Testing the interplay between immersive virtual reality and spatial analysis in urban design

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Abstract

Traditional design methods, e.g. physical 3D models or artists' impressions, have been used extensively in the history of spatial design, but they are oftentimes lacking in their capacity to represent the end-user experience. Virtual reality has become a field of interest for spatial design researchers and professionals, as its capacities have expanded over a long time and is now projected to hold great potential for incorporating more experience-based decision making into the design process. This is achieved by immersing a user in their design and experiencing it as if it were already built. This allows for early collection and processing of feedback. While much experimentation has been done on the visualization side, the effect of combining visuals and quantitative analyses is relatively unexplored. This report set out to test the added value of combining these two dimensions. This was done with a focus on density and the quantitative measure of Floor Space Index. An experiment was set up and conducted using a tool developed at the University of Groningen, in which participants explored and redesigned a pre-built area. Focus group discussions were conducted afterwards to evaluate experiences. Based on these discussions, it appears that the idea of combining immersive designing and data analysis holds promise in terms of engaging participants and producing useful feedback, but requires high quality data and a carefully chosen level of detail to be a truly effective tool in a designer's toolkit.

Keywords: immersive virtual reality, evidence-based design, design iteration loop, human-model interaction, perceived density

Preface

It is with great pleasure (and equally great exhaustion) that I present to you my master's thesis. At the beginning of the year, I chose VR as my core topic, not knowing what I was about to get myself into. As an enjoyer of new technology, especially related to gaming, the concept of using VR in a spatial design setting sounded new and enticing to me. Being able to be at the forefront of development of innovative spatial design methods also seemed very promising.

However, the initial excitement quickly made way for the realization that writing a master thesis is still a monumental task, no matter how much a topic might interest you. In this year, I have had to challenge myself many times over, and there were times where I genuinely wondered if I was going to make it. It was a long and arduous endeavor, but now that it is (hopefully) over, I can look back with a sense of enormous pride.

I know for certain that this was only made possible thanks to the supportive people aiding me in the process, and I would like to take this time to thank each of them. First and foremost, of course, is my supervisor Gerd Weitkamp, who guided me through the process with patience and understanding, even in the face of my stubborn procrastination behavior. He assisted me in every step of the way, made time for me even when it was not reasonable of me to ask for it, and helped me through my personal struggles during the writing process.

Second, I extend my gratitude towards the development team of the VR tool at the University of Groningen. Their tool allowed me to conduct my experiment in the first place, and they also gave technical assistance during the testing of the tool.

Third, I would like to thank Veronika Petrasova for lending her assistance during the testing and evaluating of the VR software, recruitment of participants and the conducting of the experiment. Your help in making the data collection run smoothly is greatly appreciated.

Fourth, I would like to thank Roy Boertien of VR-X. Having written a thesis on a similar topic under the same supervisor a couple years prior, he provided me with useful insights on how to approach the data collection methods, as well as with his own thesis from which I gained a lot of inspiration and useful sources.

Last but certainly not least, I extend my heartfelt thanks to my parents, who provided me with emotional support and encouragement when I needed it most. Not just this year, but in all my university years where I questioned myself and my capabilities whenever I felt like it was all getting too much. I can never thank you enough.

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List of abbreviations

2D: two-dimensional

3D: three-dimensional

CAD: computer-aided design

FAR: floor area ratio

FSI: floor space index

GIS: geographic information systems

GSI: ground space index

HMD: head-mounted display

LOD: level of detail

VR: virtual reality

VRISE: virtual reality-induced symptoms and effects

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1. Introduction: digitalization of spatial design

1.1. The rising need for advanced spatial design tools

Spatial planning and spatial design processes have seen a significant shift in approach over time. Traditionally, urban design was rather limited in focus, mainly being concerned with project-based design with a strong focus on aesthetics and architecture (Cuthbert, 2010). As the profession of spatial planning, and subsequently spatial design, matured throughout the second half of the 20th century, it became more concerned with social, economic and environmental issues, thus broadening its scope of activities (Cuthbert, 2007). Spatial designers had to adopt a more holistic view of the city's dynamics, as both private and public realm, as well as multiple spatial scales, are affected by spatial interventions (Frey, 1999). Next to this, the people who are affected by such interventions are also varied. Large pluralist, multicultural populations nowadays inhabit cities, each with their own experiences of urban life. Spatial planners and designers need to provide suitable living space for these varied populations, while also accounting for the social, economic and environmental aspects as mentioned above (Sandercock, 2004). This broadening scope also set in motion a change in the role of the designer: it was no longer considered plausible to assume that one single entity, i.e. the designer, was sufficiently capable of accounting for all the intricacies of the societal and environmental elements that they wish to impose change on; this knowledge is spread out across many different stakeholders which need to be brought together (Arias et al., 2000). Communication and collaboration with multiple stakeholders across many different fields of expertise became necessary in order to make informed design decisions, as opposed to the traditional approach of technical-rational, quantitative-driven models (Innes, 1996).

