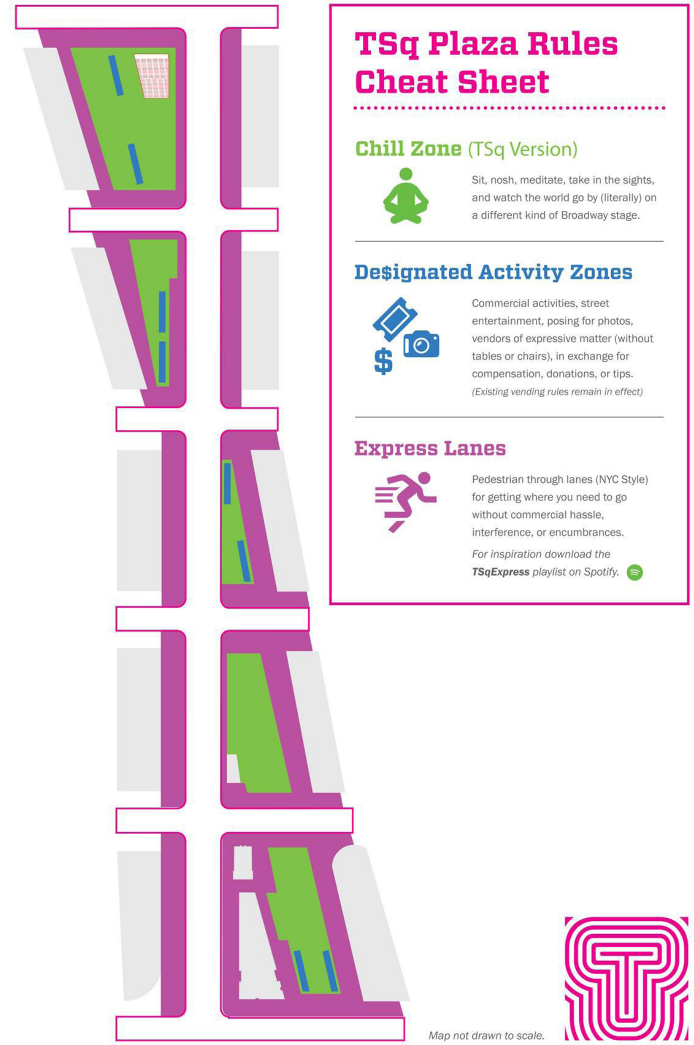

Figure 3.4 *Zone designations in the Times Square renovation project*

8 David Owen, "The Psychology of Space," The New Yorkers, January 21, 2013, https://www.newyorker.com/magazine/2013/01/21/the-psychology-of-space.

9 IIT Architecture Chicago, *Deans Lecture Series Video: Craig Dykers* (Chicago, IL, 2015), https://vimeo.com/160148973.

places where the occupants are as important to the atmosphere of the space as the architecture itself. Extravagant theaters like Paris' Palais Garnier (Fig. 3.5) often have a grand central staircase. It is not an efficient use of space nor is it efficient in moving people in and out of the theater. The grand staircase is not just a means for circulation, but also as a stage for the wealthy and fashionable to put on a display as they make their way to the coveted private boxes[10]. This notion is not exclusive to the theater; places like coffee houses and arcades throughout Europe were also seen as stages for people to put themselves on display.[11] These are spaces that can benefit from a medium like VR that can bring to life the energy generated by the interplay between people and architecture.

10 Charles Garnier, "Le Théâtre, Chapter 4, Staircases," in *Architecture and Movement: The Dynamic Experience of Buildings and Landscapes*, ed. Peter Blundell Jones and Mark Meagher (New York: Routledge, 2014).

11 Levi Mullan, "Coffee Houses and Arcades: A Forensic Inquiry into the Myths of Modernity," May 16, 2018, http://hdl.handle.net/10012/13294.

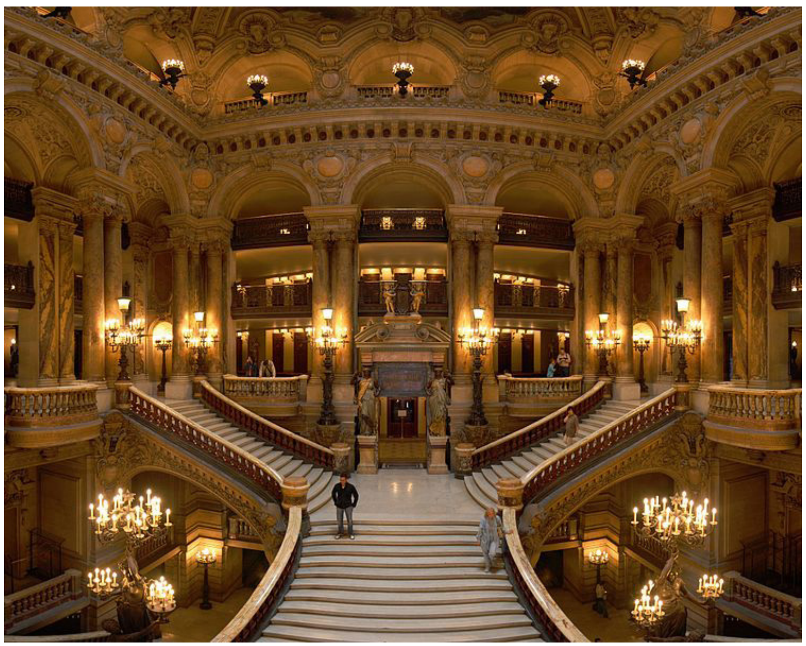

Figure 3.5 *The grand staircase in the Palais Garnier takes center stage, overlooked by a multitude of balconies and vantage points.*

VR in the lab

Figure 3.6 *Screenshots from the videos used in the study looking at how 360° videos of drastically different environments – an urban environment surrounded by people (top) and a serene rural environment (bottom) – have different effects on people.*

In one experiment, researchers showed two different 360-degree videos to two groups of participants: one of a peaceful forest environment, and another of a bustling urban environment (Fig. 3.6). The group that was shown the video of the urban environment exhibited higher levels of fatigue and decreased levels of self-esteem, while the group the was shown the video of the forest environment had the opposite effect[12]. These results appear to mirror the real-life associations of mental stress to urban living and mental rejuvenation to rural living[13]. Furthermore, what this experiment suggests is that 360-degree videos – a partially immersive VR experience – can generate the associated effects of each environment. This research may be relevant because the video the researchers have chosen places the viewer in a busy pedestrian area full of people, which could be a major source of the mental stress inflicted upon participants.

VR in the field

Therapists are experimenting with VR to help patients overcome social anxiety or situations where the presence of other people is stress-inducing. Similar to the use cases presented in the previous chapters, this is another type of therapy where *in vivo* therapy is often not feasible, let alone convenient. In this case it is because it is not a simple matter to assemble a large group of people in a standardized and controlled manner. Instantaneous control over the scalability of stimuli – in this case the people – is important for therapists, and would also be for architects using VR for crowd simulations.

Overcoming a fear of public speaking (Fig. 3.7) is a use case that has been successfully trialed with VR. Researchers have found that patients improved much more quickly when they could hold exposure therapy sessions on their own with VR headsets from the comfort of home in between weekly sessions with a therapist, compared to a control group that only saw the therapist[14]. The convenience that VR offers signifi-

12 Chia-Pin Yu, Hsiao-Yun Lee, and Xiang-Yi Luo, "The Effect of Virtual Reality Forest and Urban Environments on Physiological and Psychological Responses," *Urban Forestry & Urban Greening* 35 (October 2018): 106–14, https://doi.org/10.1016/j.ufug.2018.08.013.

13 Kalpana Srivastava, "Urbanization and Mental Health," *Industrial Psychiatry Journal* 18, no. 2 (2009): 75, https://doi.org/10.4103/0972-6748.64028.

14 Philip Lindner et al., "Therapist-Led and Self-Led One-Session Virtual Reality Exposure Therapy for Public Speaking Anxiety with Consumer Hardware and Software: A Randomized Controlled Trial," *Journal of Anxiety Disorders*, July 2018, https://doi.org/10.1016/j.janxdis.2018.07.003.

Figure 3.7 *Using VR to overcome anxiety from public speaking*

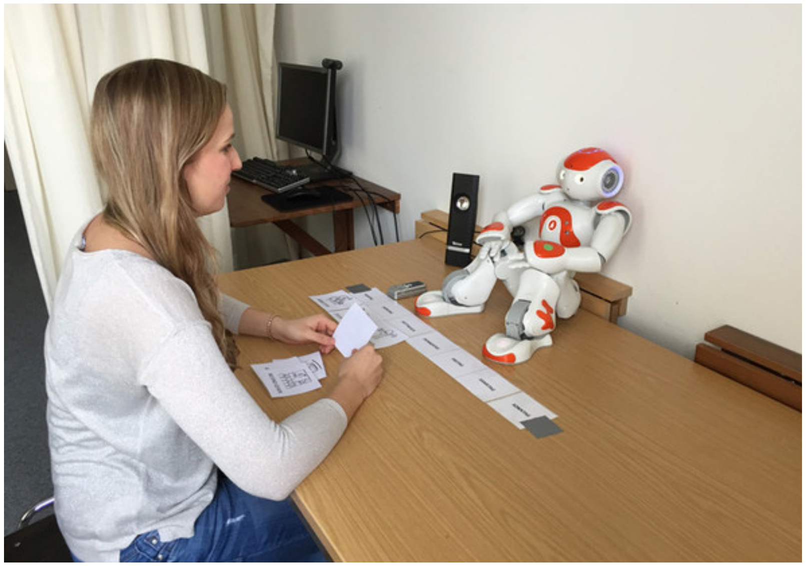

Figure 3.8 *Participants in this study performed several activities with the robot before being instructed to turn it off.*

Figure 3.9 *Screenshot of the virtual environment built to examine physiological responses to human characters as opposed to basic geometrical shapes.*

cantly speeds up improvements in patients. In an architectural design context, this might translate into a scenario where an architect needs to test many different iterations of an idea and how they might feel when populated.

Outlook

The *uncanny valley* is a common concern when discussing virtual humans. It is a term coined by roboticist Mashiro Mori to refer to digital characters that neither feel like caricatures or realistic humans, but something in between that can feel unsettling[15]. Creating a perfect simulation of a human being is still a distant possibility; the difficulty of giving AI characters natural-feeling eyes is on its own a major stumbling block[16].

Fortunately, there have been research studies that suggest it is not necessary to create virtual humans that feel completely natural in order to make spaces feel populated. Humans in general are empathetic creatures; tendencies like pareidolia, the inclination to see faces in inanimate objects, is well-documented.[17] In one study, participants are given a series of tasks to complete with a robot before switching it off (Fig. 3.8). With half of the participants, the robot is programmed to ask

15 Jeremy Hsu, "Why 'Uncanny Valley' Human Look-Alikes Put Us on Edge," Scientific American, April 3, 2012, https://www.scientificamerican.com/article/why-uncanny-valley-human-look-alikes-put-us-on-edge.

16 Mark Wilson, "The Impossibly Complex Art of Designing Eyes," Fast Company, October 7, 2016, https://www.fastcompany.com/3064303/the-impossibly-complex-art-of-designing-eyes.

17 Rebecca Rosen, "Pareidolia: A Bizarre Bug of the Human Mind Emerges in Computers," The Atlantic, August 7, 2012, https://www.theatlantic.com/technology/archive/2012/08/pareidolia-a-bizarre-bug-of-the-human-mind-emerges-in-computers/260760.

participants not switch it off. When that is the case, participants took on average twice as long to switch the robot off. Some even refused to do so at all. When asked about their decisions, many replied that they hesitated because the robot did not want to be switched off[18].

In a study using VR, researchers compared physiological responses when participants were approached by either a virtual human or a basic geometrical cylinder (Fig. 3.9). What they found was that there are no significant differences in anxiety levels – measured with skin conductance response – between the two types of character models[19]. There was, however, an increase in anxiety when larger groups of character models, in either humanoid or cylindrical form, approached participants, suggesting a linear relationship between anxiety levels and crowd size. In another study, researchers at the Korea Institute of Science and Technology set out to examine the correlation between the realism of avatars and levels of anxiety when participants were put in a VR job interview scenario. What they found was that even though there is an increase in levels of anxiety when participants are faced with a more graphically realistic interviewer, there is not a significant decrease when the virtual human is more cartoon-like[20]. The researchers conclude that a certain level of immersion is required to activate anxiety in participants and maintain it, and that the attitude of the virtual avatars are more important factors than visual fidelity when looking to elicit an affective response[21]. These studies indicate that it is not necessary to create lifelike and photorealistic humans to have the effect of achieving crowdedness in a space.

For architects looking to perform simple crowd simulations in VR, the technology available at the moment is likely sufficient. If more complex interactions are required, one solution could be to create a multi-player simulation and have several VR users at the same time. There have been applications where VR users can congregate in virtual settings to mingle and engage in social activities like attending concerts[22]. Similar applications can be made so that architects can put a group of people into a VR experience of a design in progress. This allows architects to observe how people might interact with the architecture and with each other as well as to obtain feedback, similar to focus group testing that is prevalent in other design professions, an option that has not been available to architects in the past.

18 Aike C. Horstmann et al., "Do a Robot's Social Skills and Its Objection Discourage Interactants from Switching the Robot Off?," ed. Hedvig Kjellström, *PLOS ONE* 13, no. 7 (July 31, 2018): e0201581, https://doi.org/10.1371/journal.pone.0201581.

19 Joan Llobera et al., "Proxemics with Multiple Dynamic Characters in an Immersive Virtual Environment," *ACM Transactions on Applied Perception* 8, no. 1 (October 1, 2010): 1–12, https://doi.org/10.1145/1857893.1857896.

20 Joung H. Kwon et al., "A Study of Visual Perception: Social Anxiety and Virtual Realism," in *Proceedings of the 2009 Spring Conference on Computer Graphics - SCCG '09* (the 2009 Spring Conference, Budmerice, Slovakia: ACM Press, 2009), 167, https://doi.org/10.1145/1980462.1980495.

21 Ibid.

22 "Things to Do," AltspaceVR Inc, n.d., https://altvr.com/things-to-do.

PART TWO

PLANNING

CHAPTER 4

Experiment Procedure

While VR technology has gotten much more accessible in recent years, it still requires more effort and more space to set-up than two-dimensional forms of representation. Room-scale VR in particular, which allows users to physically walk around the virtual environment (Fig. 4.1), requires a certain amount of space that architectural practices are now considering for when planning new offices.[1] The following chapter outlines the components necessary to the experiment.

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[1] *The Now and Future of Virtual Reality for Design Visualization* (Las Vegas, NV, 2016), https://www.autodesk.com/autodesk-university/class/Now-and-Future-Virtual-Reality-Design-Visualization-2016

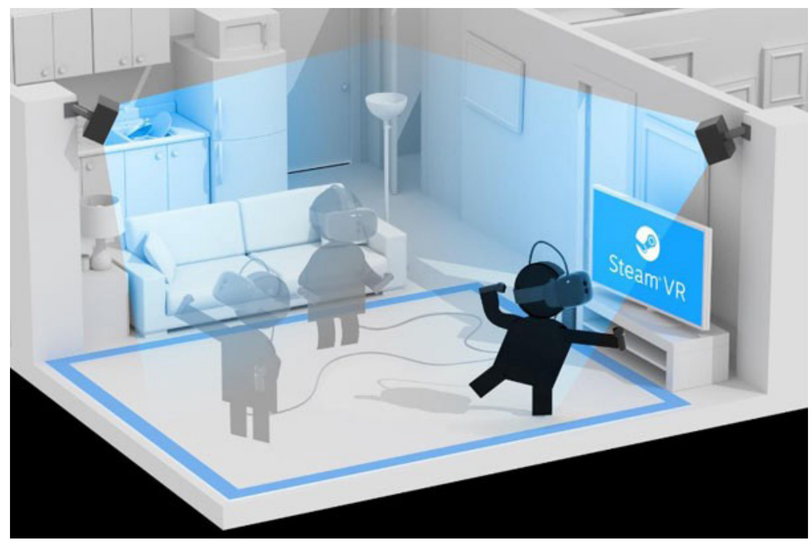

Figure 4.1 *Artist's rendering of a room-scale VR set-up. The blue rays emanating from the wall-mounted boxes indicate the field-of-view of the sensors that track the locations of the headset and the hand-controllers so that the user's movements in the physical world translate to the virtual.*

Equipment

The head-mounted display used in the experiment is the Oculus Rift VR headset, which displays images with two OLED screens (one for each eye) at a resolution of 2160 x 1200 and at a refresh rate of 90 Hz. User movements are tracked using two infrared cameras that monitor the position of the infrared LED lights that are embedded inside the headset and the hand controllers (Fig. 4.2). Sensors on-board the headset monitor the user's positional and rotational movements, which are updated at a rate of 1000 Hz.[2] The Oculus Rift must remain connected to a computer through a 10-foot long cable that provides the image, audio, and power.

The Oculus Rift works in conjunction with a pair of hand controllers called the Oculus Touch controllers. These are also tracked with a set of embedded infrared LED lights, which allows users to see the position of their hands. Interactions in VR can be initiated by using the buttons on the controllers, motion gestures, or a combination of both. With these controllers, participants can point at walls in the virtual environments in this study to move them back and forth.

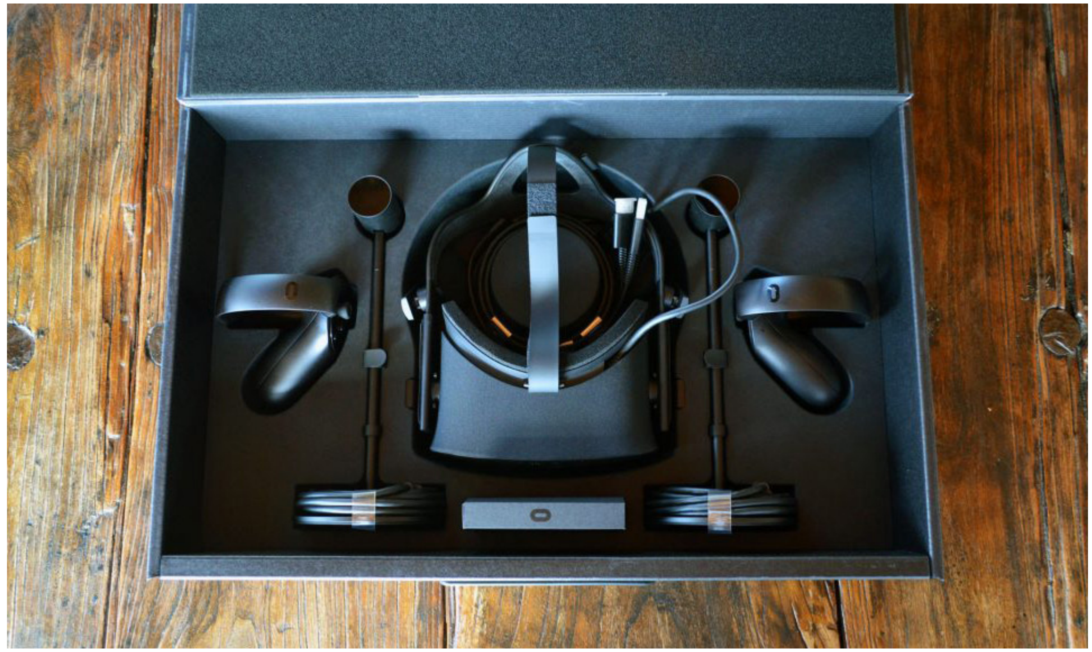

Figure 4.2 *The different components of the Oculus Rift VR system; starting from the center is the Oculus Rift headset, then the infrared sensors that track the user's movements, and on the outside are the Oculus Touch controllers.*

Software

The virtual environments used for this study are primarily created with Unreal Engine 4, which handles the real-time rendering in VR as well as the interactions with the user. Walls, floors, and ceilings are programmed to scale in size when participants move the architectural elements. Constraints in the location of the walls and ceilings are put in so that the data is set within a reasonable range.

For the two-dimensional portion of the exercises, a custom inter-

2 Evan Noronha, "Oculus Rift CV1 Teardown," iFixit, March 30, 2016, https://ifixit-guide-pdfs.s3.amazonaws.com/pdf/ifixit/guide_60612_en.pdf.

face (Fig. 4.3) is created to perform the task of moving the walls around in plan and section so that participants will not have access to the measuring tools that are available with conventional drafting software. This is done in order to simulate an environment where participants are reading the drawings as though it is a presentation, and to eliminate factors that would augment the ability of participants to read drawings. This custom interface is also created with Unreal Engine so that participants can see a perspective view of the rooms in the same graphic style as the VR portion of the exercises.

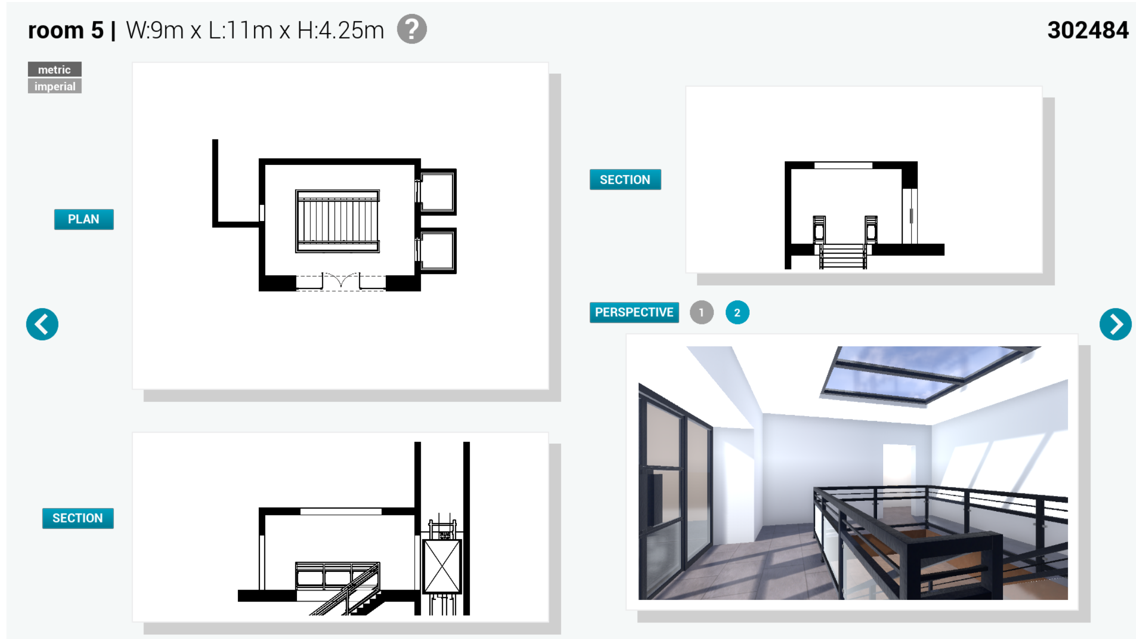

Figure 4.3 *Custom 2D interface created with Unreal Engine. The walls and ceilings can be moved by clicking and dragging with the mouse cursor. When users make changes in one view, all the others update simultaneously to reflect the changes.*

Safety

Because human subjects are involved in this study, ethics clearance had to be obtained from the Office of Research Ethics (ORE) here at the University of Waterloo. The ORE reviews the study to make sure that the process is safe and ethical, and that participants will remain anonymous. While there are a few safety concerns when using VR, the risks involved in this study are minimal and can be easily mitigated.

A common concern when using VR is the chance of becoming nauseous after an extended period of time. The user is a big factor in the likelihood of this: people prone to nausea may be more at risk of simulation sickness, and resistance may build up with experience in VR.[3] The factors that can be controlled are the quality of the equipment, pace of the VR experience, and the amount of sensory conflict involved.

The Oculus Rift reduces the chance of nausea with its high refresh rate screen (90 Hz), which is significantly higher than mobile phone-

3 Almar Suarez, "How and Why Our Experiments with Virtual Reality Motion Made Us Ill," Venture Beat, February 27, 2018, https://venturebeat.com/2018/02/27/how-and-why-our-experiments-with-virtual-reality-motion-made-us-ill.

based VR headsets.[4] The slow pace of the experiments also helps to decrease the chance of nausea. Participants can go through the exercises at a leisurely walking pace, and are warned that quick and sudden movements are not necessary and may induce nausea. There is no artificial locomotion mechanic included in the software (except for rooms 7 and 8 which introduce teleportation), meaning that participants move through the virtual rooms by walking in physical space, minimizing the risk of sensory conflict.

Another common concern is that VR users cannot see their immediate surroundings. To prevent any tripping hazards or collisions, participants are carefully monitored so that they stay within the area demarcated for the experiment, which is cleared of obstacles before each session. The Oculus Rift's built-in safety features will be turned on, which warns users when they are near the demarcated area by overlaying a wall of the boundaries on the display (Fig. 4.4).

As a final precaution, participants are given a safety briefing before putting on the headset, where they are warned to be mindful of the Oculus Rift's cable, to be careful about making quick and sudden movements, to not lean on anything they see in VR, and to remain attentive to any warnings they hear from the administrator of the experiment.