This increased recognition of the complexity of urban design issues also necessitated the use of new tools and techniques for visualization and data analysis that could more appropriately deal with this complexity. Masterplans, maps and eye-level perspectives were traditionally drawn on paper, and physical 3D models constructed out of wood or cardboard, in order to express, explore and communicate ideas with clients and professionals (Fung et al., 2004; Štefancová et al., 2020; Thompson et al., 2006). While these physical tools are still used and have their own benefits, mainly in terms of accessibility and interpretability (Ajene & Sylvester, 2014), they tend to be limited in their level of detail, accuracy, adjustability and integration of external information and data (Meeda et al., 2006). Physical 3D models, in particular, are expensive and time-consuming to produce, and larger models are hard to move around, making ease of access a pressing issue (Thompson et al., 2006). This becomes especially complicated when a design process goes through numerous design iterations, and many such models would need to be constructed (Ajene & Sylvester, 2014).

These issues create limitations to how effectively designs can be visualized and assessed in the design process. This process is far from linear; design proposals go through multiple iterations before they are transferred to concrete plans (Moughtin et al., 1999). These iterations create a feedback loop during the process, where every new iteration is visualized and presented to the design participants and generates additional insights and points for improvement (Yan & Tamke, 2021). But the traditional methods of visualization, e.g. 2D drawings or 3D models on a desktop screen, are not adequately suited for simulating how a person will experience a design once it is built (Zhang et al., 2021). This discrepancy between the presented design idea and the real-life experience can negatively affect the designer's understanding of the space (Azarby &

Rice, 2022), and subsequently what adjustments are necessary. More accurate and, importantly, *immersive* visualization tools that can provide the user with a ground-level view of the design and a strong awareness of spatial scale, may help alleviate this problem.

Furthermore, merely focusing on the visual aspect of a design is not enough to provide solutions that will satisfy prospective users of the space (Gehl, 2010). Designers oftentimes do not adequately account for the values and opinions of the end users (Nisha & Nelson, 2012), and do not have a full understanding of how their designs will be interacted with (Tang et al., 2019). Design decisions need to be informed using both scientific data and experiences from the past, so designers can better account for how their design affects people (Dyer et al., 2017). Designing with a tool that can seamlessly utilize such data sets could lead designers to take on a more data-driven perspective in the design process.

1.2. The way to virtual reality

Over the past decades, advancements in computer technology have greatly enriched the spatial design practice (Kouzeleas & Mammou, 2012). Digital visualizations are now created and shared online with others with relative ease (Ajene & Sylvester, 2014), and provide much more detail and insight in the complexity of the built environment than was previously possible (Al-Douri, 2010). Additionally, rather than just visualizing what is out there, digital models can have attribute data attached to them, with which spatial analyses can be conducted (Döllner et al., 2007; Kolbe, 2006; Ohori et al., 2018a). The model objects and their geometry are themselves a data set with which volumetric analyses can be performed (Ohori et al., 2018a). This increasing digitalization of spatial design has greatly enhanced collaboration with other stakeholders in the design process, both professionals and the general public (Fröst & Warren, 2000; Jamei et al., 2017).

One of such modern developments is the use of immersive virtual reality (VR) technology. VR visualizes objects in digital three-dimensional space, creating an artificial environment for the user to experience and experiment in (Chavan, 2016). These images are delivered to the user through a specially made head-mounted display (HMD) to immerse the user in the virtual experience (Mazuryk & Gervautz, 1996). This technology has recently seen more attention and usage thanks to developments in computing power which have made the technology more commonly accessible (Jamei et al., 2017). With this increased attention, it is being applied in a variety of research settings to test what kinds of answers the use of VR can provide. This also includes the domain of spatial design, though it is still in its relative infancy (Jamei et al., 2017). City governments are taking to using 3D models of their respective cities to aid in envisioning future developments and their impacts on the wider urban system (Stauskis, 2014; Thompson et al., 2006). El Araby (2006) notes that VR provides a better image of new projects, and can lead to better decisions being made in new project developments. Nisha (2019), in comparing design tasks using both 3D printed material and immersive VR environments, concludes that participants working in VR were more holistically engaged in the process and showed heightened learning capacity. Al-Douri (2010) recognizes VR as a valuable tool in the spatial design process, allowing insights in the spatial structure that traditional design methods are not capable of fully capturing.