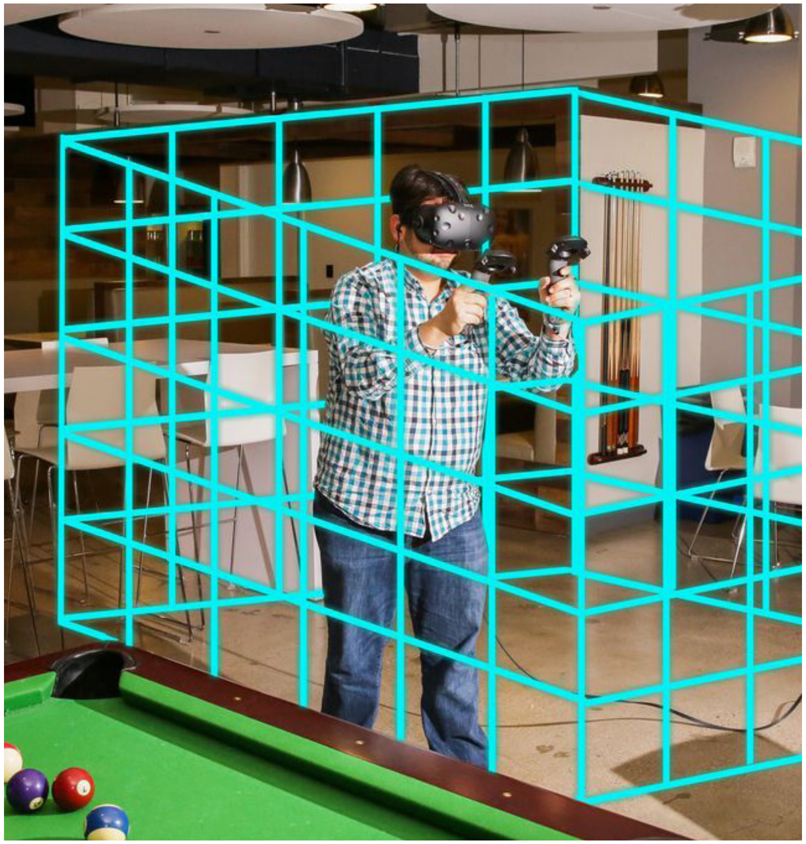

Figure 4.4 *Artist's representation of a VR boundary system that alerts users when they approach the edge of the area that they define. The blue grid is only visible when the user is near.*

4 Essa Kidwell, "How to Avoid Motion Sickness Caused by VR Headsets While Gaming," Windows Central, April 27, 2018, https://www.windowscentral.com/how-avoid-motion-sickness-caused-by-vr-headsets-while-gaming.

Participants

A convenience sample was obtained from the population at the University of Waterloo's School of Architecture. Posters were pinned up around the school building and there were posts put up on the school's social media page. The sample of 30 people consists of 24 graduate students, 2 undergraduate students, 2 professors, and 2 non-professionals.

In future iterations of this thesis, a broader sample group with a balance of different experience levels could be of interest to researchers exploring the correlation between experience in architectural design and spatial processing in VR. Because the sample group here is predominantly made up of graduate students, no conclusions are drawn regarding demographics in this study. However, there is a study conducted at the Georgia Institute of Technology that suggests that practicing professionals perform better at completing spatial tasks than architecture students and people of other professions.[5] Also, while professional architects and architecture students benefitted from using VR in completing the tasks, people of other professions did not.

Procedure

Participants are given a survey (Appendix A, page 105) that collects demographic information such as age, gender, and experience with architecture in a professional setting. Once the exercises have been completed in VR, participants will then be given a post-study survey (Appendix A, page 106). The surveys are designed to gain an understanding of how participants felt about the exercises, and to divide the participants into groups based on how they would usually approach a design problem.

Participants first go through the exercises with orthographic drawings on a computer monitor. Using the mouse cursor, participants click and drag the walls and ceilings to manipulate the drawings. As seen in Fig. 4.3, each room is represented in three orthogonal views and a perspective rendering. The drawings are programmed to update instantaneously to match the alterations that the participants make. With the perspective view, participants can switch between two camera angles that are placed on opposing corners of the room.

Once the exercises have been completed with the drawings, participants repeat them with the Oculus Rift. Using the Oculus Touch controllers, participants can point to a wall or a ceiling with one hand and move the element they have selected with their other hand by pushing the thumb-stick on the controller up or down (Fig. 4.6). Up moves the element away from them, and down moves the element towards them.

Data is collected in the form of Cartesian co-ordinates that indicate how far the participant has moved the wall. This information is only linked to a 6-digit identification number that is only used to link the data from the 2D portion of the exercise to the data from the VR portion, as well as to the demographic information.

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5 Daniel Paes, Eduardo Arantes, and Javier Irizarry, "Immersive Environment for Improving the Understanding of Architectural 3d Models," *Automation in Construction* 84 (December 2017): 292–303, https://doi.org/10.1016/j.autcon.2017.09.016.

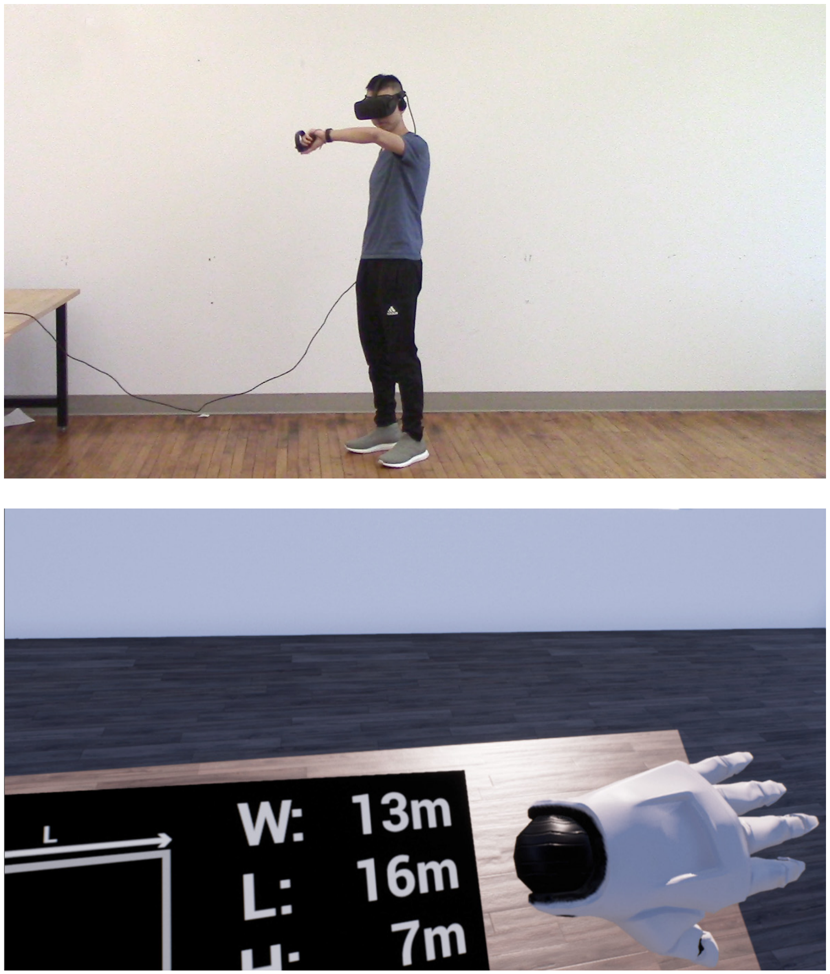


Figure 4.5 *Top: User looking at arm to check target dimensions in VR. Bottom: Target dimension indicators and virtual representation of the user's hand, as seen by participants.*

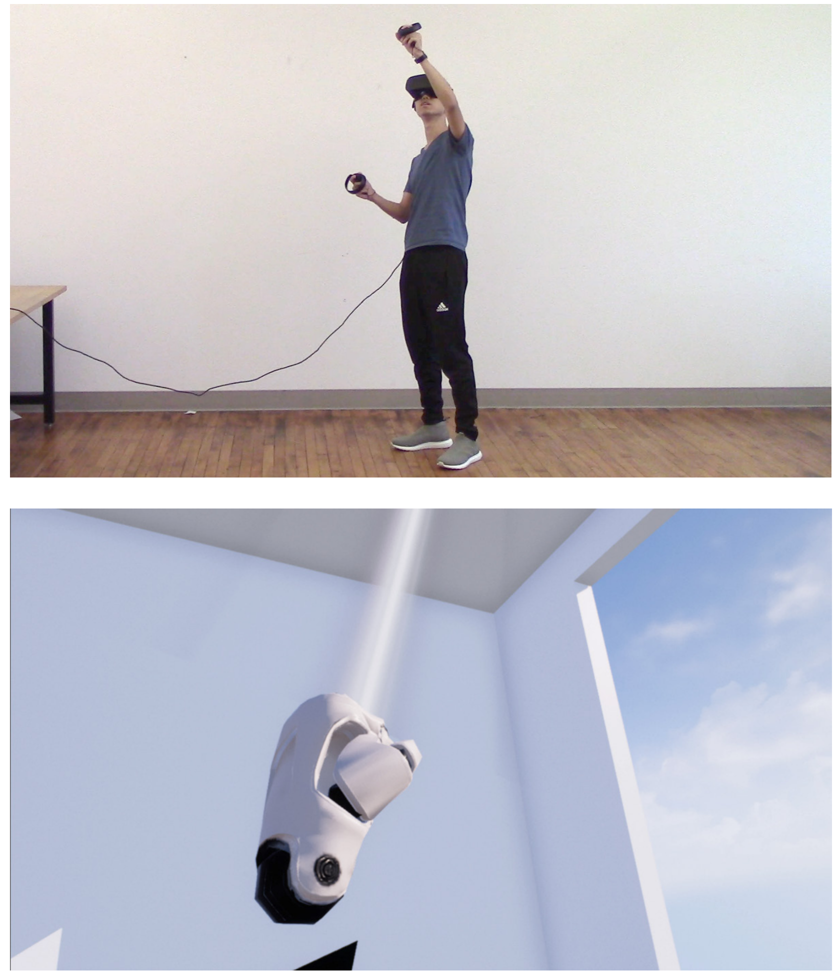


Figure 4.6 *Top: User pointing towards ceiling to adjust it. Bottom: Beam of light indicates to user where they are pointing at.*

CHAPTER 5

Experiment Design

Prior to 2016 when the VR headsets from Oculus and HTC were released to the public, the cost of VR was exponentially higher and warded off any interest from all but the most technologically-inclined architects. Another development that the aforementioned VR headsets brought with them was a lowering of the bar in the technical expertise required to create VR experiences. Since it is in the best interest for the growth of the VR industry if there is more VR content being made, Oculus and HTC have worked with software developers to ensure that small studios and even independent developers can create VR content.[1] With these developments VR has become much more accessible, maybe even viable to architects who are typically on tight monetary and time constraints.

Studies that focus on VR in architecture are disproportionally scarce compared to studies that focus on medical and psychological applications, or research into other digital aspects of architecture. In a survey of over 200 studies into VR and architecture, researchers found that the most common topic of discussion is how to implement VR into different architectural workflows. Studies where architectural representation is the focus of attention only make up 5% of the studies that were found. Consequently, the work presented so far has relied heavily on research conducted in other fields to support the thesis that VR is a substantially different medium than drawings and perspectives.

That is why the goal of this study is rather broad: to find out how representation of architecture in VR is different from two-dimensional

1 Keith Stuart, "Oculus Rift: Valve Promises to Take Virtual Reality to the Masses," The Guardian, January 23, 2014, https://www.theguardian.com/technology/games-blog/2014/jan/23/oculus-rift-valve-virtual-reality-kickstarter.

forms of representation. Of course, architectural representation is an extremely multi-faceted topic. This is compounded by the fact that VR in itself is also a somewhat nebulous realm. The experiment in this thesis is designed as a pilot study to find footholds – in the form of concrete and tangible figures – that can launch more grounded and focused explorations into how VR adds to the discourse of architectural representation.

Variables

Throughout the study, the dependent variables that are being observed are the dimensions of the rooms, and the positioning of individual walls (in R3-R6). The main independent variable is the medium (drawings or VR) that participants complete the exercises in. From one room to the next, parameters are modified to test how they affect the perception of space in each medium (Fig. 5.1).

As explained in the previous chapter, the procedure for the experiment is that participants are asked to manipulate the walls and ceilings of the rooms to match a set of dimensions given to them, using their best judgment of the visual cues available to them. One hypothesis about the experiment as a whole is that the room sizes will be more accurate and consistent in VR because participants can use their body's dimensions as an additional reference. As the target dimensions of the rooms get smaller, accuracy and consistency should improve. However, this might not be evident when participants complete the exercises with drawings because architects are used to reading and working with scale drawings.

Theme 1: shape

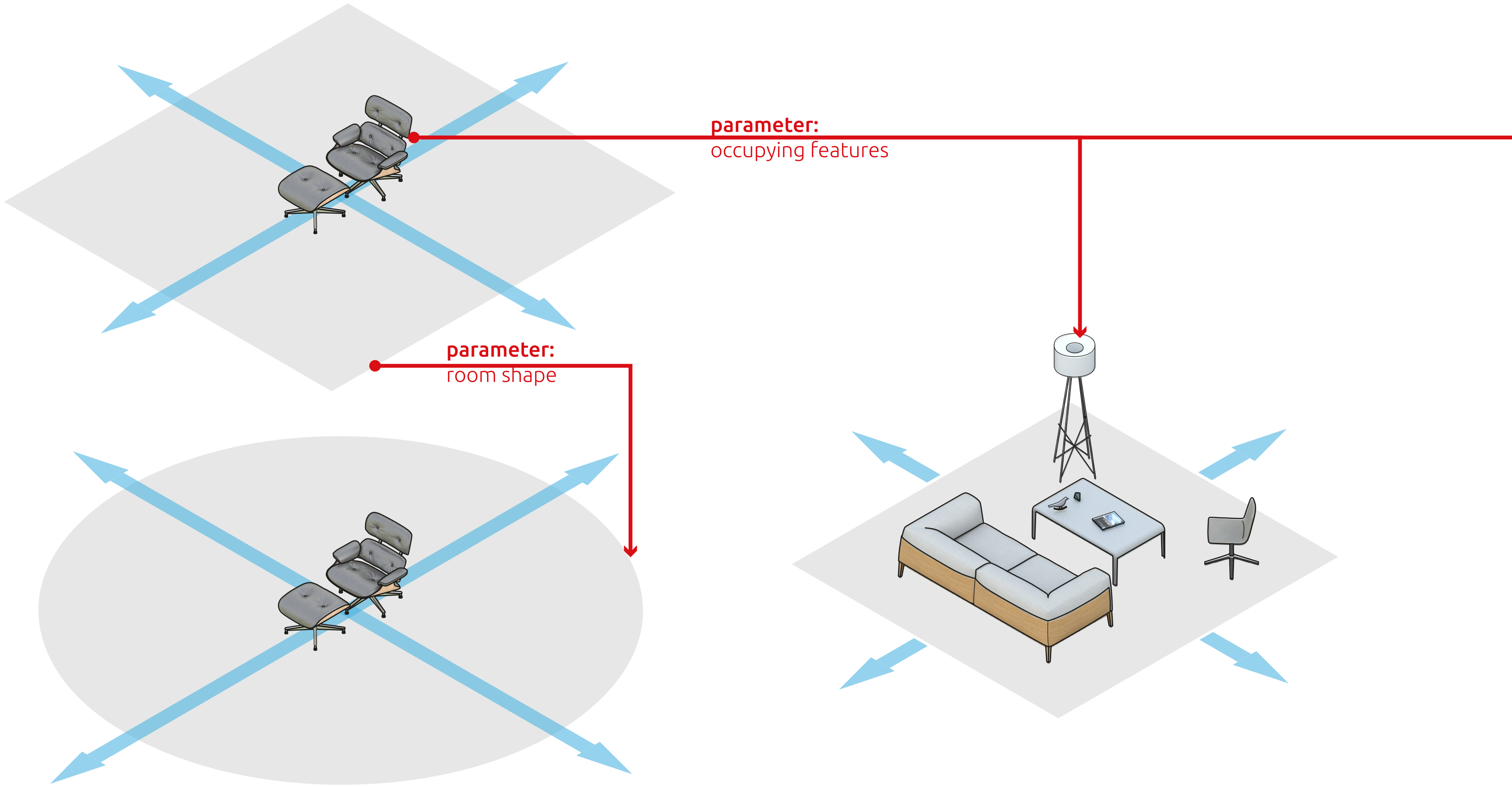
The first two rooms are as minimal in detail as possible, using plain white walls and dark flooring to focus on the shape of the rooms. In both rooms there is an opening to let light into the space and a single armchair and ottoman that is used for reference to scale. The target dimensions in this set of rooms is 13m x 16m x 7m, making the room rather large and challenging for participants.

The difference between the two rooms is that the first room (R1) is rectangular in shape, and the second (R2) is curvilinear. The R2 is based on Ryue Nishizawa's design for the Teshima Art Museum, with the slight modification of removing one of the openings to make it more similar to R1.

Visually, curvilinear spaces tend to be preferred by architects for their aesthetic flourish, at the expense of efficiency and ease of programmatic layout that rectangular spaces provide (page 14).[2] In terms of this exercise, curvilinear spaces provide fewer points of reference for gauging distances. Rectangular rooms have edges and corners, clear visual markers that help people understand its geometry. This may be a part of the reason why in the study mentioned in Chapter 1, non-architects had a tendency to find the square room more pleasant than the less familiar round, angled, and curvy rooms.

One hypothesis is that the rectangular room will be more accurate and consistent than the curvilinear room, which is more difficult to understand. Another hypothesis is that VR will improve dimensional accuracy, where the extra reference points that the body provides will

2 Avishag Shemesh, Moshe Bar, and Yasha Grobman, "Affective Response to Architecture," *Architectural Science Review* 60, no. 2 (December 21, 2016): 116–25.



Shape

R1: rectangular room

R2: curved room

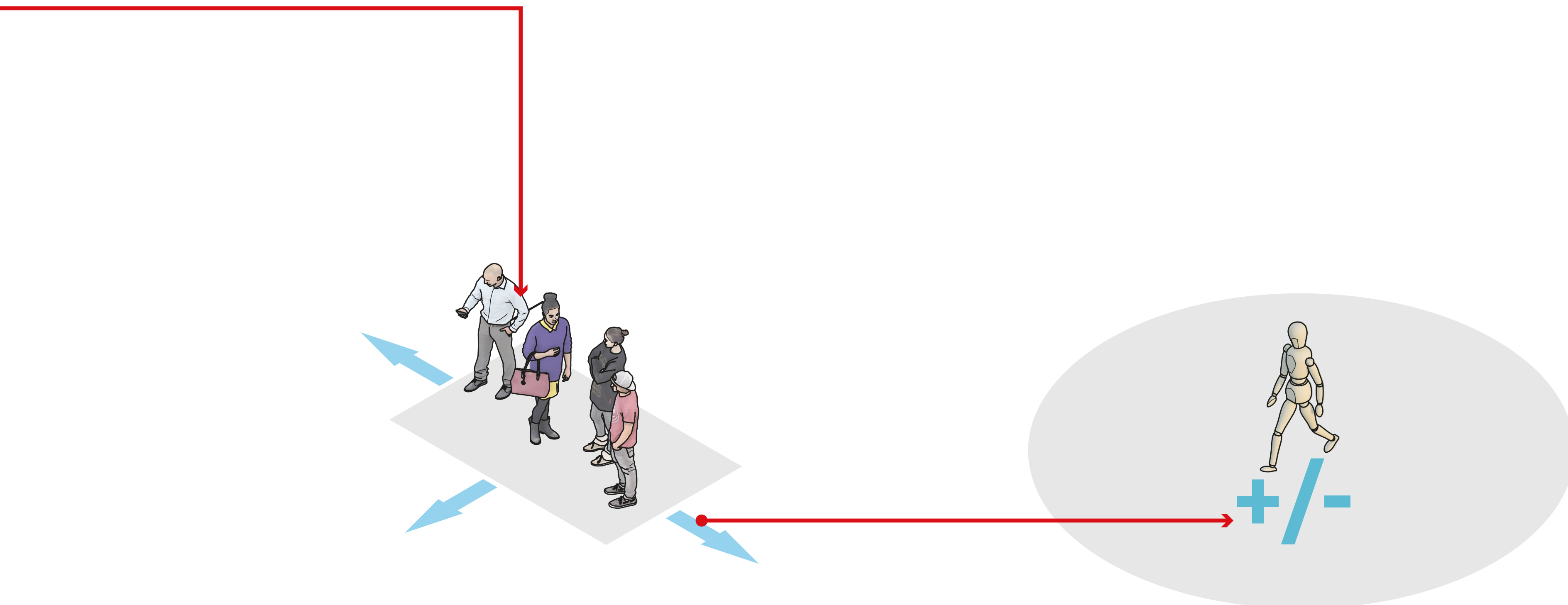
Complexity

R3: dark room

R4: bright room

R5: lobby

Figure 5.1 *Overview of the different themes explored in the experiment.*



Populated

R6: bus shelter

Populating

R7: porous/bright pavilion

R8: solid/dark pavilion

be significantly helpful in a space where there are especially few visual cues.

Curvilinear architecture can be great spectacles when designed well, but it is exponentially more difficult to plan and represent with drawings, posing many challenges in coordination between architects, clients, engineers, and builders. This set of experiments hopes to find out if VR can help to eliminate some of the confusion that comes with difficult geometry.

Theme 2: complexity

This set of rooms (R3, R4, R5) is a variation of the rectangular room (R1), with the main difference being that instead of only a single armchair and ottoman, there is an arrangement of furniture in the center of the room. The walls and ceilings are also no longer plain and simple; different surface conditions test how finishes may affect the perception of space. The target dimensions in this set of rooms is 9m x 11m x 4.25m, which is slightly larger than a comfortable size for the layout of the room. The difference from the target dimensions in the rooms that participants make will help gauge how the different contextual details in each room affect the reading of space in each medium.

The dark room (R3) and the bright room (R4) are designed to be diametric opposites. The layout for both rooms is designed to be identical, but the furniture, fixtures, and finishes are selected to create atmospheres that are antithetical to each other.

R3 is designed to feel dark and restrictive. The walls and ceiling are cracked and dirty, and the feature wall behind the sofa is made

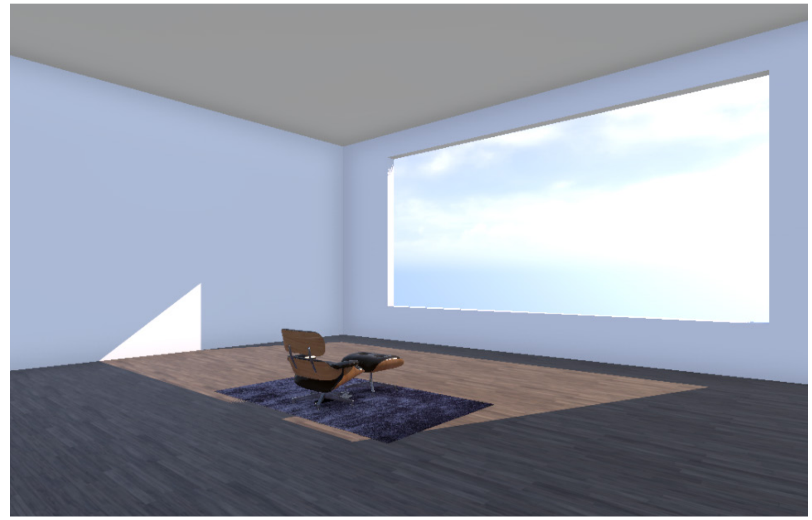


Figure 5.2 *R1: Rectangular room*

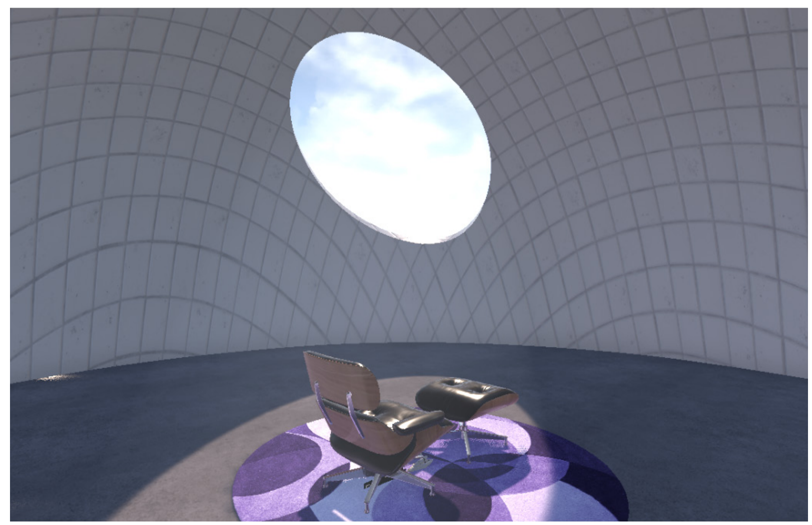


Figure 5.3 *R2: Curvilinear room*

of rough, coarse stone (Fig. 5.4). Furniture pieces that appear visually heavy or busy are chosen. Near the center of the room is an open fireplace, which carries with it a buffer zone that people would normally avoid for fear of the fire. Moving parts like the swinging lounge chair, the entry door, shelf doors require small areas of space to accommodate a full range of motion. A planter is placed by the window, which would (in the real world) dissuade people from leaning on the windowsill to look out the window. The view outside is of a dense forest, creating an atmosphere of obfuscation. The trees filter the sunlight, making the room darker. Between the cabinets is a television with a looping video playing on it. People are conditioned to keep some distance between themselves and televisions for viewing comfort and to reduce eyestrain; the purpose of this element in the experiment is to see if participants will compensate for the viewing distance when determining the placement of the wall.