1.3. Research aim

This thesis aims to contribute to the understanding of how the rapidly developing technology of virtual reality (VR) can help overcome the challenges faced in adequately visualizing and analyzing spatial design ideas within the inherently iterative nature of the design process. The capacity for VR technology to provide methods of visualizing prospective designs and generating useful qualitative and quantitative feedback for continuing the iteration loop, as described by Yan and Tamke (2021), will be tested. The concept of urban density will be used as a case study to test the applicability of VR in the spatial design process. This will be done by reviewing the mechanisms, benefits and drawbacks of visualizing and analyzing spatial data in VR, as well as exploring similarities and differences in interpretations of quantitative and perceived urban density as described in the theory. Such research has been rather scarce (e.g. Fisher-Gewirtzman, 2018). By paying attention to quantitative measures of density and the ways in which VR enables spatial data analyses, this thesis will also attempt to respond to the call by Yan and Tamke (2021) to substantiate feedback on spatial designs with quantitative measurement; in this case, density measures which can be compared and discussed. The results of this research can be relevant to current and future spatial designers aiming to make their designs more suitable for prospective users of the space, as well as professors and students in the field of spatial design aiming to obtain better spatial awareness of their designs and supplement them with ground-level experiences. Making use of VR experiments in their toolset of research and design methods has been shown to enhance spatial perception, which gives users a better grasp of the actual scale and interrelations of the space and improve spatial learning (Nisha, 2019). If sufficiently tested and refined, VR can become a more effective research method for any academic field that can benefit from using virtually constructed environments to experience certain phenomena.

1.4. Research questions

Provided the VR technology sufficiently immerses a design participant in the virtual world, a mental state comparable to that of real life can be achieved in a VR setting, according to Hermund et al. (2019). It is therefore assumed that experiments on perceived density can be sufficiently executed in virtual space. To achieve this, the following research questions are central to this thesis:

> *-How can the interplay between spatial analysis and immersive virtual reality contribute to the urban design process?*

This question has been divided in the following sub-questions:

> *-In which phases of the design process can VR be most effective?*
> *-What factors influence the immersive experience provided by VR?*
> *-How do subjective experiences of urban environments in virtual space provide meaningful input in the spatial design process?*
> *-What role do quantitative measurements of urban density serve in spatial design?*
> *-What features must a VR tool have to provide useful qualitative and quantitative feedback to a spatial designer?*

1.5. Report structure

This research report is laid out as follows. The necessity for more a more immersive design method has been outlined in chapter 1 above. Chapter 2 will discuss theoretical insights in the design process and the added value of designing in VR, as well as how model quality and spatial analysis affect its usefulness. The concept of density and how it affects to livable urban designs will also be introduced here. Chapter 3 describes the specific tool used to conduct this research, and how the data was collected and analyzed. Chapter 4 shows the results from this research, and chapter 5 will discuss these results in the theoretical context. Conclusions and recommendations will be made in chapter 6. Chapter 7 serves as a reflection on the conclusiveness and generalizability of the conclusions drawn.

2. Theoretical framework: how technology influences the spatial design process

2.1. Design process flow

Before delving into how technological advancements are enriching the design process, it is important to highlight multitude of spatial design phases and how they proceed from one another. Abd Elrahman and Asaad (2019) have compared and summarized multiple process models into the following:

-1: *Data collection*: basic gathering of information, visual surveys;

-2: *Data analysis*: discerning information patterns;

-3: *Setting vision, goals and objectives* with the involved stakeholders, identifying potentials, taking into account constraints and problems given the economic and political circumstances;

-4: *Concept generation and strategies*: creating multiple concepts and possibilities, using different design theories and past experiences;

-5: *Develop options*: moving from concepts to solutions, testing and refining;

-6: *Evaluation* of the solutions against the initial vision, goals and objectives (from step 3), and appraising cost efficiency and other constraints;

-7: *Transfer to plans/implementation* once a solution has been agreed upon.