R4 swaps out all of the features above for ones that feel bright and inviting. The walls are clean and flat, and the feature wall is a crisp coat of blue paint. Furniture pieces are lightweight and minimalistic, and the fireplace is swapped out for a simple floor lamp. The swinging doors are removed in favor of an open entryway and open shelving. In place of the planter, there are seat cushions on the windowsill, encouraging people to get closer to the window. Unlike the restrictive view of a forest in R3, outside R4 is an unobstructed view of the ocean stretching beyond the horizon, sunlight flooding into the room. The television is removed and in its place is a painting, which can be viewed comfortably from any distance.

R3 is designed to have affordances that require more space to com-

Figure 5.4 *R3: Dark room*

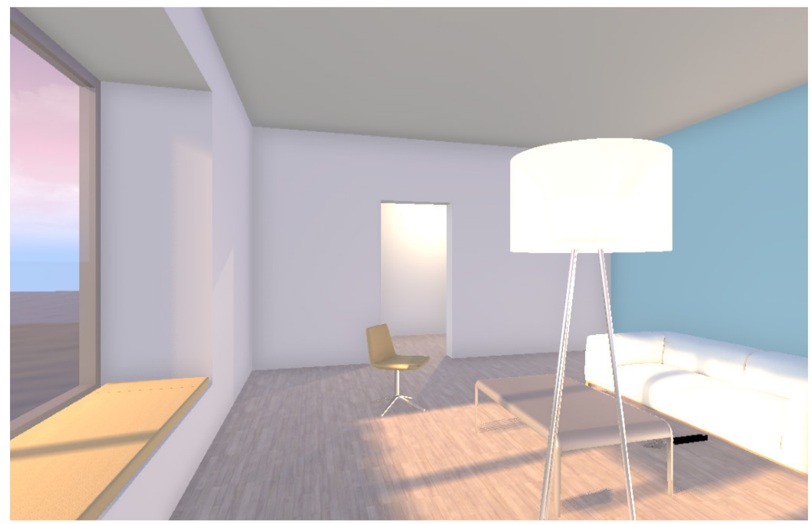
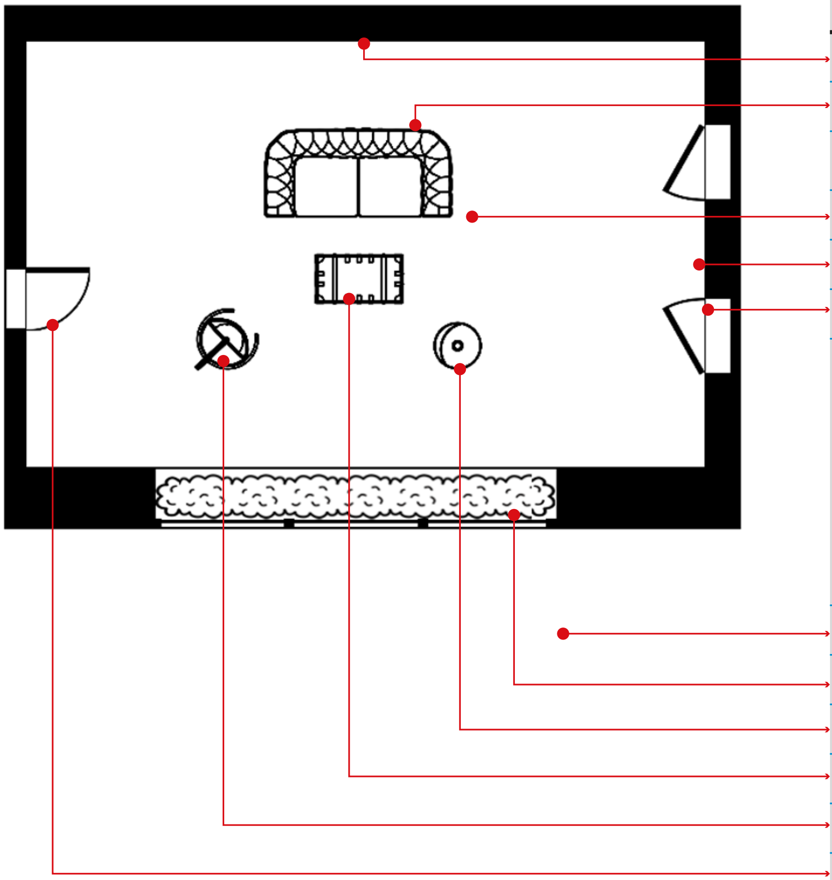


Figure 5.5 *R4: Bright room*



R3 DARK ROOM	ELEMENTS	R4 BRIGHT
stone	**feature wall**	light blue paint
rustic, tufted	**sofa**	modern, minimal
rug	**floor treatment**	plain wood flooring
television	**wall ornament**	painting
closed cabinets	**shelves**	open shelving
forest	**view**	lake
planter	**windowsill**	seat cushions
open fireplace	**lighting element**	lamp
rustic chest	**coffee table**	plastic
swinging chair	**armchair**	simple chair
door	**entry**	open entryway

Figure 5.6 *Comparison of elements in R3 and R4.*

plete the hypothetical action, whereas many of the affordances in R4 do not and in fact encourage users to reach in. Of course, participants cannot touch and feel these features. However, the hypothesis here is that the visual representation of them in VR will evoke memories of how they feel to touch and interact with; R3 should tend to be dimensioned larger than R4 to compensate for its compressive feeling. It is also hypothesized that this effect will not be seen in the two-dimensional version of the exercises.

Unlike the previous set where the furniture is fixed to the middle of the room, each wall in this set can move individually. The reason for this is to explore how participants will consider the relationship between the walls and the interior of the room.

R5 is designed to test the different circulation configurations present in this set of rooms. Instead of the seating arrangement in the center, there is a large staircase leading to a lower level. In place of the shelves in R3 and R4 are a set of elevators, and in place of the window is a set of glass doors. These changes alter the circulation conditions at these points from locations where people would stop and interact into thresholds where people would pass through in and out of the space (Fig. 5.7).

While participants will not be able to physically walk through the entire area, this is acceptable for the purposes of the study because a visual understanding of circulation spaces should still have an effect how participants position the walls (Fig. 5.8). For example, people are generally wary of standing directly in front of elevator doors and tend to wait at a slight distance. In this room, this waiting area coincides with the top of the stairs, which also needs some space so that people do not walk right into the wall once they reach the top. Also, for the people waiting for an elevator, if the stairs are too close it creates an anxiety-inducing space where they feel uneasy standing with their backs to a descending staircase. Part of the experiment is looking at how participants may or may not pick up on this, and whether it is more likely to be considered when participants are using drawings or VR.

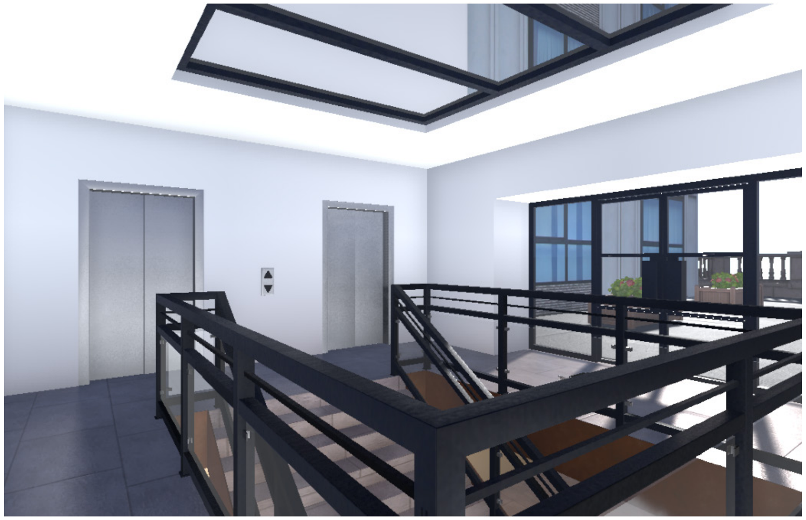


Figure 5.7 *R5: Lobby*

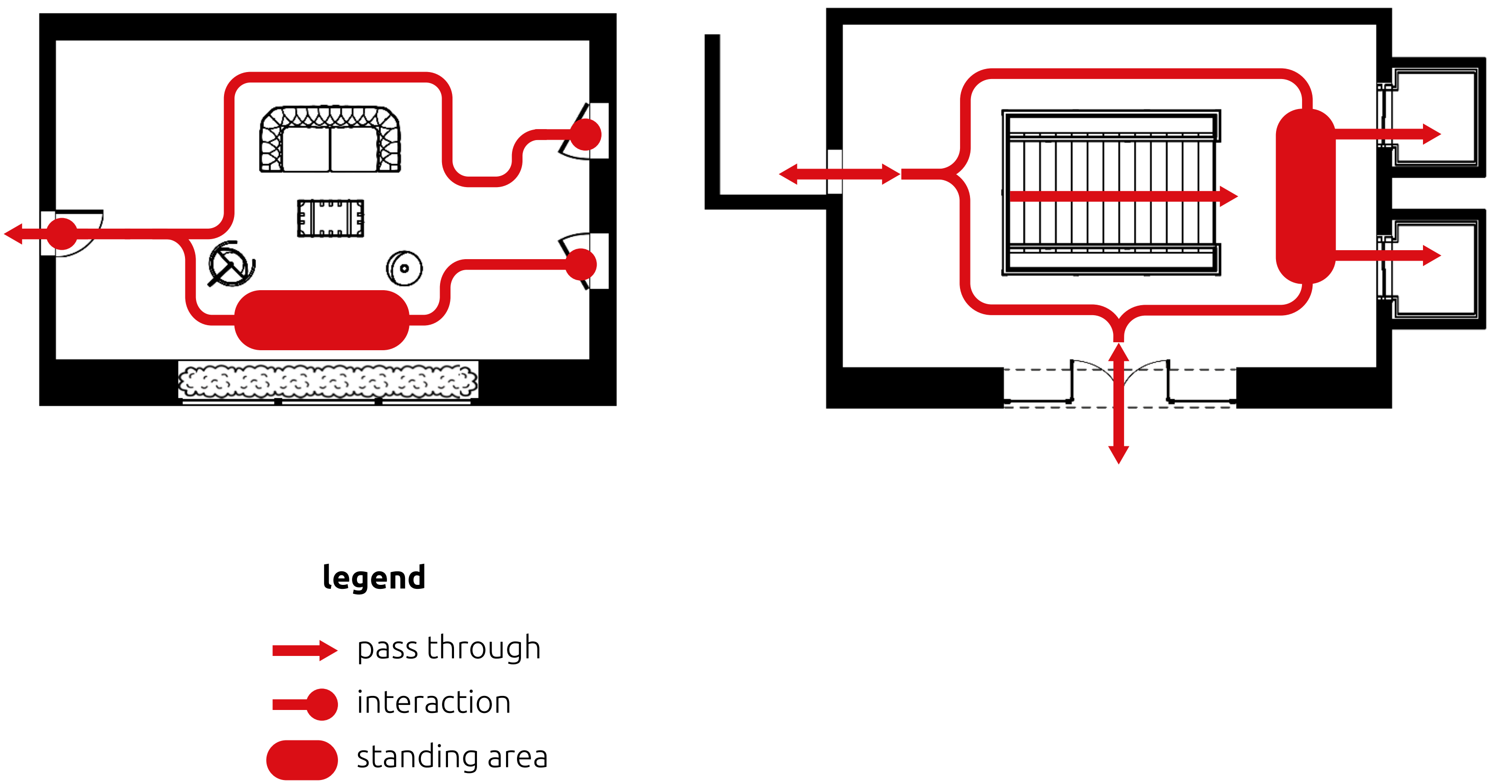


Figure 5.8 *Implied circulation paths comparison between R3/R4 (left) and R5 (right).*

Theme 3: population

R6 is a continuation of the methodology in previous rooms, where participants move the walls of a structure around a group of still figures (Fig. 5.9). Here the target dimension is set to be 3.05m x 10m x 2.75m.

In R7 and R8, the methodology is flipped around; instead of adjusting the amount of space around a fixed group of people, participants add or remove people in a fixed space until they feel it is at capacity. Participants are given the target density of 0.4 m^2 per person, the capacity for a standing assembly space according to the Ontario Building Code.

There are two rooms here to test how the atmosphere of the space affects the perception of density. R7 is based on the Serpentine Pavilion designed by BIG, slightly modified to have be shorter and more square in plan. This particular pavilion can be easily transformed into a Richard Serra-esque sculpture by taking the shape of the structure and changing it to a solid Cor-Ten steel surface (Fig. 5.10). The curvilinear shape of the pavilions makes it difficult for participants to simply estimate the area of the space and calculate the target density, forcing them to rely on their sense of the surroundings.

The hypothesis here is that the darker, solid pavilion (R8) will feel more constricting than the porous R7. As a result, participants will tend to insert fewer people into it. Similar to the previous set of rooms, it is also hypothesized that this effect will not be evident in the two-dimensional version of the exercises.

An unexpected obstacle in the building of these density exercises was in the form of the mannequins that would populate the pavilions.

Figure 5.9 *R5: Bus shelter*

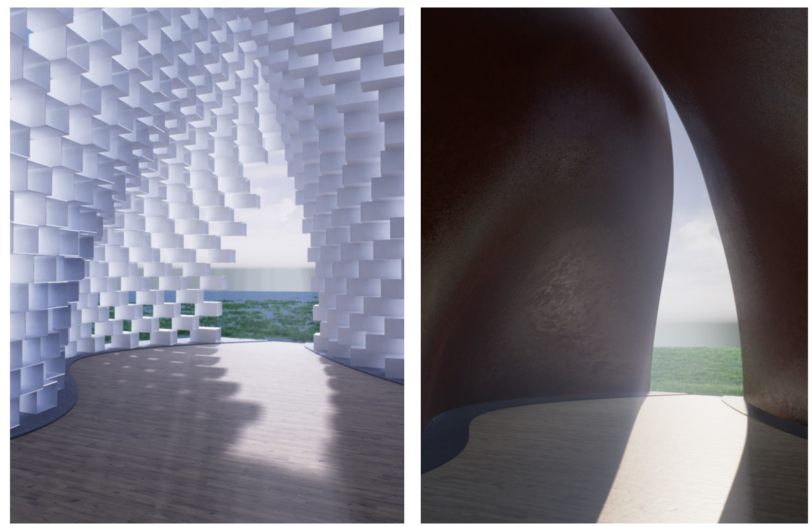


Figure 5.10 *R7: Porous pavilion (left), R8 Solid pavilion (right)*

The default model provided with the software, Unreal Engine, is designed for general use by video game designers, who gave the mannequin an aggressive design and stance (Fig. 5.11). This complication is compounded when the mannequins occupy the space in numbers, forming a menacing horde that makes the pavilions extremely uncomfortable. This is not a type of crowd that architects would generally design for, so a more neutral-looking artist's mannequin (Fig. 5.12) was selected in place of the default model. The mannequins are programmed to walk around the pavilion and periodically stop in clusters, where they mime conversations. Movement and talking motions were downloaded from Adobe Mixamo, a free service that provides a variety of character animations.

Figure 5.11 *Default mannequin model included with Unreal Engine 4.*

Figure 5.12 *Artist's mannequin.*

PART THREE

DISCUSSION

CHAPTER 6

Experiment Results

This chapter presents some basic data obtained from the experiments. The goal is not to draw definitive conclusions, which is not sensible with this sample size, but to gain a clearer view of the big picture of how VR helps architects evaluate space and direct future researchers towards areas of interest that could be explored further.

Two main metrics are explored in the dataset. One is the distribution of dimensions in each room, which gives us a general picture of how the parameters – such as shape, materiality, and scale – that change between each room may have affected the "feeling of bigness"[1] that the space gives the participant. The other metric is the amount of participants who were more accurate in one medium versus the other, which tells us whether or not VR might be more helpful in understanding the *mechanical measurements*, the "bigness which [each room] actually has."[2] In the experiment design, rooms have been grouped based on the parameter that is being examined. In addition to this, drawings of each participant's rooms have been overlaid on top of each other, so that the proportions of each can be compared with each other and with the proportions of the target dimensions.

The following analysis will compare the rooms within each group based on the described metrics. All data from the study can be found in Appendix A (page 105).

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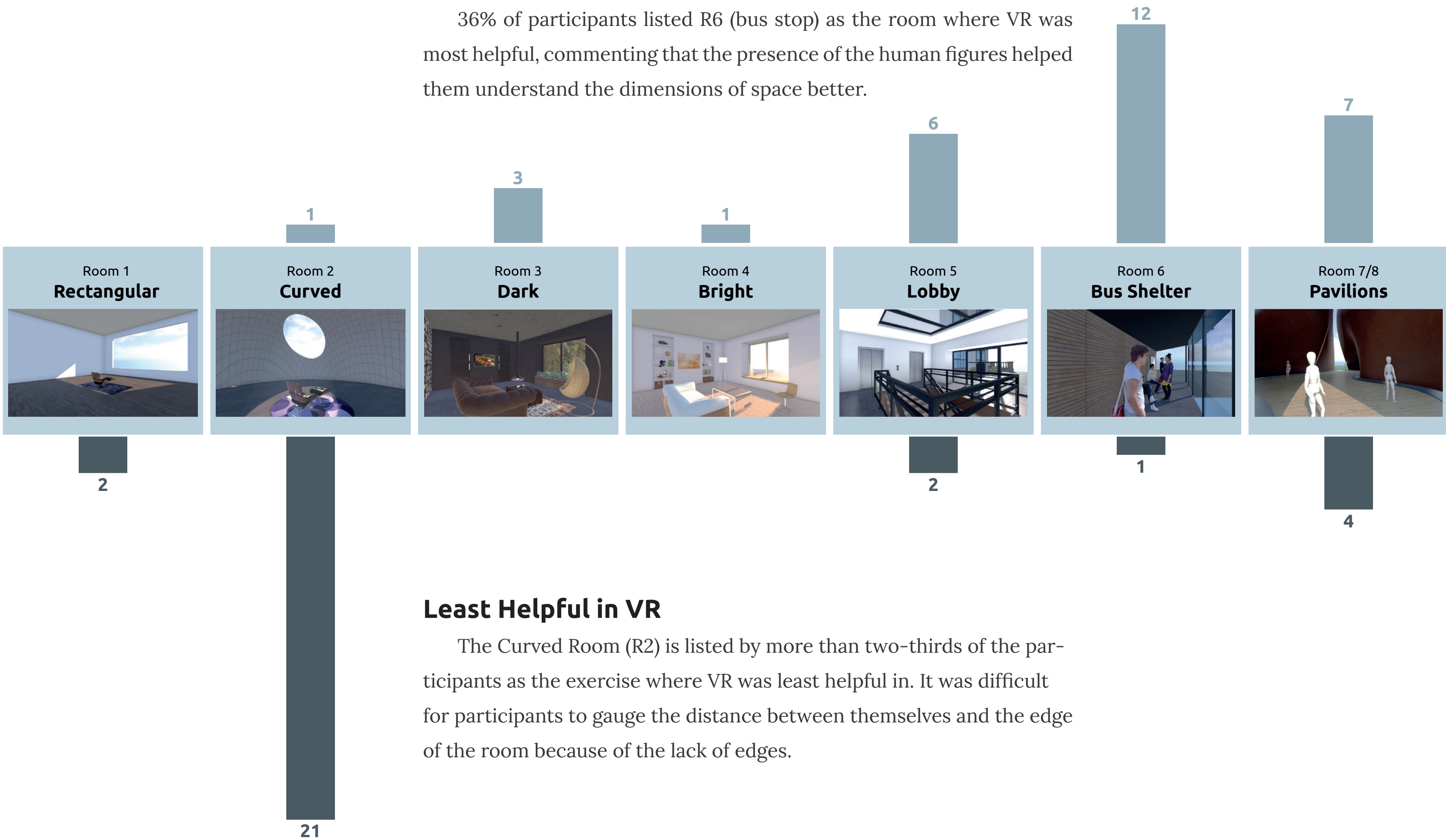
1 Geoffrey Scott, The *Architecture of Humanism: A Study in the History of Taste* (New York: W.W. Norton, 1974), 95.
2 Ibid.

Figure 6.1 *Participants were asked in the post-study survey to identify the exercise where they felt VR was most helpful and the exercise where they felt VR was least helpful.*



Most Helpful in VR

36% of participants listed R6 (bus stop) as the room where VR was most helpful, commenting that the presence of the human figures helped them understand the dimensions of space better.

Least Helpful in VR

The Curved Room (R2) is listed by more than two-thirds of the participants as the exercise where VR was least helpful in. It was difficult for participants to gauge the distance between themselves and the edge of the room because of the lack of edges.

Shape

The purpose of these first two rooms is to examine how different shapes might influence perceptions of the amount of space in the room. To look at the shape of the space in particular, the details of the room are kept to a minimum, with only an armchair and ottoman in the center of the room for reference. Because of this, many participants found these first two exercises to be somewhat challenging.

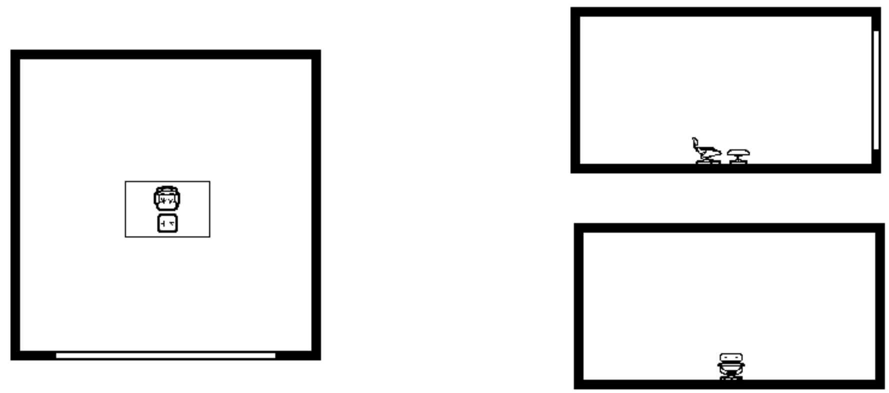


Figure 6.2 *Plan and section drawings for R1.*

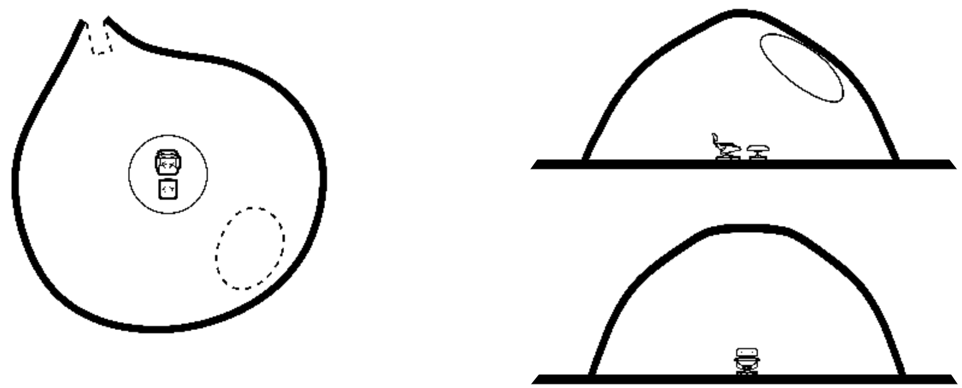


Figure 6.3 *Plan and section drawings for R2.*

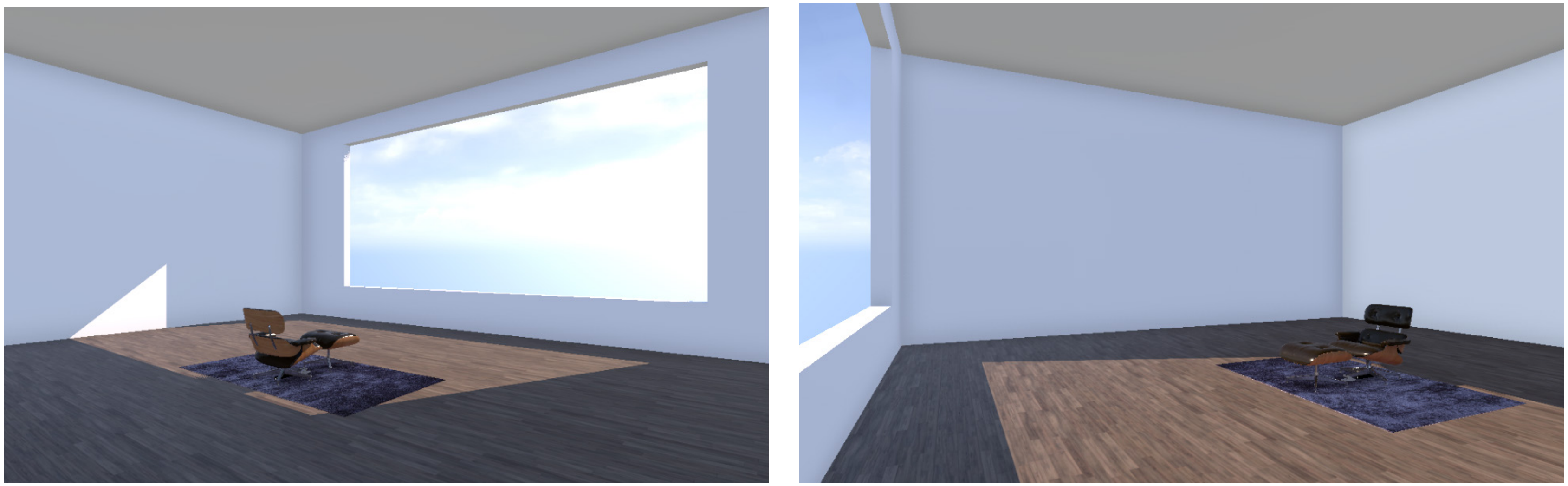


Figure 6.4 *Perspective views for R1*

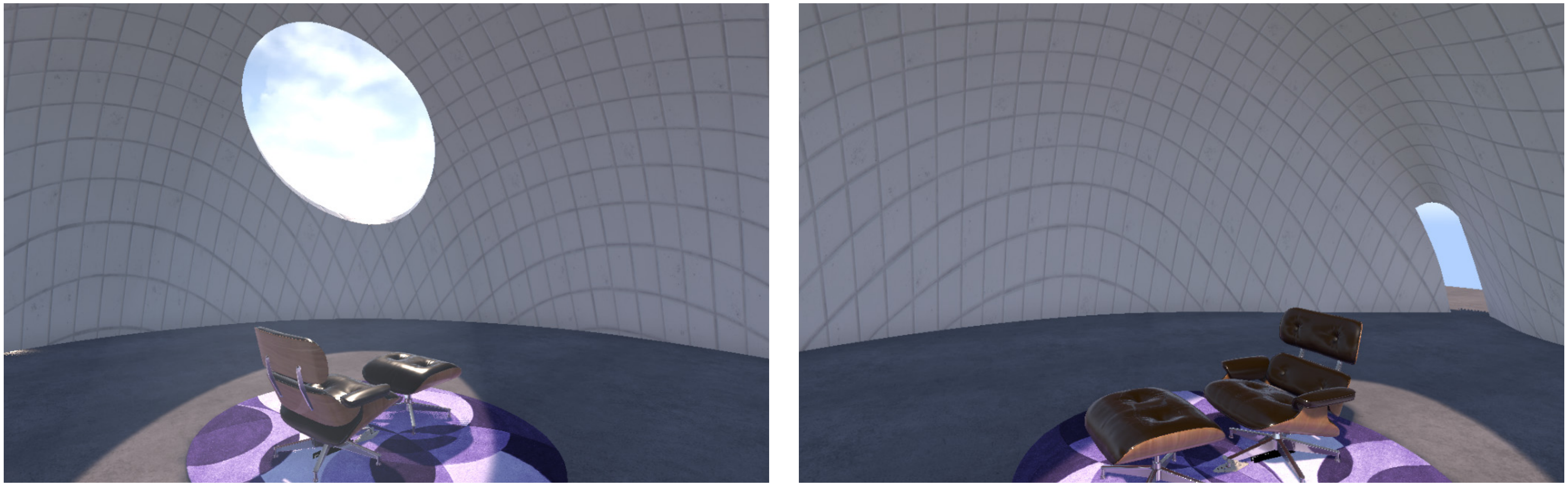


Figure 6.5 *Perspective views for R2*

Room 1 | Rectangular

From the data in R1, we can find several observations that will be a common theme throughout the exercises.

The first is that the resulting dimensions when the exercises are completed with drawings tend to be more spread out than when the exercises are completed with VR. They also tend to be closer in proportion to the target dimensions.

The second is that the VR results tend to be smaller than the target. In Figure 6.3, it can be seen that only a handful of results are larger than the target. The charts on the opposite page show that the average dimensions from the results in VR are much smaller and less accurate than the results from drawings.

However, a redeeming quality for VR is that there is a smaller spread of results and a slightly higher peak in frequency. While the average dimensions from the results with drawings are much closer to the target, there is a higher variability of results. This suggests that VR might be slightly better in drawing a concensus about the "feeling of bigness" of a space.

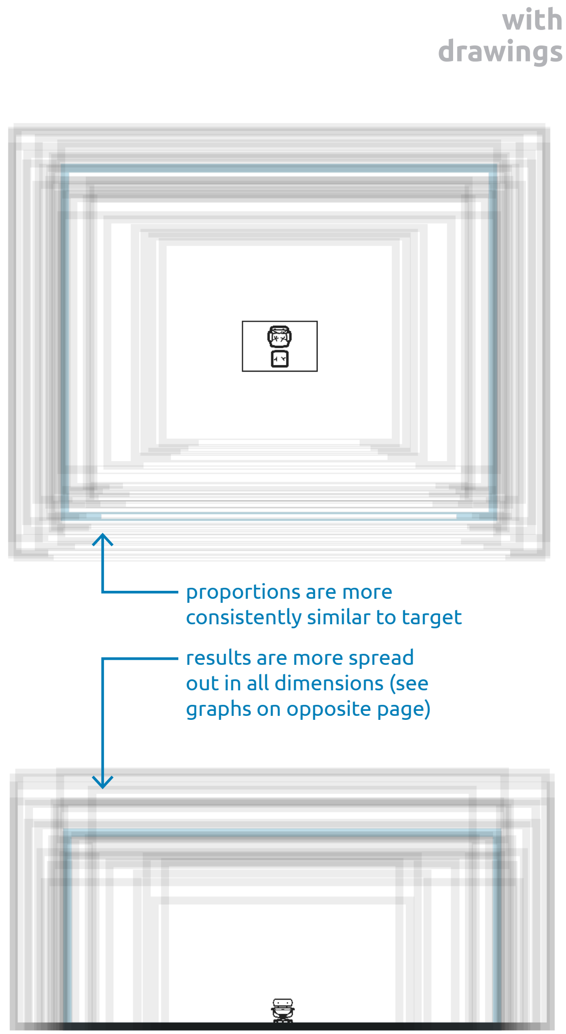


Figure 6.6 *Aggregated plans (above) and sections (below) from R1; completed with drawings (target dimensions in blue).*

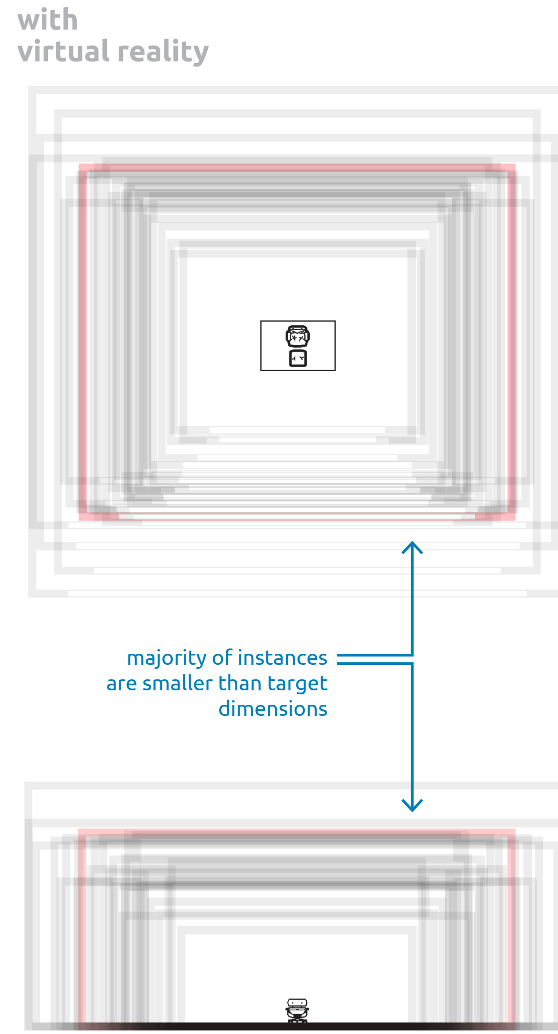


Figure 6.7 *Aggregated plans (above) and sections (below); completed with VR (target dimensions in red).*

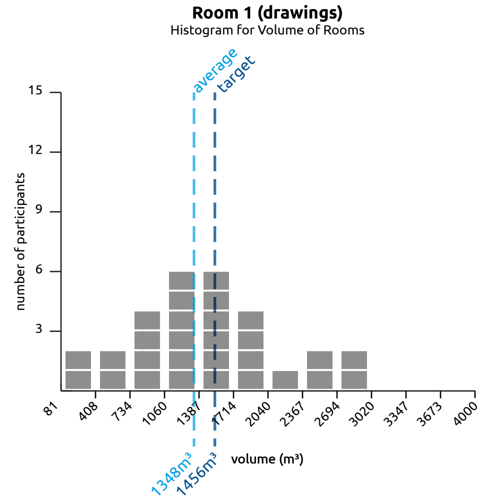


Figure 6.8 *Histogram for R1 with drawings*

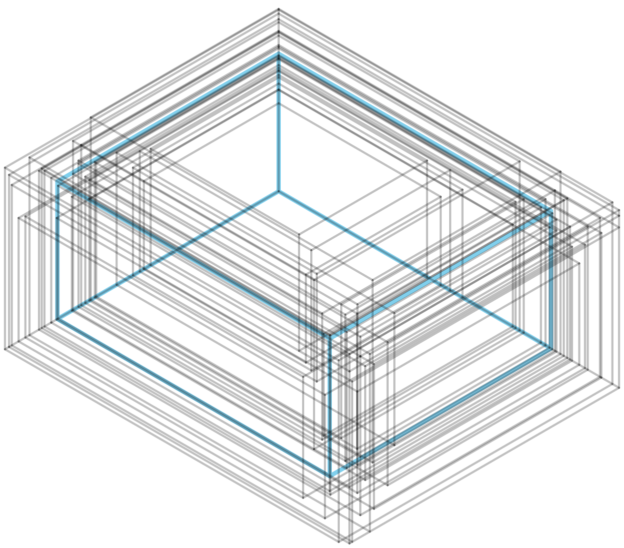


Figure 6.9 *Overlaid axonometric drawings of R1; completed with drawings (target dimensions in blue).*

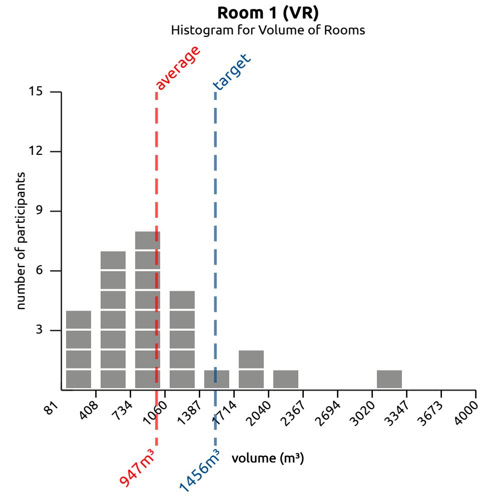


Figure 6.10 *Histogram for R1 with VR*

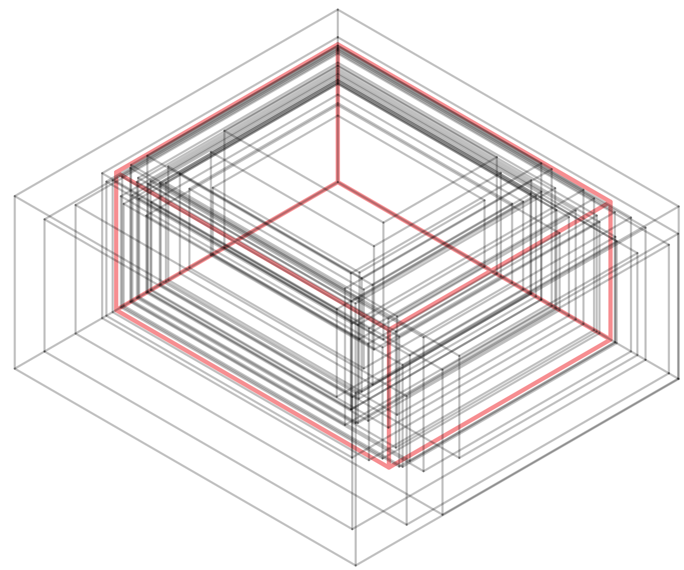


Figure 6.11 *Overlaid axonometric drawings of R1; completed with VR (target dimensions in red).*

Room 2 | Curved

It was hypothesized that R2, because of its irregular shape, would generate less accurate and less consistent results. When the exercises were completed with drawings, R2 was indeed less consistent (Fig. 6.4 and 6.10). However, surprisingly this is not the case with VR. When dimensioned in VR, R2 has a slightly smaller spread and a higher peak than R1 (Fig. 6.6 and 6.12).

It is notable that in the post-study survey, 71.4% of participants listed R2 as the room where VR is least helpful (Fig. 6.1). However, the results indicate that R2 is where VR has been most helpful in providing accurate and consistent results. It would appear that the participants' perceived helpfulness of VR is not necessarily a reliable metric in determining the actual effectiveness of the tool.

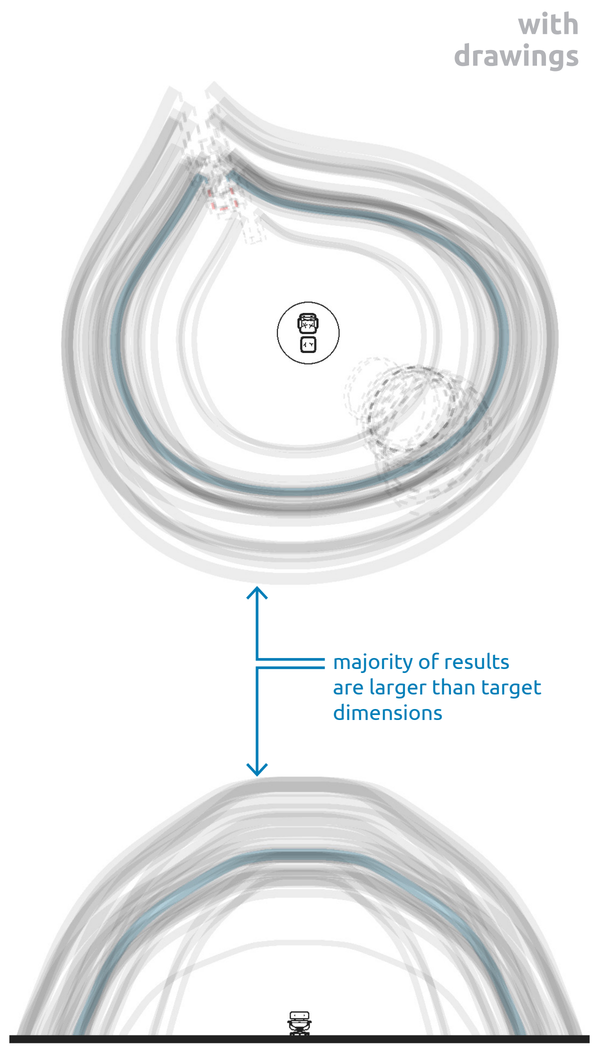


Figure 6.12 *Aggregated plans (above) and sections (below) from R2; completed with drawings (target dimensions in red).*

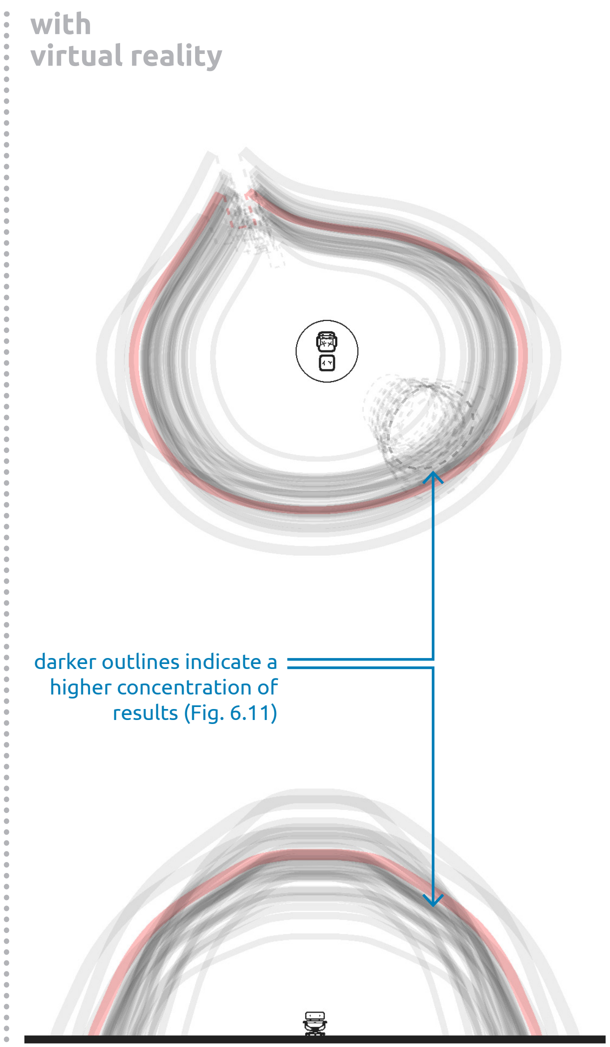


Figure 6.13 *Aggregated plans (above) and sections (below) from R2; completed with VR (target dimensions in red).*

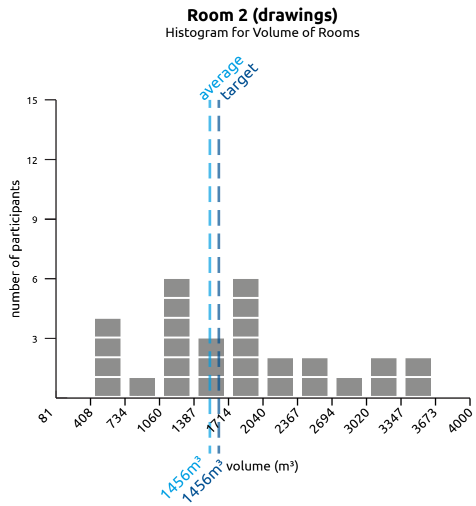


Figure 6.14 *Histogram for R2 with drawings.*

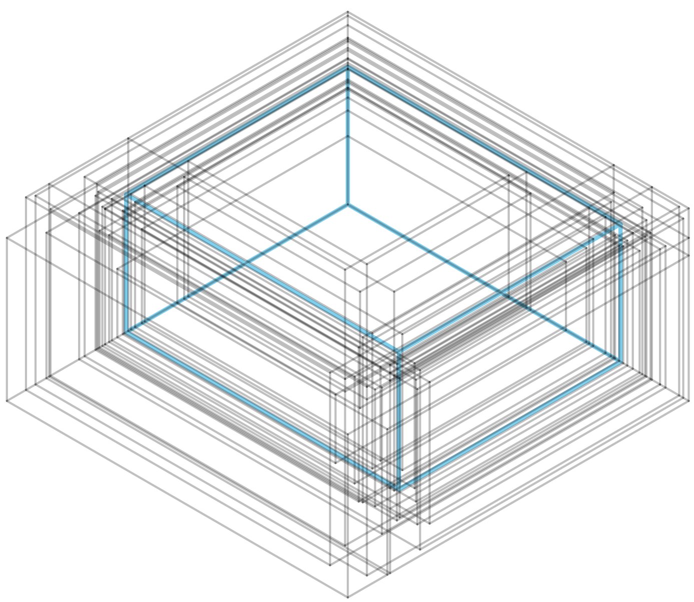


Figure 6.15 *Overlaid axonometric drawings of R2*; completed with drawings (target dimensions in blue).*

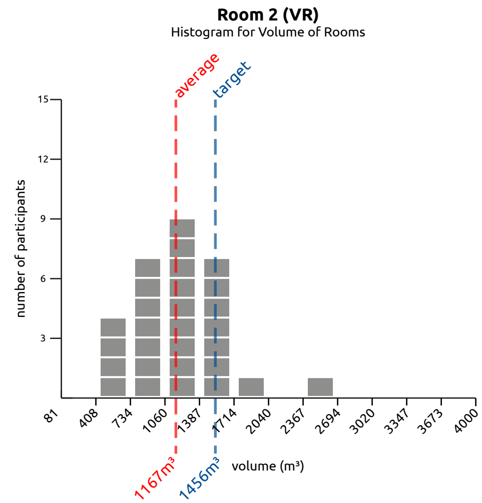


Figure 6.16 *Histogram for R2 with VR.*

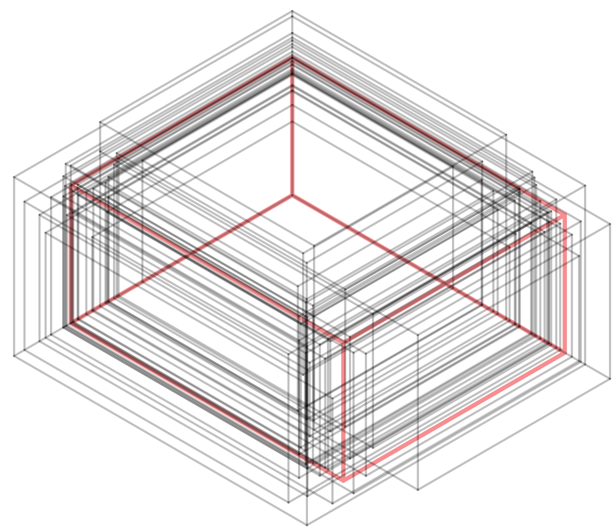


Figure 6.17 *Overlaid axonometric drawings of R2*; completed with VR (target dimensions in red).*

**Axonometric drawings for R2 indicate the interior bounding box dimensions of the space*

Complexity

The objective for this part of the study is to explore how choices in materiality and furnishings affect the perception of a space. To isolate this as much as possible, the layout of these spaces are organized as similarly as possible.

Each room is designed with different affordances in mind (page 53-57). In order to examine how these potential actions affect how participants perceive the space, each wall can be moved separately, unlike the previous two exercises.