Although design processes are oftentimes projected as being linear, this is rarely the case. Spatial design proceeds through many iterative design loops before moving on to the implementation phase (Moughtin et al., 1999; Yan & Tamke, 2021). Proposed design ideas can offer new insights in the design problem as a whole, inviting the participants to redefine the vision, goals and objectives back in step 3 (Abd Elrahman & Asaad, 2019; Yan & Tamke, 2021). Additionally, because urban design is a multidisciplinary endeavor involved both with architecture and spatial planning, the decisions made on the design level also feedback into the analysis phases of upper and lower spatial scales (Moughtin et al., 1999).

In every step of this process, a proper visualization of the design is essential (Yan & Tamke, 2021; Zhang et al., 2021). As discussed before, visual representations of designs are highly effective communication methods, aimed to help decision makers understand the implications of their ideas and inform future steps to take (Zhang et al., 2021). However, Yan and Tamke (2021) note that traditional spatial design lacks appropriate methods for visualizing design ideas. Artist's impressions and physical models are oftentimes deliberately made to look a certain way, creating distorted visions of what the actual design will represent once built. Furthermore, it cannot accurately represent how a person traversing through the design experiences the space. This combined means that the feedback obtained from stakeholders viewing these designs, i.e. the evaluation stage of the design process, is often ambiguous and complicated to properly link back to the design, hindering the ability to make effective changes to the design. Users must be able to obtain feeling for the space to properly assess the spatial quality. Additionally, the different users need to share this sense of space with one another to effectively work towards the same goal with the same values. This is difficult when relying on the aforementioned 'traditional' visualization techniques, which will be elaborated upon below.

2.2. Technological advancements and tools in the urban design process

The following section gives a brief overview of the tools that many urban designers currently use to create their design ideas, with special attention to the benefits that computer-aided design (CAD) have over their non-digital counterparts. Here, CAD is defined as the creation, analysis or modification of designs assisted in any way through computer systems (Ajene & Sylvester, 2015).

Visualization is a vital element of the urban design process, and is argued to be the most effective method of communicating design ideas to others (e.g. Batty et al., 2000). Most traditional methods of visualization produce 2D representations of design ideas. Masterplans and eye-level perspectives are among the most fundamental graphics used in the design process. The former serves to represent the overall built form, layout and structure of an area without much extraneous detail, providing measurable distances and assigned functions to certain areas. The latter accentuates certain spaces with a higher level of detail and provides a better sense of scale and relative distances between elements (Štefancová et al., 2020). Using computer software for these types of drawings (2D CAD) has become mainstream, for a number of benefits over hand-drawn versions. Information can be displayed at a high level of accuracy, design solutions appear complete and detailed with many possible complex views and realistic renders, external information and databases can be linked to the design, and adjustments are more easily made (Meeda et al., 2006). There are drawbacks, however: creating such designs at a high level of detail can be more complicated and time-consuming than hand-drawn sketches, and may require extensive training depending on the available software. Furthermore, the polished appearance of high-quality renders can cause important details and flaws to be overlooked during evaluation (Ajene & Sylvester, 2014). These disadvantages, among others, are the source of ongoing debate on the position of hand drawings in the modern urban design (Štefancová et al., 2020).

Regardless of the medium used, 2D graphics seem to have a strong disadvantage in their ability to be correctly interpreted. Jamei et al. (2017) mention how 2D data layers can quickly become complex with increasingly high levels of detail, and are therefore hard to understand for non-professionals. This can lead to false assumptions and misunderstandings during evaluation (Al-Douri, 2010). Despite this, Stauskis (2013) found that 2D visualizations are still useful for orientation, and Herbert and Chen (2015) add that 2D graphics are relevant for simple evaluation tasks where accurate measurements are important. For more complex and detailed analyses, however, 3D visualizations are more preferable, with 2D graphics serving a more supportive role (Herbert & Chen, 2015).

Physical 3D models have long been a staple in urban design, and are still being used frequently (Larsen, 2019; Thompson et al., 2006). These models provide a bird's eye view of the built environment, from a single project to an entire city. This expanded view provides insight in how individual pieces of a city fit into the greater urban fabric, and how change in one part of the city can affect the overall city image (Thompson et al., 2006). Whereas these models used to be expensive and time-consuming to construct, this process has been made cheaper and more time efficient due to increasing mainstream use of 3D printing and computer-controlled cutting techniques. Larsen (2019) argues that these developments allow physical models to retain their relevance in modern design processes. Such models still have major disadvantages, in that they cannot be adjusted once built, and that larger models are hard to move around, meaning that design participants are required to be present in a certain location (Thompson et al., 2006). This becomes especially complicated when a design process goes through numerous design iterations, and many such models would need to be constructed (Ajene & Sylvester, 2014).