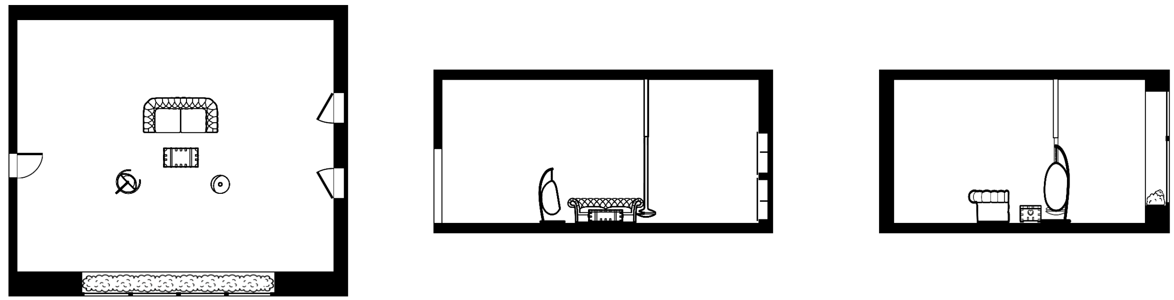


Figure 6.18 *Plan and section drawings for R3.*

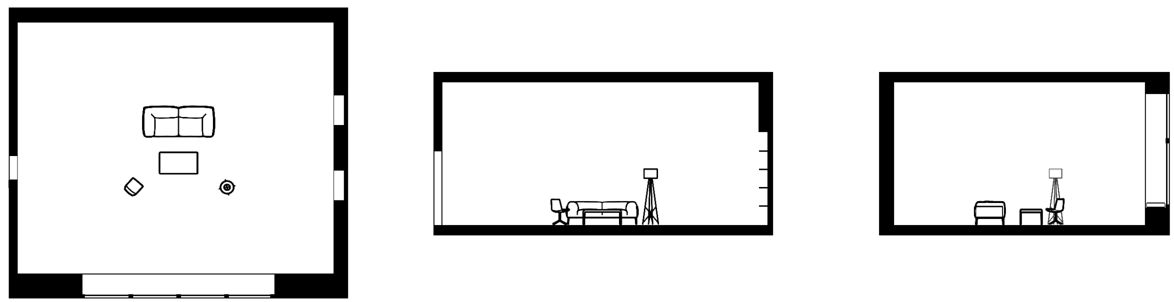


Figure 6.19 *Plan and section drawings for R4.*

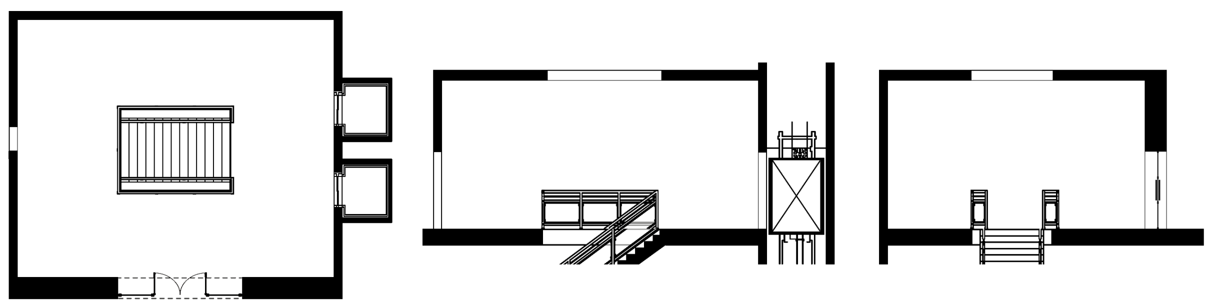


Figure 6.20 *Plan and section drawings for R5.*

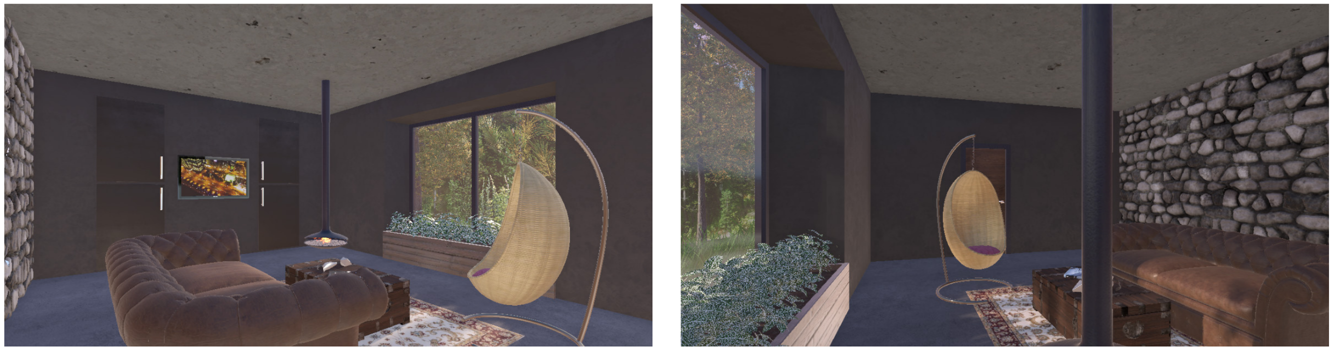


Figure 6.21 *Perspective views for R3.*

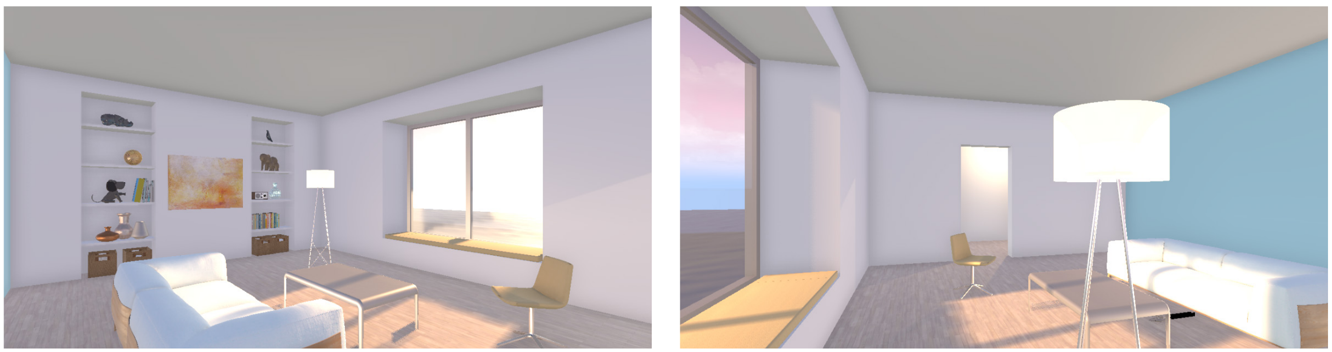


Figure 6.22 *Perspective views for R4.*

Figure 6.23 *Perspective views for R5.*

Room 3 | Dark Room

R3 is designed to feel small and compressed, using rough elements like the coarse stone and damaged walls to cause some discomfort in participants. The furniture that is chosen is deliberately bulky and involve moving features to add to the compressiveness of the space. The hypothesis is that these elements acting together would make participants feel constrained and as a result give larger dimensions to the room in VR than they would with drawings, where these elements have a more neutral appearance.

Contrary to expectations, it appears that this room is on average much smaller when dimensioned in VR as opposed to with drawings. However, many participants remarked that the space felt "warm" and "cozy", which is opposite of the design intentions. In future iterations of this experiment, it may be necessary to be more deliberate in the dishevelment of the room.

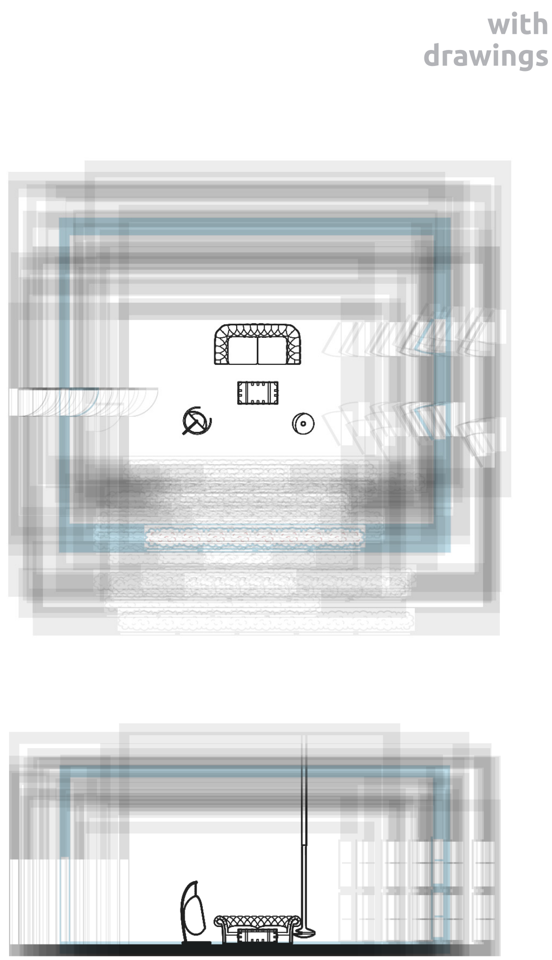


Figure 6.24 *Aggregated plans (above) and sections (below) from R3*; completed with drawings (target dimensions in blue).*

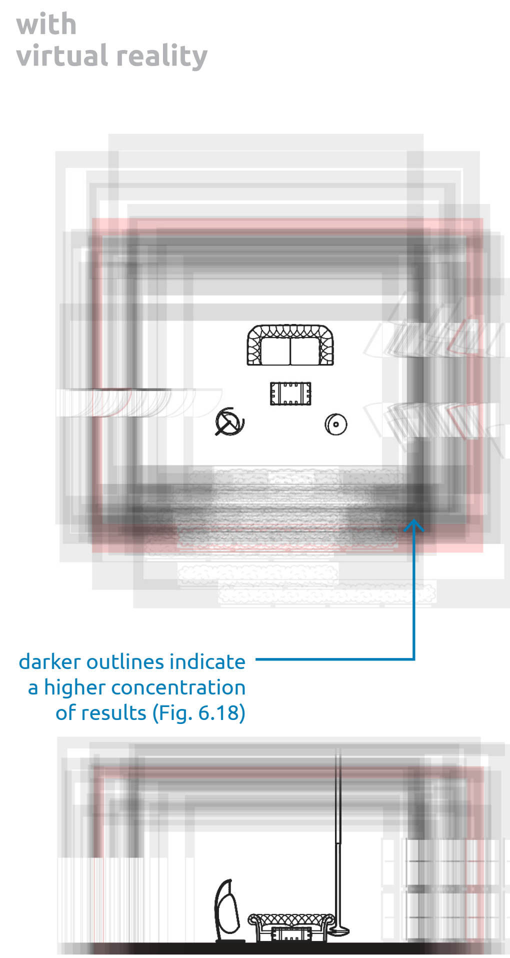


Figure 6.25 *Aggregated plans (above) and sections (below) from R3*; completed with VR (target dimensions in red).*

**Overlay diagrams for Rooms 3/4/5 indicate the placement of walls, not scale, because they are positioned independently of each other.*

***target dimension outlines indicate positioning of walls if the room is centered around the furniture arrnagement.*

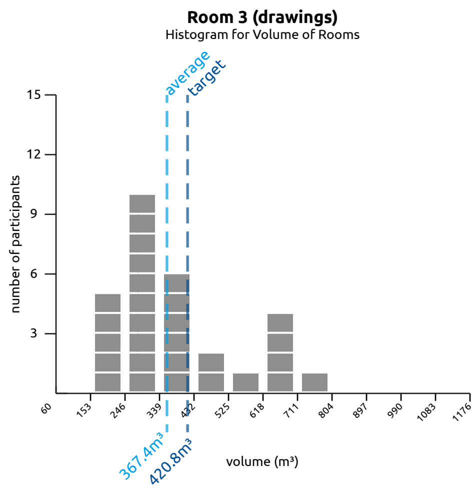


Figure 6.26 *Histogram for R3 with drawings.*

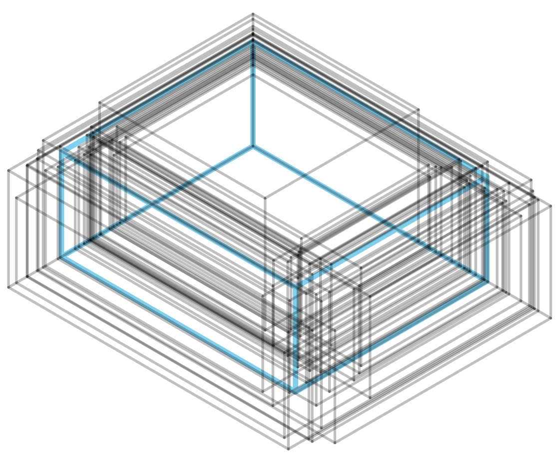


Figure 6.27 *Overlaid axonometric drawings of R3; completed with drawings (target dimensions in blue).*

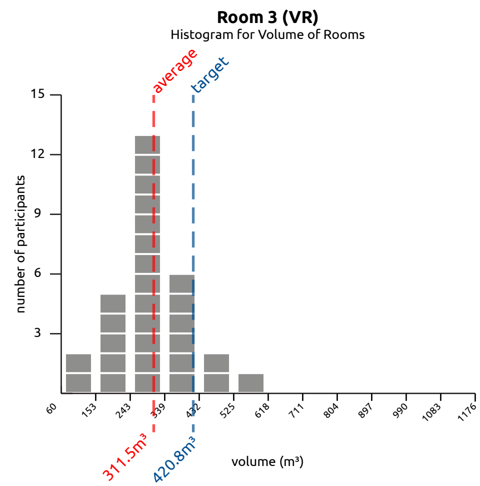


Figure 6.28 *Histogram for R3 with VR.*

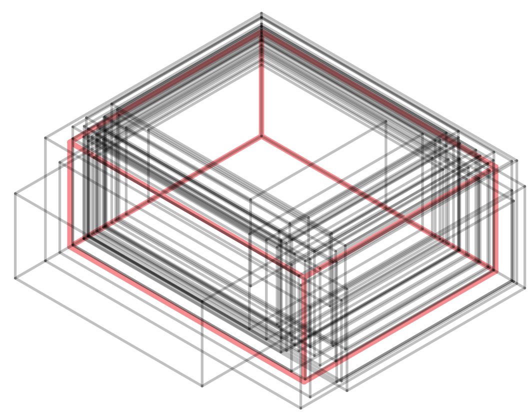


Figure 6.29 *Overlaid axonometric drawings of R3; completed with VR (target dimensions in red).*

Room 4 | Bright Room

R4 is designed to be the antithesis of R3, while keeping the layout as similar as possible. It was predicted that the brighter and airier space would mean that participants would tend to dimension the space smaller than R3 because the space would feel larger than it actually is.

The results are not significantly different from R3, although the average dimensions for R4 are slightly larger.

with drawings

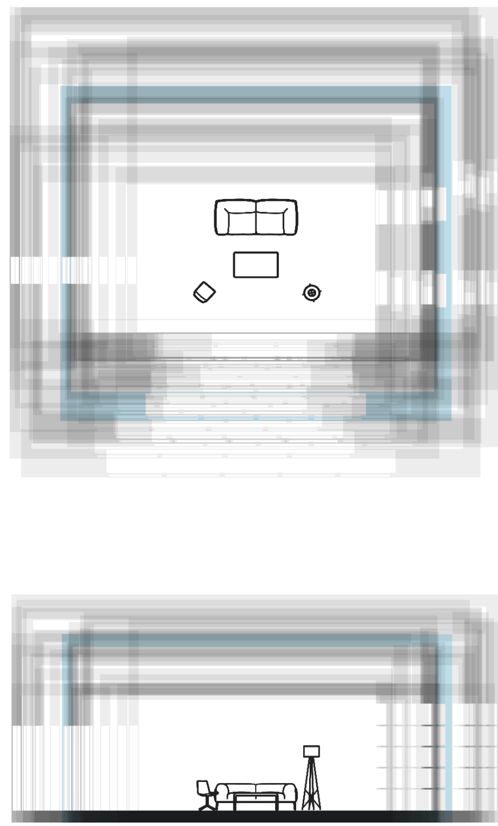


Figure 6.30 *Aggregated plans (above) and sections (below) from R4*; completed with drawings (target dimensions in blue**).*

with virtual reality

Figure 6.31 *Aggregated plans (above) and sections (below) from R4*; completed with VR (target dimensions in red**).*

**Overlay diagrams for Rooms 3/4/5 indicate the placement of walls, not scale, because they are positioned independently of each other.*

***target dimension outlines indicate positioning of walls if the room is centered around the furniture arrnagement.*

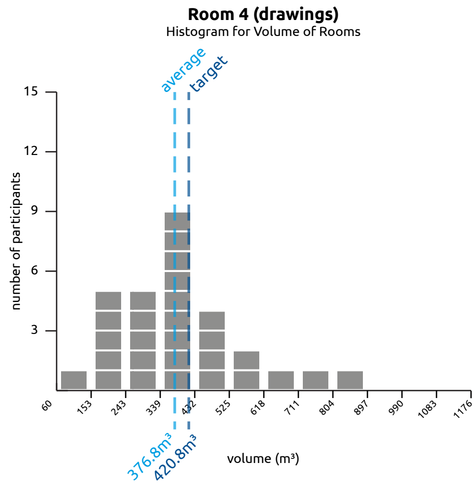


Figure 6.32 *Histogram for R4 with drawings*

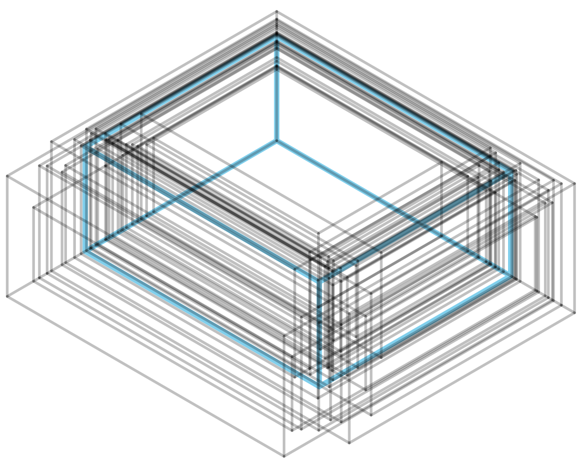


Figure 6.33 *Overlaid axonometric drawings of R4; completed with drawings (target dimensions in blue).*

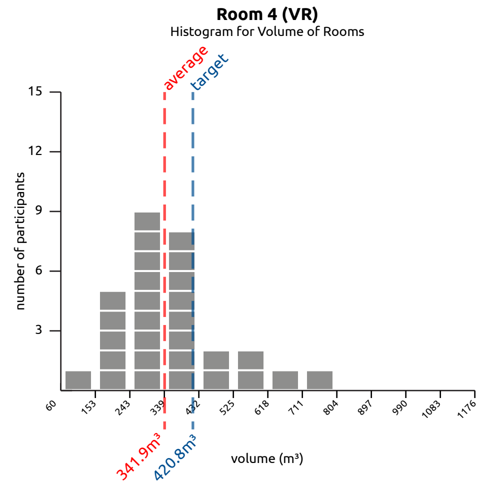


Figure 6.34 *Histogram for R4 with VR*

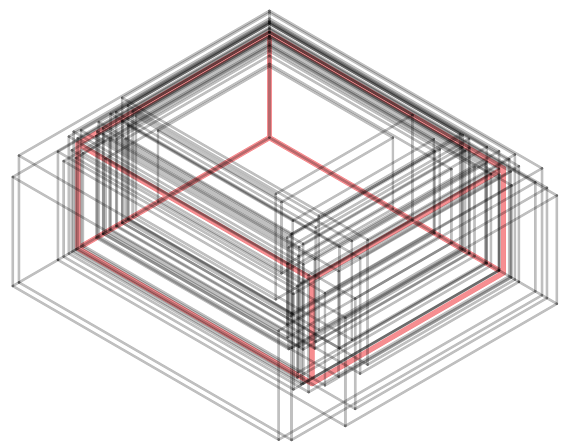


Figure 6.35 *Overlaid axonometric drawings of R4; completed with VR (target dimensions in red).*

Room 5 | Lobby

While the average dimensions in R5 with drawings are much closer to the target dimensions, the histogram shows a relatively flat distribution of results.

The overlaid drawings show that there is a wider range of positions that

Figure 6.40 (opposite) shows that 72% of participants are more accurate at placing the ceiling in VR than they are with the drawings. A theory as to why this might be the case is that there are more elements with standardized heights in R5, such as the stairs, the railings, and doors. In VR, these elements might be more visually dominant because participants are standing next to the railing looking over the stairs.

with drawings

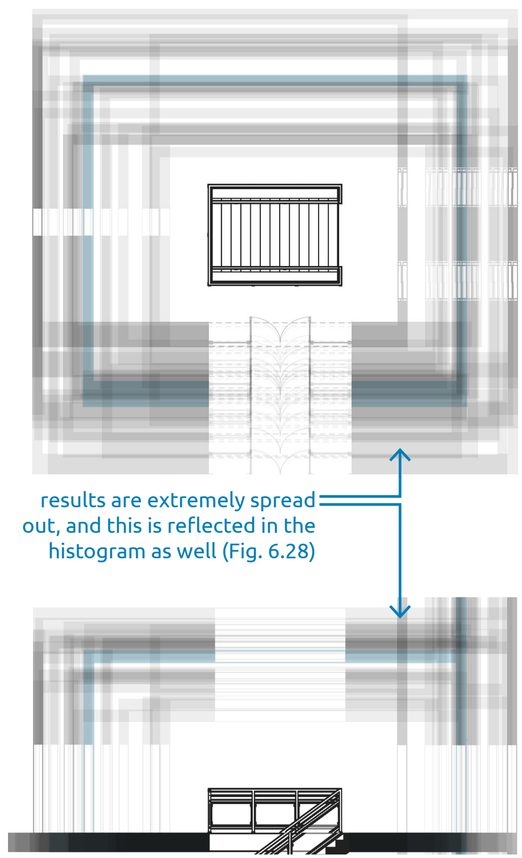


Figure 6.36 *Aggregated plans (above) and sections (below) from R5*; completed with drawings (target dimensions in blue**).*

with virtual reality

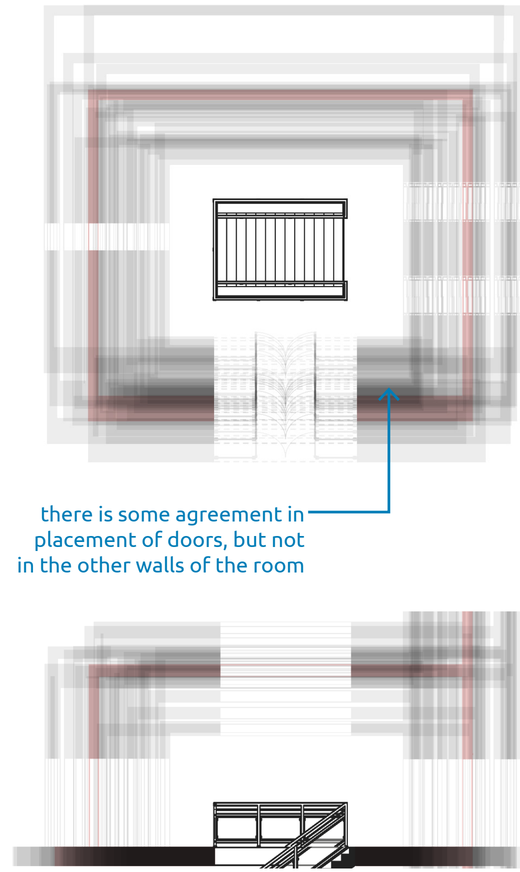


Figure 6.37 *Aggregated plans (above) and sections (below) from R5*; completed with VR (target dimensions in red**).*

**Overlay diagrams for Rooms 3/4/5 indicate the placement of walls, not scale, because they are positioned independently of each other.*

***target dimension outlines indicate positioning of walls if the room is centered around the furniture arrnagement.*

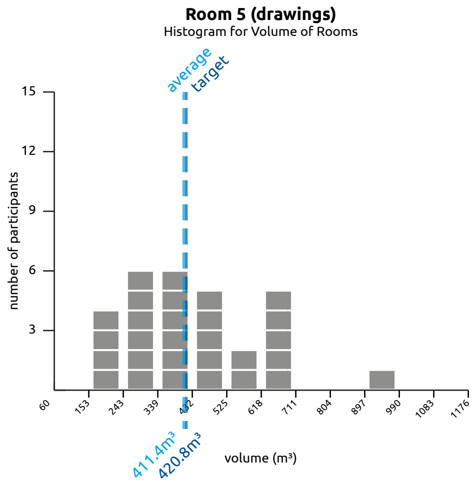


Figure 6.38 *Histogram for R5 with drawings*

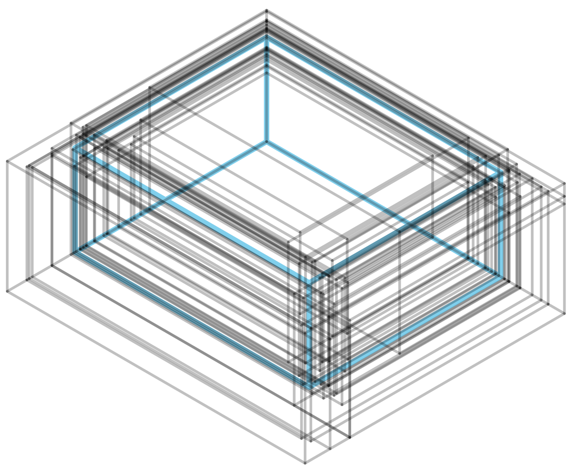


Figure 6.39 *Overlaid axonometric drawings of R5; completed with drawings (target dimensions in blue).*

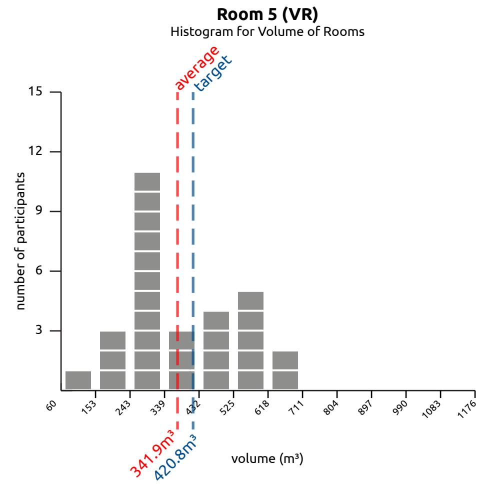


Figure 6.40 *Histogram for R5 with VR*

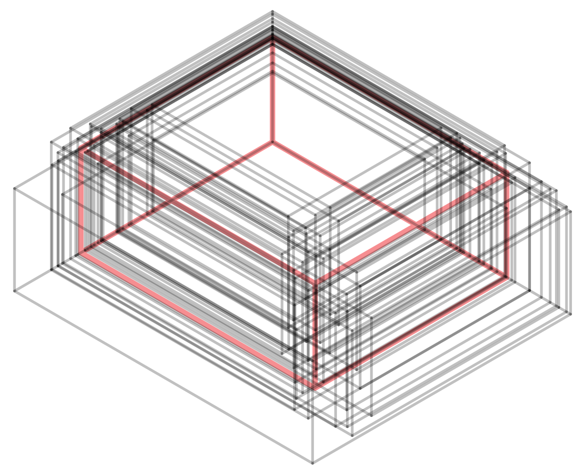


Figure 6.41 *Overlaid axonometric drawings of R5; completed with VR (target dimensions in red).*

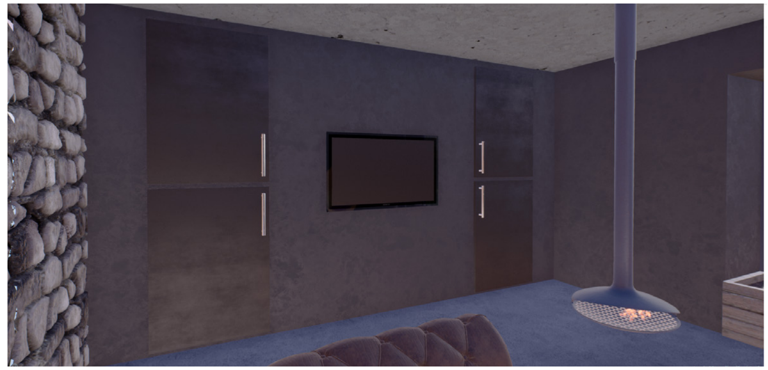
Affordances & Movement

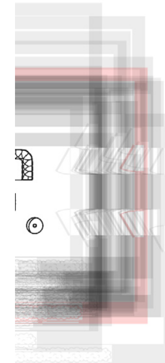
On this wall, different types of affordances are experimented with. The intentions behind these different elements are discussed in Chapter 5 (pages 53-57).

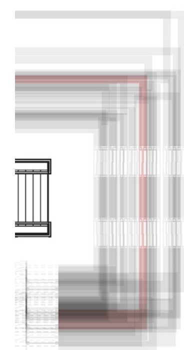
There are not many significant differences between the three rooms. A case could be made that there is more of a concensus in the placement of the wall in R3 and R4, while the placement in R5 is more spread out. This could be the result of participants wanting to keep the elements on the wall close to the fixtures and furniture in the room to form a more cohesive composition.

In R5, the waiting area for the elevators coincides with the top of the stairs. The hypothesis is that this area will tend to be given more space, because it would not be a pleasant waiting area if people have their backs turned to a descending staircase. Looking at the overlaid drawings, it does appear that there are fewer instances that are close to the stairs, but it is not significantly fewer.

In future investigations, it may help to add a few AI characters that walk around the space and act as reference points for dimensioning the widths of the passageways.

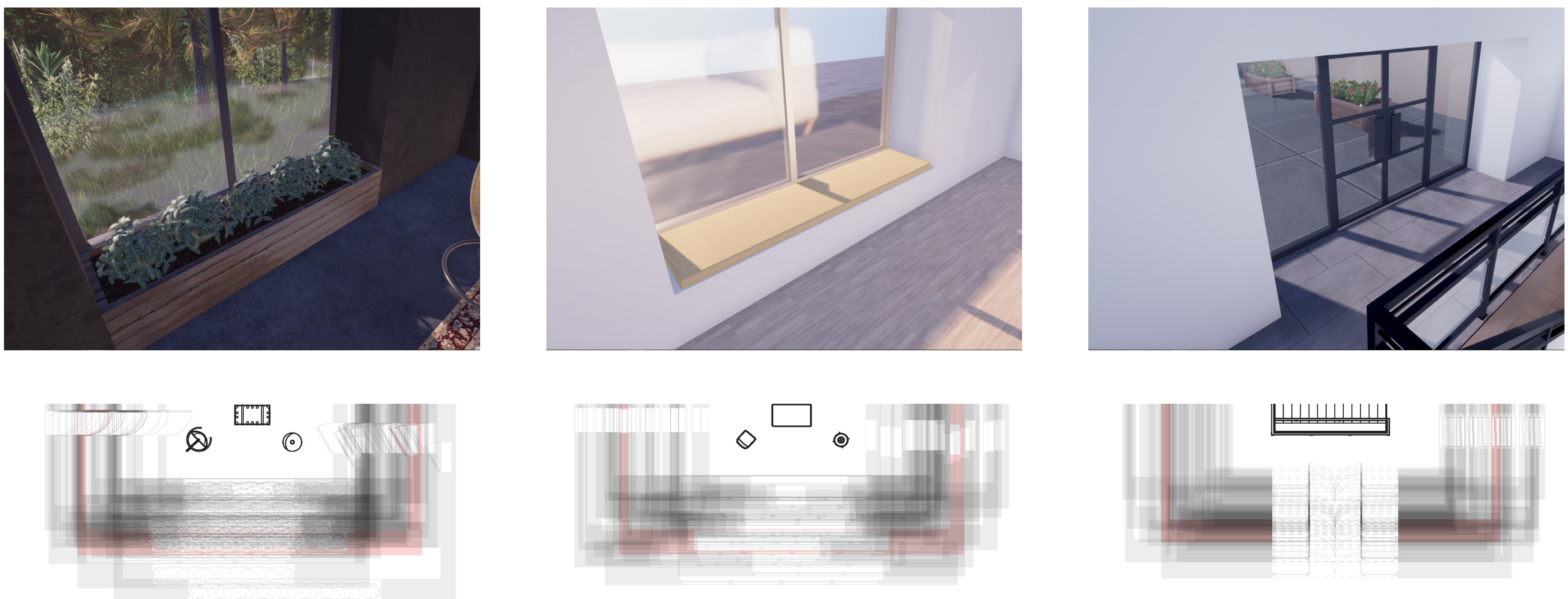






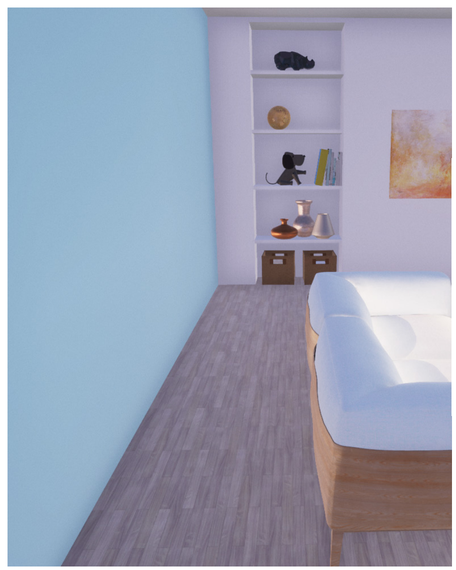
In this wall, there are different types of interactions as well. Again, these are described in more detail in Chapter 5 (page 53-57).

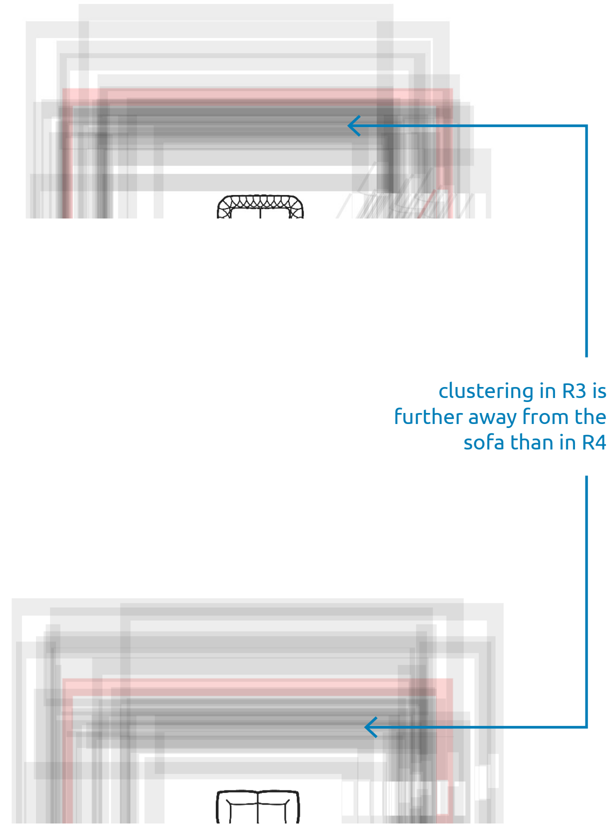
There does not appear to be a significant difference between R3 and R4. R5 however, which features a door instead of a window, tends to be placed further away, confirming the hypothesis that this area of potentially higher traffic would be given more space than an area where people would be static in motion.



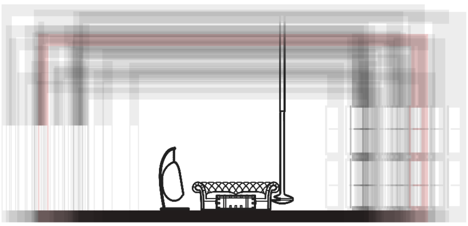
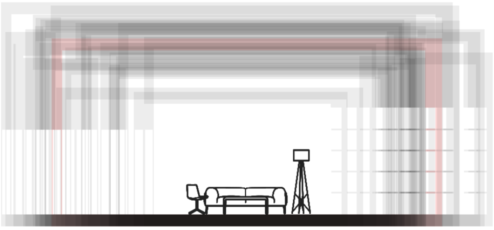
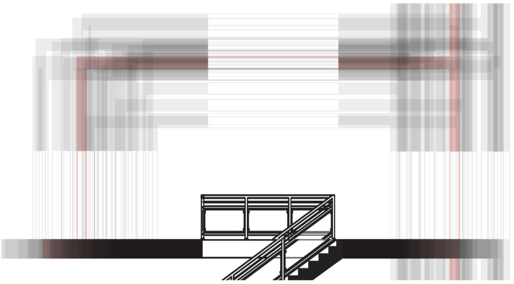
Materiality

A prediction about R3 and R4 that was correct is that the stone wall in R3 will tend to be placed further away from the sofas than the smooth painted wall in R4, and that this tendency will not be as prevalent when the exercises are completed with drawings. In VR, 77.8% of participants placed this wall closer to the sofa in R4 than they did in R3. With drawings, this number is 55.6%, demonstrating that the materiality of the wall is not as impactful when represented with the drawings even with the aid of a fully rendered view. This is a promising sign that supports the hypothesis that in VR, the visual stimuli of a material like the stone wall used in R3 will be more strongly associated with the feeling that it would be rough and uncomfortable to touch, leading to participants subconsciously positioning the wall further away. However, more research is required to fully understand this relationship.







A final area of investigation in materiality is the ceiling. It was predicted that the ceiling in R3, with its chips and cracks, would tend to be placed higher than the clean ceiling in R4, or the glass ceiling in R5. However, it is difficult to find any significant differences in the results. Of the three, the ceiling in R5 is largest and on average the closest to the target dimension.

Unsurprisingly, the topic of complexity in architectural design is not a simple matter. Because of this, it is probably too soon to discard the hypothesis that the design features of this room have no impact on the perception of space. Future investigations of this topic might need to study individual elements of a room in isolation to find more observable results.

Population

The last set of exercises explores how the presence of virtual humans affects spatial perception.

R6 (bus shelter) continues the format of R1-R5; participants move the walls of the space around a stationary group of people. R7 and R8 flips this formula around; participants control the amount of people inside a pavilion. The virtual humans placed into the pavilions can move about the space, but the walls of the pavilion remain fixed.

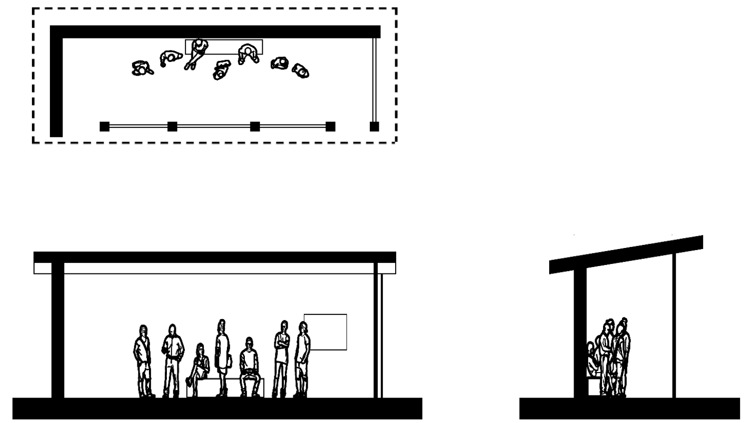


Figure 6.42 *Plan and section drawings for R6.*

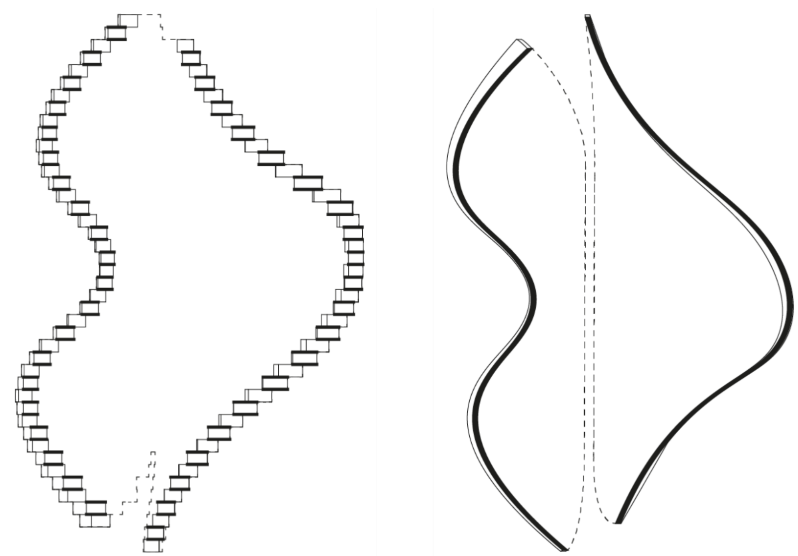


Figure 6.43 *Plan drawings for R7 (left) and R8 (right).*

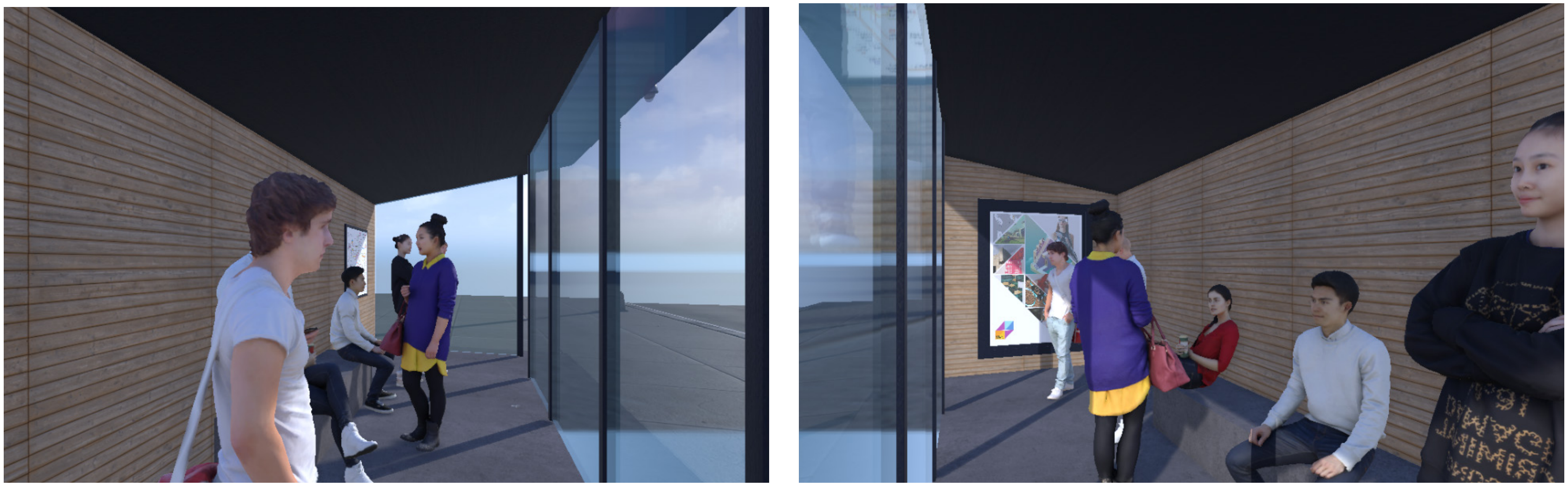


Figure 6.44 *Perspective views for R6.*

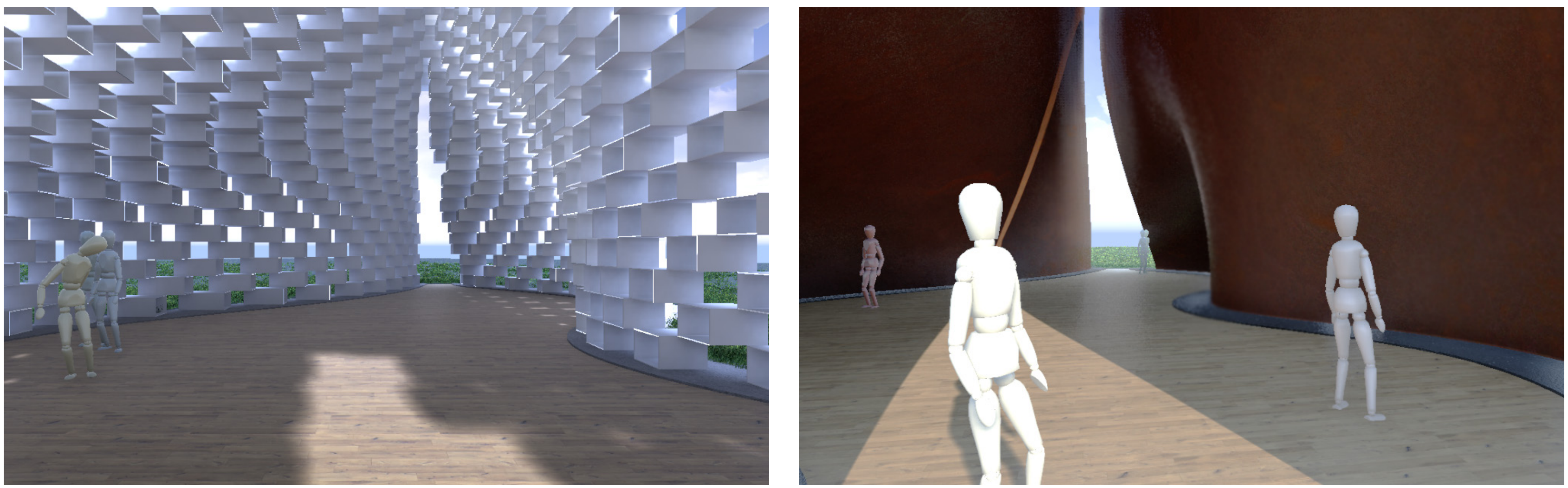


Figure 6.45 *Perspective views for R7 (left) and R8 (right).*

Room 6 | Bus Shelter

In the post-study survey, R6 is most frequently listed as the room where VR is most helpful in, and the results would appear to reflect this.

The results between the mediums do not display many noticeable differences, if at all. One that does stand out is that the vertical dimension in R6 is more frequently more accurate in VR (Fig. 6.40, page 72).

This increased accuracy could be attributed to the presence of the human figures, the smaller target dimensions, or a combination of the two. Future research should isolate the two parameters to see which is the greater contributor to accuracy in VR.

One drawback is that the 3D-scanned humans, which are fixed in motion like wax statues, may take some time to get used to. Participants are placed into R5 looking outwards and facing the glass. As they turn around to face the human figures, some are startled and unsettled by them.

with drawings

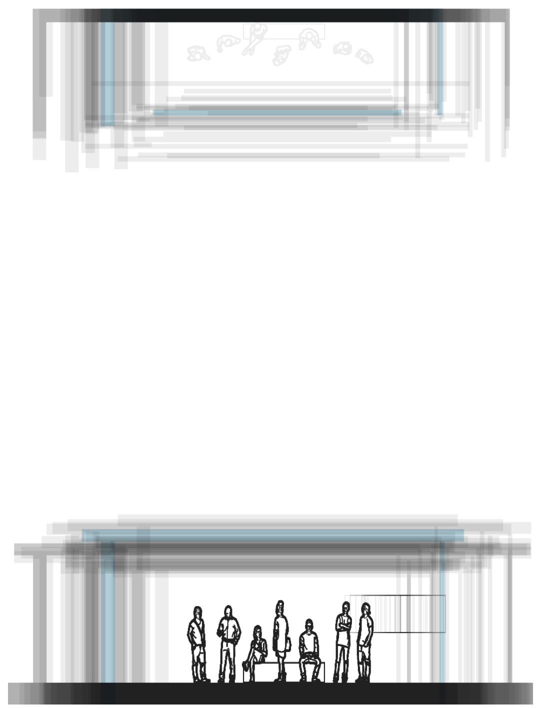


Figure 6.46 *Aggregated plans (above) and sections (below) from R6; completed with drawings (target dimensions in blue).*

with virtual reality

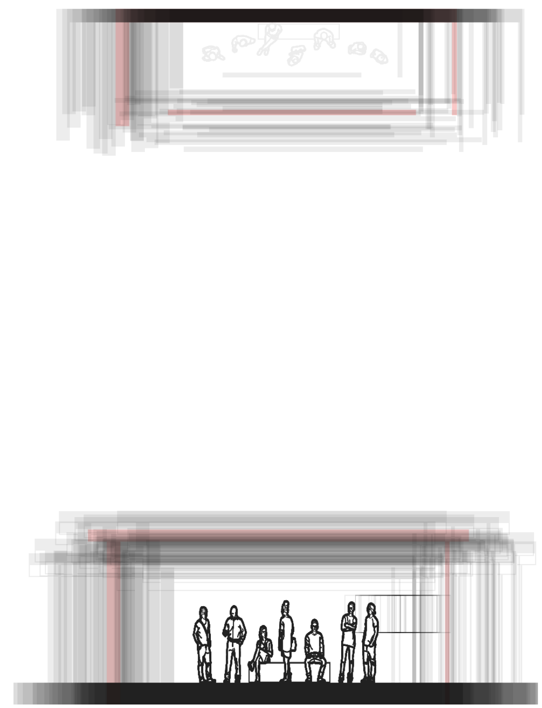


Figure 6.47 *Aggregated plans (above) and sections (below) from R6; completed with VR (target dimensions in red).*

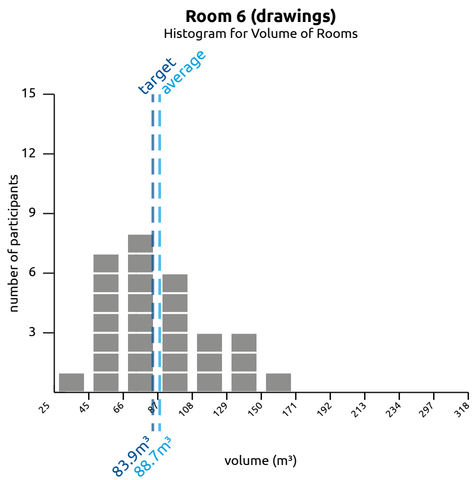


Figure 6.48 *Histogram for R6 with drawings.*

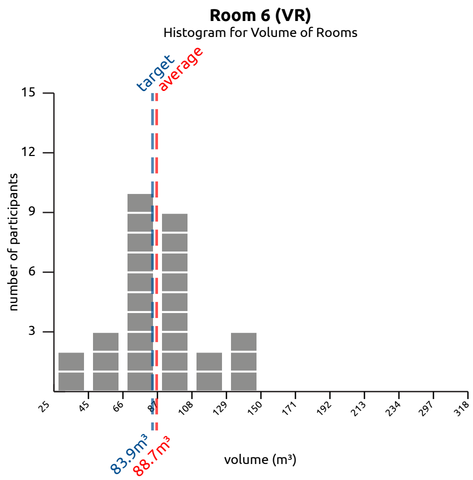


Figure 6.49 *Histogram for R6 with VR.*

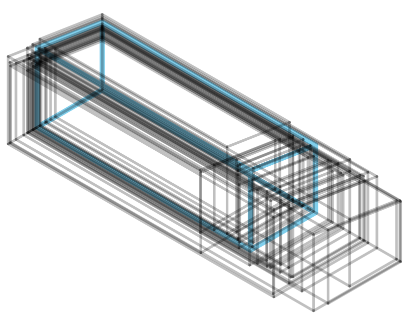


Figure 6.50 *Overlaid axonometric drawings of R6; completed with drawings (target dimensions in blue).*

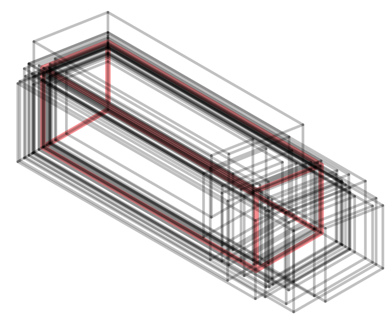


Figure 6.51 *Overlaid axonometric drawings of R6; completed with drawings (target dimensions in red).*

Room 7&8 | Pavilions

As discussed in Chapter 3, mental boundaries of interpersonal space can be affected by qualities of architectural space. R7 (porous pavilion) and R8 (solid pavilion) tests how this effect may be transferred into the mediums of architectural drawings and VR. The two pavilions are designed to have the exact same geometry, with the only difference being the tectonics of the enclosure, which creates drastically different atmospheres.

The hypothesis is that R7, which is a brighter and airier space, will tend to receive more people than R8 because to porous membrane of the pavilion will make the space feel less crowded. The solid pavilion, on the other hand, creates a dark environment with restricted views to the outside environment, which might make the space feel more crowded.

When the exercises were completed in VR, this is only slightly observable, as only 55% of participants inserted more people into R7 than R8. However, when the exercises are completed with drawings, a large majority of participants placed more people into R8, which is the opposite of the prediction above. One possible explanation for this is that the drawings for R7 are much more visually busy than R8 (opposite), and that might have made the space seem more crowded. To mitigate the impact that repeating the exercise might have on the results, half the participants completed R8 before R7.

Another hypothesis is that the people in VR will feel more intrusive to the personal space of participants, causing participants to place fewer people into the space in VR than when they complete the exercises with drawings. This appears to be true in both pavilions (Fig. 6.39).

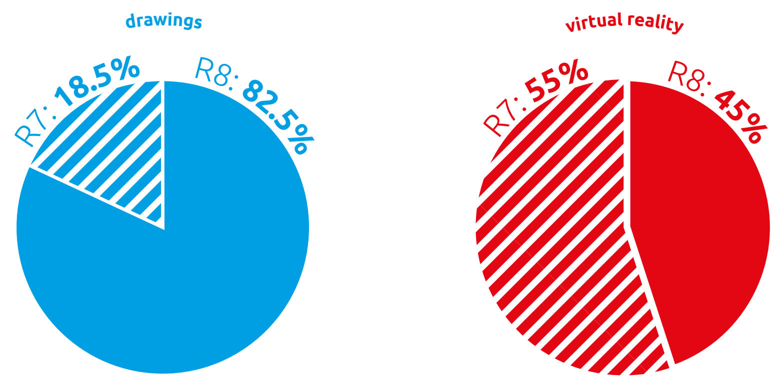


Figure 6.52 *Percentage of participants who added more people into R7 (hatched) compared to percentage of participants who added more people in R8 (solid). There is a much larger discrepancy in the results of the exercises when participants are using two-dimensional drawings. One potential reason for this is that R7 is more visually busy on the screen than R8, leading to a false impression that it is more crowded than it seems.*

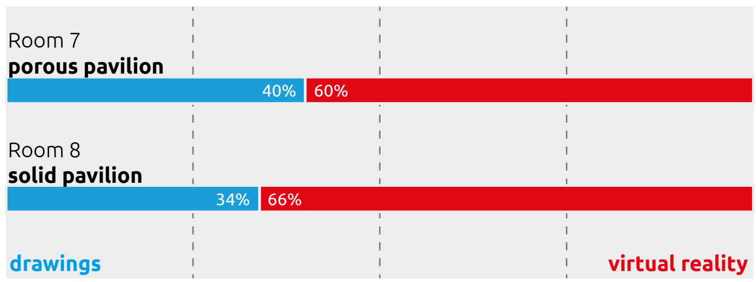


Figure 6.53 *Percentage of participants who added fewer people into the pavilion when using drawings (blue) as opposed to VR (red). This indicates that participants had a tendency to insert fewer people when experiencing the pavilions in VR, possibly because of the increased sense of proximity with the virtual characters.*

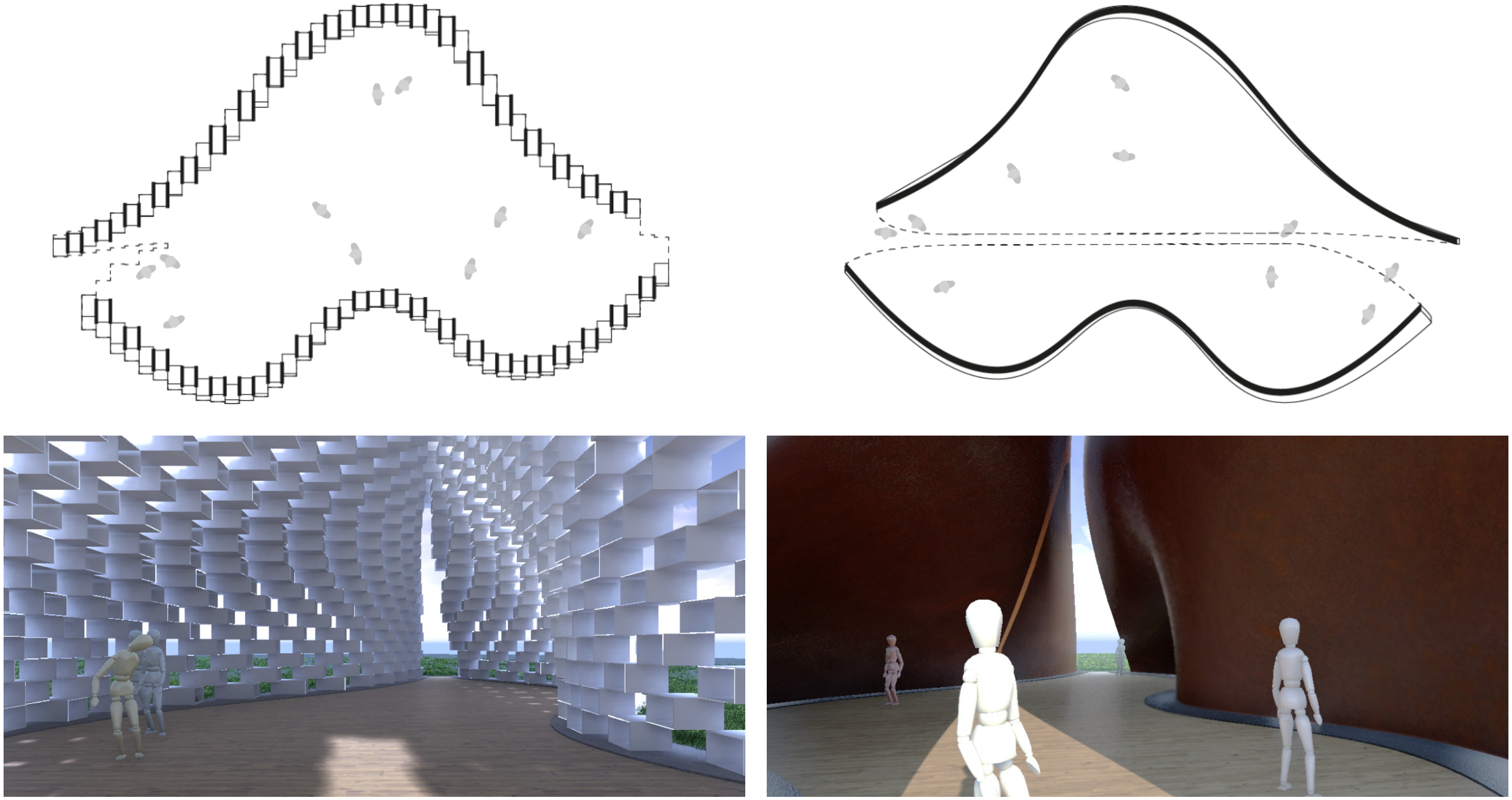


Figure 6.54 *Virtual human figures occupying the pavilions in R7 (left) and R8 (right).*

The observable reactions to the moving mannequins varied on a wide spectrum. Some participants were focused on the task and seemed unfazed by the mannequins walking around them. Others were unnerved by the crowd of human-sized wooden mannequins and seemed keen to finish the task and exit the space. There is a study that demonstrates a correlation between perceived height in VR and self-esteem[3]. Future iterations of R7 and R8 could vary the heights and sizes of the mannequins or the eye level of the VR user to see if perception of crowdedness changes. Further investigations into this topic could also look into how VR can be used to examine proxemics, the study of the sociological effects of interpersonal space.

Size

Size is an overarching topic that spans the different themes/ groups, and since room dimensions are the main indicators of whether or not a parameter change has any effect on the perception of space, we can see patterns emerge from the resulting dimensions of the rooms in the experiments.

From Figure 6.40, it can be seen that the longer dimensions tend to be less accurate in VR than with drawings. VR tends to have an advantage in the vertical dimensions, particularly R5 and R6. As discussed previously (page 77), the presence of standardized elements like stairs, railings, and doors may be more impactful in VR because they are more visually dominant than they are in the drawings. In R6, many participants remarked that the human figures helped with the understanding of height, an observation that appears to be reflected in the results.

From Figure 6.41, it can be seen that the average dimensions of the results from completing the exercises with drawings are closer to the respective target dimensions. While it would appear that accuracy is more easily achieved with drawings, the histograms and overlay diagrams in previous pages show that there tends to be a wider range of dimensions when participants complete the exercises with drawings.

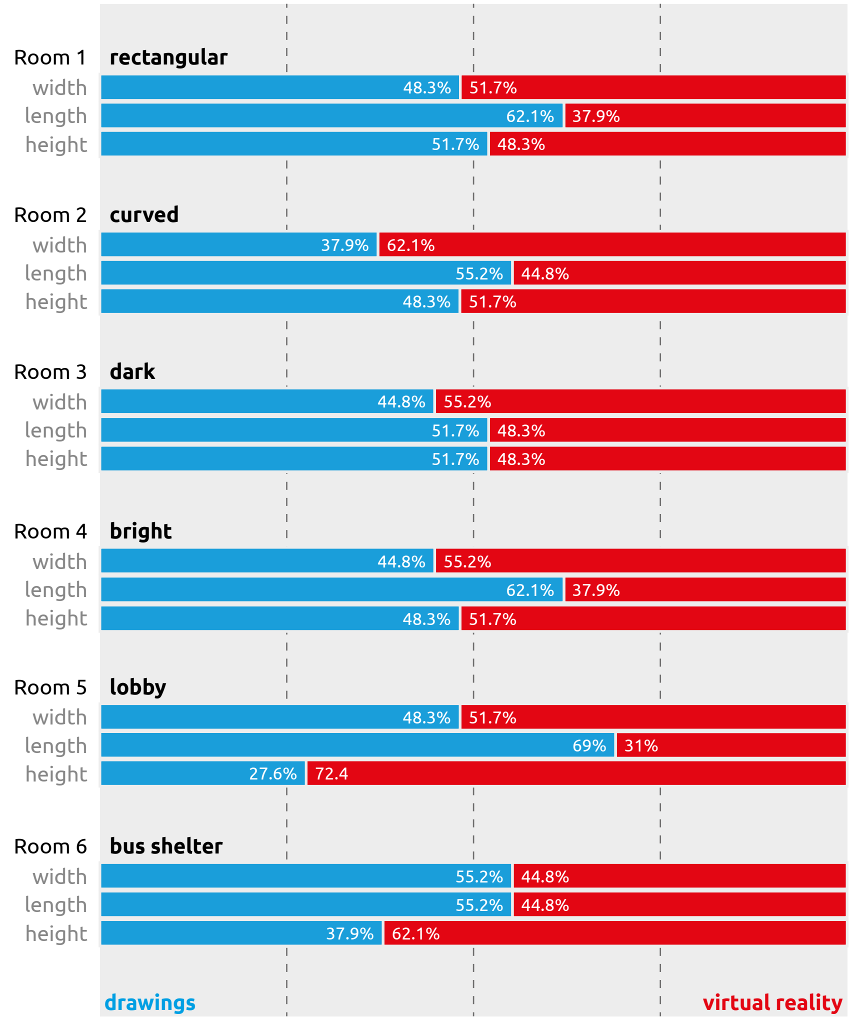


Figure 6.55 *Percentage of participants that were closer to the target dimensions when using drawings (blue) as opposed to VR (red).*

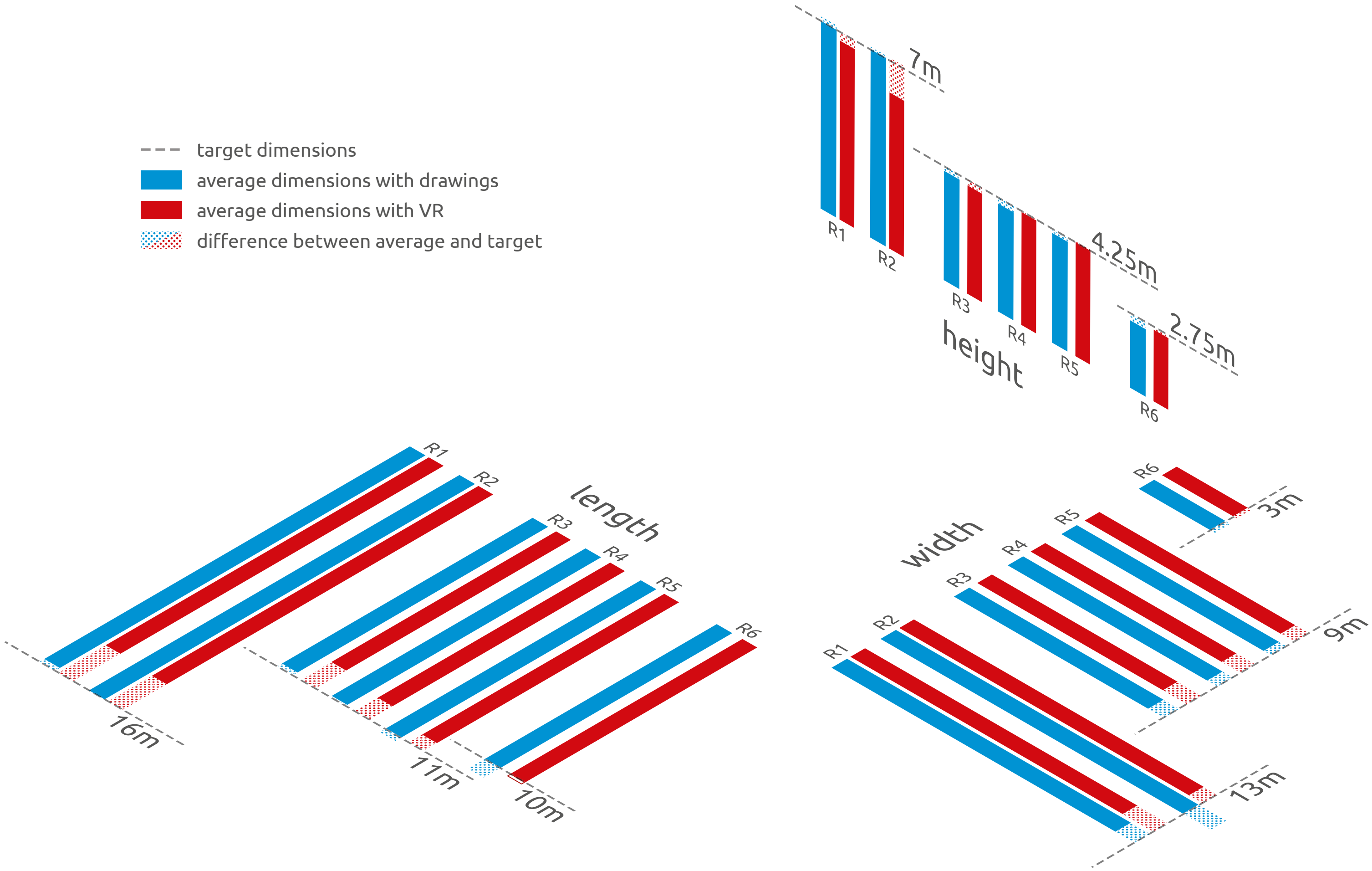


Figure 6.56 *The differences between the target dimensions (dashed lines) and the average dimensions from each exercise when completed with drawings (blue) and VR (red). Although the average dimensions when the exercises are completed with drawings tend to be closer to the target dimensions, it should be noted that the distribution of dimensions are more spread out, as can be seen in the histograms in this chapter.*

Observations and Comments

Participants had different methods of deducing dimensions in VR. Some tried to use their stride length as a reference, but gave up quickly because of the restrictions of the cable and the limitation that only the user's hands are represented, not the full body. Many used the beam of light – which acts as a cursor for selecting which wall to move – as a pointer to help measure out the room in cadences. Another strategy that participants used was to first make the room as small as possible so that they could understand the room relative to their body's dimensions, before expanding the space towards the target dimensions.

Participants also commented that the vertical dimensions were easier to estimate in VR because they could use their eye level as a guide. The results would appear to confirm this. Some participants added that the more reference points there were - such as furniture, textures, people - the easier it was to make estimates about dimensions. Some commented that the change in lighting as the room shrunk or grew helped them understand the spaces better as well.

Some participants commented that they felt that VR helped them make an estimate faster than they did with the drawings. The answers from the question asking participants what they relied on most in each medium more or less corroborates this. Almost a third of participants said that they relied most on their intuition in VR, but none of the participants did so with the drawings (Fig. 6.42).

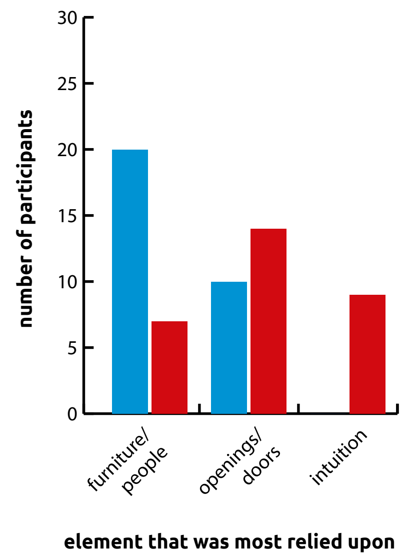


Figure 6.57 *Participants were asked to identify the elements that helped them the most in each medium.*

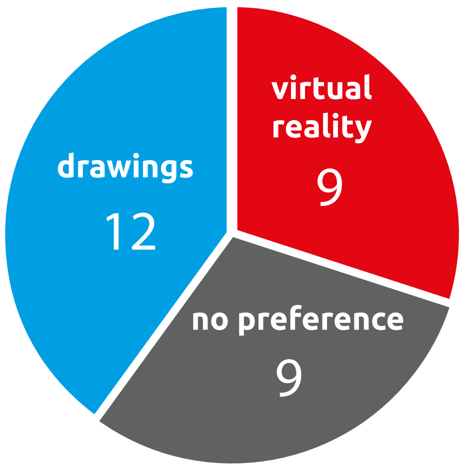


Figure 6.58 *Number of participants who felt more confident with either drawings or VR.*

Limitations

To make more definitive conclusions, more investigation should be conducted with a larger and more diverse sample of participants. The sample in this study consisted mostly of graduate students here at the University of Waterloo's School of Architecture. It would be of interest to see how results may change if participants were practicing professionals in architecture, or in another field of work.

More freedom of movement could help participants understand the different affordances within the spaces better. An untethered HMD with motion tracking like the Oculus Quest, which has not been released to the public at the time of writing, could be a significant upgrade in this regard.

Lastly, the perception of amounts of space is the main criterion that this study uses to compare the mediums of architectural drawings and VR, but there are many other points of comparison to be explored.

CONCLUSION

The Medium is the Message

If a picture is worth a thousand words, how many is VR worth? Communication is an important part of being an architect; many people from different backgrounds and skillsets must be brought together to overcome the different challenges that are involved in the design and construction of buildings. Although the results from the experiments in this thesis appear to indicate that the interpretation of space from VR experiences are less accurate than orthogonal and perspectival drawings, there were smaller discrepancies between the participants' interpretations of space in VR. In other words, VR brings people together towards a common understanding of space, an attribute that strengthens its claim as an effective medium for communicating spatial ideas.

In his book, *Understanding Media*, Marshall McLuhan writes that "the 'message' of any medium or technology is the change of scale or pace or pattern that it introduces into human affairs."[1] McLuhan believed that it is more important to look past the contents of a medium and examine how the characteristics of the medium affect our interactions with each other and with ourselves. In his view, media is an extension of human capabilities. A hammer extends the ability of the arm to strike metal, and the written word extends the ability to spread information. VR might not necessarily make an architect a better designer, but maybe a better visual communicator by extending their capabilities to represent abstract ideas. According to Louis Kahn, "A great building must begin with the immeasurable, must go through measurable means when it is being designed, and in the end must be

1 Marshall McLuhan, *Understanding Media: The Extensions of Man*, 1st MIT Press ed (Cambridge, Mass: MIT Press, 1994), 8.

unmeasured."[2] The results from the experiments in this thesis would suggest that VR is not likely to be the "measurable means" in this process. Architectural drawings are much more well-suited to resolving this aspect of the design. However, there are many examples throughout this document demonstrating how VR excels at conveying the immeasurable and representing space in an unmeasured manner.

While VR has limited potential in mass media because it requires specialized equipment, this is not necessarily a disadvantage for architects because it diminishes the influence of marketing decisions on the visualization of architecture. Perspective renderings in marketing can sometimes be detrimental to communication. Wide-angle lenses are often used so that more of the space can be shown, but this leads to a false impression that the space is larger than it is. Sometimes this is taken a step further in rendering software by clipping away parts of the room so that the camera can be placed further back than physically possible. Parts of the building that are deemed unappealing can be hidden away from view or cropped from the frame altogether. VR is a somewhat more "honest" medium because it is not possible to frame buildings in a more appealing fashion. However, there are still ways to block access to parts of the building that the architect wishes to remain hidden. Nonetheless, without the frame architecture is presented in a more comprehensively with fewer opportunities for the visualization artist to insert their biases.

By presenting the architecture in a comprehensive but easily understood format, VR can help clients understand design proposals

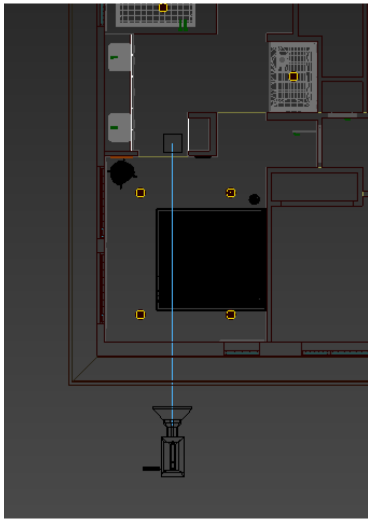


Figure 7.1 *Various perspectival rendering techniques can make spaces seem larger than they are.*

[2] Louis I. Kahn and Alessandra Latour, *Louis I. Kahn: Writings, Lectures, Interviews* (New York: Rizzoli International Publications, 1991).

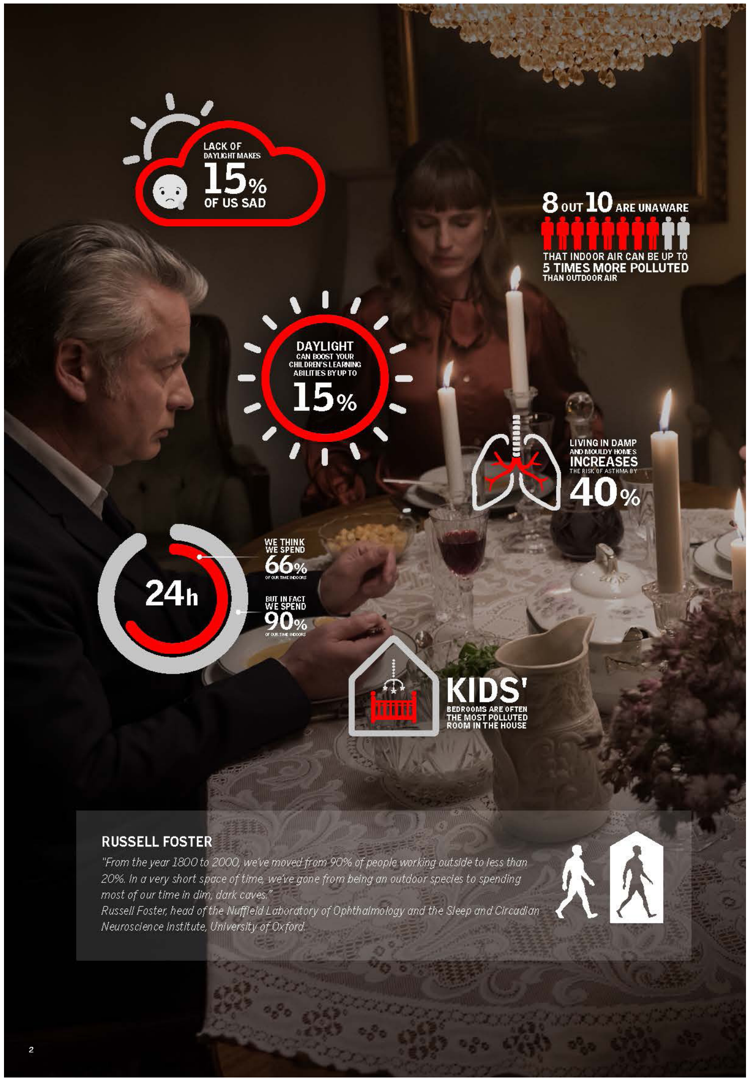


Figure 7.2 *Summary page from Velux's* Indoor Report.

better and express to architects how they feel and what they think about the project. Richard Neutra was well-known for giving clients a thoroughly-detailed questionnaire to gain a deeper understanding of them before beginning to design so that he could provide clients with buildings that would be both physically and psychologically fulfilling.[3] In today's fast-paced world, there are so many intricacies that it would be unrealistic to expect architects and clients to understand each other within a reasonable time-frame. VR can facilitate understanding between architects and clients by bringing them together on a common ground: the human experience of the built environment. This is important because as many examples throughout this document have shown, architecture has a significant influence on our psychology. As Winston Churchill succinctly puts it, "We shape our buildings, and they shape us." According to Velux's Indoor Generation report, the vast majority of people surveyed over 14 countries now spend more than 90% of their time indoors, a tremendous upsurge that also signifies an increased amount of influence and responsibility for architects.[4]

In order for VR's influence to materialize in the architecture that we build, the technology should be integrated into various parts of the design process so that architects can experience how their spaces feel as they develop them (some of the tools to do so are discussed in pages 5-6), instead of relying on conventions and graphic standards. VR's impact is limited when it is just a tool for creating highly detailed visualizations to present the finished product. It is early in the design process

3 Stephen Leet and Richard Joseph Neutra, *Richard Neutra's Miller House*, 1st ed, Primary Material (New York, N.Y: Princeton Architectural Press, 2004), 65.

4 "Future Generations Face Health Risks from Life Indoors," Velux, May 15, 2018, https://press.velux.com/future-generation-of-brits-faces-health-risks-from-life-indoors.

where VR potentially holds a larger advantage over other mediums. The immersiveness of VR brings to life even the crudest of sketches and the simplest of models, whereas the same types of content conveyed in other mediums require much more development or vivid imagination to become useful.

It is difficult to predict whether or not VR will have a direct impact on the form of architecture similar to the impact of prior disruptive technologies like CAD and parametric software, but the results from R2 (curved room) are encouraging for architects who work with unusual shapes. Participants did not feel confident in their comprehension of the curved space, as reported in the post-study survey, but their evaluations of the space were relatively accurate and consistent. Irregularly shaped buildings often require additional sectional or perspective views, and even then, are easily misunderstood. It is not entirely clear if the hypothesis that the perceptibility of the user's bodily dimensions would aid in the understanding of space is correct; it appears that it is most helpful in the perception of height, but not in the horizontal axes. This might change as the technology progresses to allow for more comprehensive simulation of the user's body and uninterrupted walking through large amounts of space.

The representation of spaces that are populated is also an exciting application of VR. It appears that the presence of people is felt more strongly in VR. Whether or not the different spatial qualities of the pavilions had a significant impact on perceptions of crowdedness, as other research have suggested, is unclear at the moment. It would be of interest to find out how crowdedness affects perception of space in the

Figure 7.3 *The Neurable EEG headset that is designed to attach to the HTC Vive.*

other environments that were built for this thesis. The study of interpersonal space in VR is a fertile ground for further investigations.

The research from environmental psychologists presented in this thesis is only a small portion of the work that architects can draw from to enrich their own practices. VR can help bridge the gap between architects and environmental psychologists by providing a starting point to test hypotheses before expanding the scale of study. In this study, it was difficult to find out if atmospheric qualities of spaces in VR affected participants with this experiment design, an unfortunate but expected outcome of the broad study design. Further insight into this topic might be obtained through a more focused approach, isolating only a single parameter of space at a time. This could possibly be aided with physiological sensors like electroencephalogram (EEG) sensors, which sense brain activity and can identify the general area of the brain in which the signals are coming from. EEG devices are becoming increasingly accessible[5] and can potentially provide a faster and more controlled way for environmental psychologists and architects to examine the relationship between the built environment and our mental processes.

This thesis focuses on how interior space is represented in VR, but there is also potential for VR in the representation of building exteriors and urban design. VR can be used to evaluate urban plans from a street-level point of view, to see how the atmosphere of a city block might change with the addition of new buildings or new urban design features. Even short exposures to urban environments can have significantly negative impacts on our psychology. Designers believe that they have the ability to at least alleviate some of the stress caused from city environments. VR might provide an avenue for urban designers to experiment and discover new solutions.

Amidst the excitement about VR, there are still many who doubt that VR will have a lasting presence in the technological landscape.[6] These concerns are not unreasonable; after all, it is a technology that requires users to find or make an area clear of obstacles and then strap a device on their heads that obstructs vision of their surroundings. However, some of the inconveniences that exist in today's VR headsets are technological limitations that can be overcome. Innovators in the field of VR believe that this is comparable to when the smartphone was at a similarly young stage.[7] When the first touch-screen phones were released in 1992, they were not practical to use. Screens were not clear and crisp enough to display enough information that would make the device practical. They were also too small to use with fingers, requiring an unwieldy stylus to operate. HMD's that are leading the VR revival like the Oculus Rift and the HTC Vive have been criticized for being too cumbersome and for having graphical quality that is not as sharp as expected. Over time these drawbacks should eventually become diminished and should not be seen as an invalidation of VR's fundamental premise. Of course, this comparison does not mean that we can ex-

5 "Reading the Brain from the Outside," The Economist, January 4, 2018, https://www.economist.com/technology-quarterly/2018/01/04/reading-the-brain-from-the-outside.

6 Natasha Lomas, "This VR Cycle Is Dead," Tech Crunch, August 26, 2017, https://techcrunch.com/2017/08/26/this-vr-cycle-is-dead.

7 Justin Pot, "It's Impossible to Predict the Future of Vr, and the Palm Pilot Proves It," Digital Trends, September 10, 2016, https://www.digitaltrends.com/virtual-reality/future-of-vr-is-unprecitable-palm-pilot.

pect VR to become as prevalent as smartphones. Even the most ardent supporters of VR would agree that to expect VR to achieve such a level of ubiquity is an unrealistic expectation; VR could very well remain and comfortably exist as a niche technology.[8] VR has proven that it can make a significant difference in the medical and education sectors.

Hopefully, this thesis has strengthened the case that architectural design is one of the many niches where VR belongs, and has also provided a deeper understanding of VR as a medium. As McLuhan writes, “Control over change would seem to consist in moving not with it but ahead of it. Anticipation gives the power to deflect and control force.”[9] The speed and volume of development in VR makes it difficult to predict how the technology will develop over the next few decades. However, with a greater comprehension of the medium, architects will have the opportunity to shape the evolution of this exciting technology.

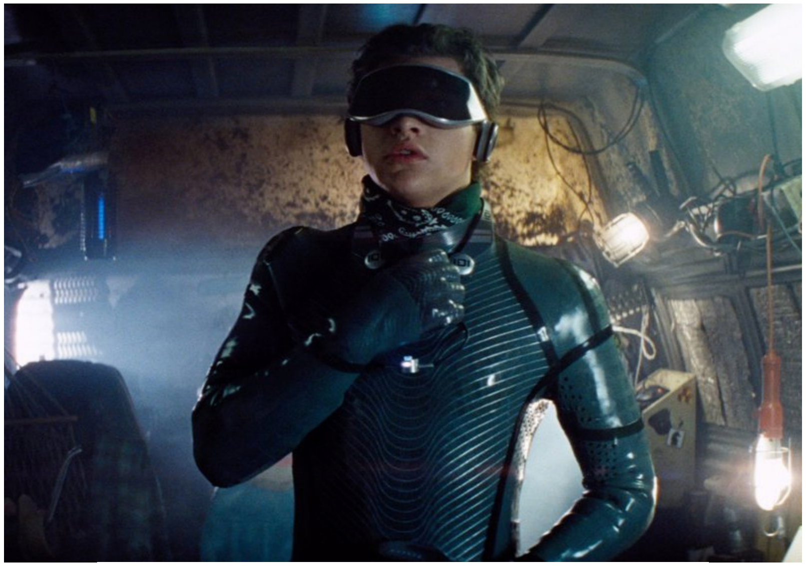


Figure 7.4 *Futuristic depiction of VR in 2018's* Ready Player One.

8 Palmer Luckey, “Free Isn't Cheap Enough,” The Blog of Palmer Luckey, October 30, 2018, http://palmerluckey.com/free-isnt-cheap-enough.

9 McLuhan, 199.

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APPENDICES

APPENDIX A

Experiment Data

Drawings Results

	R1: rectangular room			R2: curved room			R3: dark room					R4: bright room				
	width	length	height	width	length	height	North	South	East	West	Height	North	South	East	West	Height
1	1336	1896	736	1424	1832	688	306	320	501	493	329	337	275	462	523	290
2	1304	1766	516	1248	1640	636	465	250	577	613	372	530	275	678	545	300
3	792	952	448	1400	1440	544	379	275	327	505	290	359	295	375	523	305
4	1584	2000	876	2000	2000	830	435	359	495	509	362	449	351	509	534	403
5	1112	1592	612	1192	1512	692	200	580	347	700	434	217	516	481	632	434
6	856	1080	548	1000	1072	592	488	275	484	375	346	597	275	675	355	466
7	920	1288	588	1312	1384	652	586	460	535	700	418	681	412	602	685	511
8	1215	1724	580	1440	1744	708	348	314	442	442	355	353	325	507	439	324
9	1112	1376	518	1208	1400	478	306	432	465	551	355	345	401	479	473	374
10	1208	1416	860	1480	1544	784	415	345	529	549	458	421	384	512	531	432
11	1296	1712	676	1472	1560	840	269	502	277	658	382	275	432	375	632	338
12	1392	1696	812	1744	1728	848	365	695	695	628	454	563	516	638	638	437
13	752	872	592	960	944	620	200	398	417	409	336	211	367	386	389	300
14	1160	1623	816	1288	1560	980	664	242	593	610	451	659	236	638	700	494
15	952	1632	672	1832	1944	960	549	600	669	647	475	589	527	700	531	456
16	816	1008	612	936	1048	688	213	507	403	375	537	575	275	507	498	473
17	1080	1541	688	1464	1752	796	337	303	585	563	398	334	303	428	700	427
18	1072	1440	680	1424	1672	692	348	401	607	692	412	695	297	630	666	396
19	1104	1656	928	1544	1968	912	315	700	700	700	456	650	617	635	666	490
20	1568	2000	816	1768	2000	740	560	426	608	700	516	700	359	700	700	526
21	1408	1888	808	1320	1568	628	471	591	683	658	451	306	482	420	700	398
22	1176	1568	744	1576	1776	744	432	320	493	476	430	454	423	557	568	442
23	1608	1961	924	1888	1784	980	384	381	507	470	427	415	390	529	537	406
24	1208	1608	692	1320	1592	584	513	323	554	532	360	566	275	518	587	386
25	1464	2000	904	1752	2000	980	546	566	700	560	346	582	561	515	700	300
26	1528	1800	628	1352	1280	348	558	261	588	591	406	449	275	515	512	302
27	1136	1392	642	1456	1616	594	275	642	420	669	374	505	505	619	644	377
28	1488	1632	616	1312	1712	620	474	502	512	509	389	460	460	507	498	439
29	1176	1816	728	1384	1864	720	334	339	507	666	355	415	356	509	489	374
30	1376	1675	792	1272	1416	688	415	594	672	431	487	547	404	658	487	480

Drawings Results (continued)

	R5: lobby					R6: bus shelter				R7: porous pavilion	R8: solid pavilion
	North	South	East	West	Height	South	East	West	Height	# of people	# of people
1	311	440	535	585	381	262	475	418	251	24	29
2	239	507	686	355	344	315	700	510	257	46	52
3	309	328	498	447	307	293	483	395	307	49	52
4	429	418	557	582	280	287	489	434	213	56	56
5	275	600	582	610	373	268	514	462	261	150	223
6	572	275	594	355	489	324	402	563	207	111	141
7	353	549	647	694	505	385	469	558	253	78	76
8	432	429	537	579	372	349	606	619	261	66	68
9	370	395	467	559	358	287	515	476	225	110	119
10	449	415	543	548	490	298	475	468	269	41	52
11	300	395	700	377	313	321	506	700	229	41	57
12	449	667	669	655	460	368	590	470	243	108	121
13	275	348	456	324	333	242	469	409	213	126	85
14	645	364	700	700	477	441	641	605	287	36	49
15	572	555	641	650	461	433	436	460	260	53	61
16	275	275	565	610	496	220	700	680	239	109	115
17	306	286	375	596	384	293	581	549	217	197	205
18	429	432	579	610	463	287	612	549	249	48	34
19	555	664	700	700	530	340	700	700	245	92	89
20	589	513	700	700	446	352	700	588	291	61	153
21	535	474	700	700	446	405	696	700	247	115	187
22	460	460	579	554	535	333	542	564	253	128	120
23	423	426	585	556	449	326	618	544	297	59	79
24	549	362	479	700	423	343	371	700	245	82	132
25	628	275	375	700	352	309	553	527	208	142	96
26	533	275	375	683	377	430	688	544	245	78	82
27	275	602	535	495	456	352	402	409	199	122	97
28	524	485	549	590	454	329	570	549	221	55	66
29	412	398	493	501	432	293	402	527	235	66	71
30	404	491	549	700	474	308	493	340	215	157	194

VR Results

	R1: rectangular room			R2: curved room			R3: dark room					R4: bright room				
	width	length	height	width	length	height	North	South	East	West	Height	North	South	East	West	Height
1	1721	1806	671	1416	1456	698	419	396	375	463	404	507	275	478	463	429
2	1538	1942	653	1128	1866	786	393	276	545	518	420	324	423	603	570	470
3	1217	1720	680	1046	1520	678	355	388	401	571	356	359	393	440	524	363
4	1273	1535	565	1323	1402	560	420	389	572	612	328	486	424	470	571	372
5	1045	1758	518	1330	1409	824	200	477	361	646	446	200	491	356	664	412
6	1265	1625	660	1286	1496	661	275	558	375	550	456	275	527	554	355	465
7	1200	1370	600	1074	1307	494	591	331	485	568	428	604	276	502	599	456
8	1321	1504	668	1301	1422	801	337	398	394	474	447	317	404	458	480	464
9	1178	1519	590	1334	1694	714	408	406	365	566	436	264	545	620	515	429
10	1382	1997	736	1344	1432	768	412	423	601	636	414	554	440	663	688	440
11	1123	1302	391	1174	1276	374	361	426	408	555	306	291	479	318	538	300
12	995	1135	577	1020	1331	697	394	401	509	561	395	415	462	502	636	375
13	871	1023	401	880	944	617	200	331	420	433	290	215	309	272	309	290
14	1895	2000	876	1633	1719	908	649	366	541	658	500	680	497	581	700	516
15	744	957	525	1168	1507	617	366	408	495	433	372	289	339	504	511	401
16	665	933	593	1096	1181	610	343	292	302	282	352	338	304	393	279	429
17	1093	1087	445	1484	1573	642	323	361	514	507	339	358	359	418	383	352
18	927	1131	506	1080	1206	528	323	417	499	590	446	584	336	473	606	485
19	1213	1255	693	1128	1256	935	275	611	662	429	481	387	556	529	599	476
20	1358	1441	681	1297	1336	701	700	456	375	503	344	654	275	491	587	413
21	1171	1275	607	1288	1482	554	555	332	469	558	433	536	349	438	584	473
22	1205	1628	536	1256	1306	627	363	584	541	635	367	527	680	551	700	443
23	1099	1396	553	1260	1336	683	421	338	452	450	409	384	397	476	444	405
24	1256	1636	518	1209	1642	620	318	457	413	455	392	570	332	676	629	448
25	1008	1356	500	1031	1115	729	424	389	396	361	386	421	394	497	408	413
26	734	861	338	1088	1312	458	458	275	375	441	389	666	301	700	380	389
27	1165	1283	499	1448	1684	533	494	275	570	447	425	388	275	411	362	380
28	1114	1194	548	1344	1506	666	401	422	612	563	486	348	344	600	554	508
29	1117	1194	692	1572	1550	753	375	329	477	448	482	339	326	433	464	463
30	1038	1163	508	1079	1112	633	355	374	402	400	313	373	303	388	388	333

VR Results (continued)

	R5: lobby					R6: bus shelter				R7: porous pavilion	R8: solid pavilion
	North	**South**	**East**	**West**	**Height**	**South**	**East**	**West**	**Height**	# of people	# of people
1	386	410	677	531	416	301	595	475	273	17	20
2	305	427	477	415	438	351	635	457	254	41	37
3	318	386	438	489	434	247	403	598	292	37	34
4	474	406	682	663	397	343	551	549	254	75	84
5	305	284	462	437	423	244	498	467	231	248	178
6	320	397	394	398	453	302	402	525	243	104	115
7	420	400	603	526	473	366	517	512	307	75	70
8	423	381	434	446	456	276	431	432	265	59	50
9	346	504	629	425	487	323	569	506	290	179	123
10	452	463	666	597	470	270	633	657	255	34	32
11	372	448	589	436	321	349	427	457	223	39	45
12	408	516	531	499	423	356	615	380	268	57	71
13	259	300	375	340	288	195	340	340	221	127	111
14	558	450	681	623	461	392	590	540	302	41	44
15	526	461	572	527	280	309	514	643	226	47	60
16	290	276	433	404	434	272	601	384	279	129	186
17	398	331	566	558	397	264	508	627	231	137	108
18	466	516	662	671	469	372	622	586	314	58	60
19	700	339	643	564	519	304	700	435	251	146	127
20	465	570	589	550	424	387	694	564	269	142	75
21	430	426	579	516	501	272	478	474	262	91	95
22	593	619	700	700	417	423	680	435	252	133	82
23	330	475	506	466	441	287	485	485	251	40	44
24	310	413	402	591	421	324	618	478	260	100	90
25	450	419	477	492	397	348	423	492	397	59	52
26	699	308	700	681	427	413	521	453	257	68	71
27	419	419	407	476	405	293	402	340	212	107	112
28	454	494	553	537	530	274	642	600	230	112	167
29	353	311	510	355	467	370	436	414	315	52	76
30	275	400	398	375	362	282	402	417	196	355	218

Pre-study Survey

	Age	Education level in architecture	Professional experience in architecture	Computer skills	VR experience	Preferred medium to design with
1	25-34	Master's	1-3 yrs	competent	none	plans & sections
2	18-24	Master's	1-3 yrs	skilled	brief	perspective/isometric
3	18-24	Master's	3-5 yrs	skilled	extensive	3D model
4	25-34	Master's	3-5 yrs	competent	brief	perspective/isometric
5	25-34	Master's	1-3 yrs	expert	brief	perspective/isometric
6	18-24	Master's	1-3 yrs	skilled	brief	plans & sections
7	25-34	Master's	1-3 yrs	skilled	brief	plans & sections
8	18-24	Master's	1-3 yrs	competent	brief	perspective/isometric
9	25-34	Master's	3-5 yrs	expert	extensive	3D model
10	25-34	Master's	3-5 yrs	skilled	brief	perspective/isometric
11	25-34	Master's	3-5 yrs	competent	none	plans & sections
12	18-24	Master's	1-3 yrs	skilled	brief	plans & sections
13	25-34	Master's	3-5 yrs	skilled	brief	perspective/isometric
14	25-34	Master's	3-5 yrs	expert	none	plans & sections
15	25-34	Master's	5-10 yrs	skilled	brief	plans & sections
16	25-34	Master's	1-3 yrs	skilled	brief	plans & sections
17	25-34	Master's	1-3 yrs	skilled	none	plans & sections
18	25-34	Master's	3-5 yrs	skilled	extensive	perspective/isometric
19	35-44	Pro/Instructor	10+ yrs	expert	brief	perspective/isometric
20	25-34	Master's	1-3 yrs	skilled	brief	no preference
21	18-24	Second Year	0-1 yrs	skilled	none	perspective/isometric
22	25-34	Master's	1-3 yrs	skilled	brief	plans & sections
23	25-34	Master's	1-3 yrs	skilled	none	plans & sections
24	18-24	Second Year	0-1 yrs	skilled	none	perspective/isometric
25	25-34	Master's	1-3 yrs	skilled	none	3D model
26	55-64	none	0-1 yrs	skilled	none	perspective/isometric
27	25-34	Master's	1-3 yrs	skilled	brief	plans & sections
28	25-34	Master's	3-5 yrs	skilled	brief	perspective/isometric
29	45-60	Pro/Instructor	5-10 yrs	skilled	brief	perspective/isometric
30	25-34	Pro/Instructor	5-10 yrs	skilled	brief	plans & sections

Post-study Survey

	Preferred Media	Most helpful element (drawings)	Most helpful element (VR)	Exercise where VR was *most* helpful	Exercise where VR was *least* helpful
1	VR	openings/doors	furniture/people	5 - lobby	2 - curved room
2	no preference	people	people	7/8 - pavilions	2 - curved room
3	no preference	furniture/people	furniture/people	4 - bright room	2 - curved room
4	drawings	all	intuition	2 - curved room	5 - hallway
5	no preference	furniture/people	openings/doors	3 - dark room	2 - curved room
6	VR	openings/doors	intuition	6 - bus shelter	2 - curved room
7	VR	furniture/people	openings/doors	3 - dark room	2 - curved room
8	no preference	furniture/people	intuition	5 - lobby	2 - curved room
9	VR	openings/doors	openings/doors	6 - bus shelter	2 - curved room
10	no preference	furniture/people	openings/doors	5 - lobby	2 - curved room
11	drawings	openings/doors	furniture/people	6 - bus shelter	2 - curved room
12	drawings	furniture/people	openings/doors	6 - bus shelter	2 - curved room
13	no preference	furniture/people	intuition	6 - bus shelter	5 - lobby
14	no preference	openings/doors	openings/doors	6 - bus shelter	7/8 - pavilions
15	no preference	openings/doors	openings/doors	5 - lobby	2 - curved room
16	VR	openings/doors	openings/doors	6 - bus shelter	7/8 - pavilions
17	VR	furniture/people	intuition	3 - dark room	7/8 - pavilions
18	VR	furniture/people	openings/doors	6 - bus shelter	2 - curved room
19	drawings	openings/doors	openings/doors	5 - lobby	2 - curved room
20	VR	furniture/people	intuition	5 - lobby	7/8 - pavilions
21	drawings	furniture/people	intuition	7/8 - pavilions	6 - bus shelter
22	drawings	furniture/people	furniture/people	6 - bus shelter	1 - rectangular room
23	drawings	furniture/people	openings/doors	7/8 - pavilions	2 - curved room
24	drawings	openings/doors	intuition	7/8 - pavilions	2 - curved room
25	drawings	furniture/people	openings/doors	7/8 - pavilions	2 - curved room
26	no preference	people/doors	people/doors	6 - bus shelter	2 - curved room
27	drawings	furniture/people	openings/doors	6 - bus shelter	2 - curved room
28	VR	furniture/people	openings/doors	7/8 - pavilions	2 - curved room
29	drawings	openings/doors	furniture/people	6 - bus shelter	2 - curved room
30	drawings	furniture/people	intuition	7/8 - pavilions	1 - rectangular room

APPENDIX B

Glossary

affect (psychology) A response to stimuli that can be emotional, physiological, or motivational.

affordance Possible actions based on one's capabilities that is apparent from sensory signals (i.e. sight, sound, touch).

augmented reality (AR) A similar technology to VR in that both involve the use of head-mounted displays. However, the premise of VR is to take users to anywhere, while the premise of AR is to bring anything to the users.

avatar A digital representation of a VR user, usually in the form of a character figure.

cognition Conscious processing of knowledge or perceived stimuli.

embodied cognition This theory refutes the Cartesian dualism that the body is a vessel controlled by the mind, like a robot controlled by a computer chip, instead proposing that the body plays an important role in the process of cognition

gesture input Interactions can be programmed to trigger when the user makes a specific movement, such as drawing a circle with their arms. Because VR headsets obscure the vision of users, computer interface elements like buttons are more difficult to use. Gesture inputs can sometimes be more intuitive and provides a different option if more interactions are needed.

haptics The simulation of tactile sensations.

head tracking Sensors in VR headsets measure the movement of the device. Lower-end VR headsets (e.g. Oculus Go, Samsung GearVR, and other smartphone-based headsets) are capable of tracking only three degrees of freedom (3DoF) - rotations in pitch, yaw, and roll. Higher-end headsets (e.g. Oculus Rift, HTC Vive) track movements six degrees of freedom (6DoF) - rotations as well as movements in all three axes.

head-mounted display (HMD) A device worn like a visor, displaying images that either augments or replaces the user's field of vision.

immersion/presence A feeling of having been transported to an entirely different place.

locomotion In most applications of VR, physical space is a limited commodity. As a result, designers of VR experiences must devise alternate methods of movement across virtual environments.

peripheral device Auxiliary devices that add functionality but are not necessary.

proprioception Awareness of where various parts of one's body are in relation to each other.

room-scale VR Used to describe VR devices like the Oculus Rift and HTC Vive that track the movements of users within a small defined area.

VR sickness/simulator sickness Nausea can sometimes be triggered when what the user sees is drastically different than what they expect, causing cognitive dissonance. A common example is when unexpected latency causes the response time of the image to be too slow and unable to keep up with the user's movements.