MacEachren et al. (2004) noticed that the general trend of increasingly complex and interdisciplinary urban design caused visualization to focus more on flexible and accessible tools for supporting the decision making process, as opposed to rigid systems that dictate decision making. New technological advancements in data collection and display have made virtual 3D models a suitable visualization method for this end, and the increased use of 3D visualization has pushed further research into the technology, causing an upward spiral in mainstream use and appreciation of 3D technology.

The large push in technology has made digital 3D models of cities an attractive alternative to physical models. Thompson et al. (2006) note their accuracy, human scale perspective and adaptability as major advantages. Döllner et al. (2007) note that 3D models can flexibly bring multiple geodata sources together, making them widely applicable for many different analyses. Al-Douri (2010) mentions how 3D models help design participants (expert and non-expert) make sense of the complexity of the built environment, making these models a powerful element in stakeholder communication. Ajene and Sylvester (2014) mention how digital models allow for easy changes of perspectives on a model, as well as rendering multiple ach sources to generate shadows. Being able to view multiple angles and hypothetical lighting scenarios before construction improves both the efficiency of the designer and the overall quality of the design. Additionally, they note that digital means of generating multiple design ideas saves on time and costs, and also makes comparing designs with one another easier.

2.3. 3D modeling in virtual space

Robinett (1992) describes the way a person interacts with the world through technologically generated models, and notes that virtual environments visualized in an HMD are a form of synthetic experience: an artificial reproduction of sensory interactions. Specifically, he categorizes working inside a virtual model that replicates, but is not connected to, a part of the real world as a *simulated* experience, in which a person acts upon the model derived from real-world data (the virtual environment), the effects of which are simulated and then displayed back to the user. Through this mechanism, a VR system provides constant feedback to the person without any influence on the real world. Only when the virtual design is approved and implemented into plans, does the designer exert direct action on the world (Figure 1, next page).

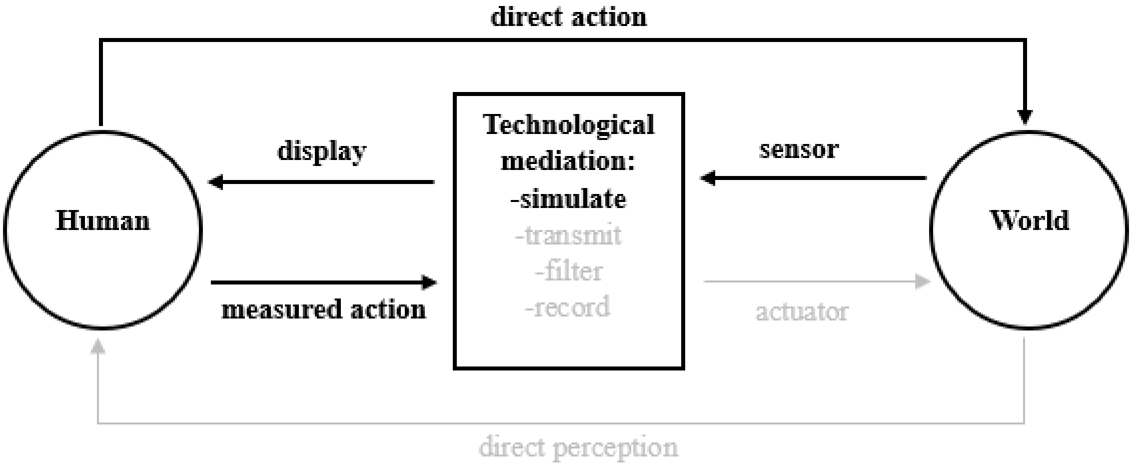


Figure 1: human interaction with a virtual simulation of the real world, highlighted for use of VR derived from real-world data. Source: author, based on Robinett (1992).

An HMD provides an egocentric experience of a model, that is, as viewed from the perspective of a single person at ground-level, as opposed to an allocentric view, which considers the position of objects as relative to one another regardless of an observer. Nisha (2019) notes that this ground-view level enables the user to better experience spatial dimensions such as volume and scale. Hermund et al. (2019), in their neurological study of human perception of architecture, found that human behavior in simulations of physical scenarios can compare to real-life situations, and can therefore be used as a proper research method, on the condition that the model provides a strong enough sense of immersion. Strong immersion is necessary for emulating a real-life experience as closely as possible. It provides the user with the feeling of actually being present in the area (Mazuryk & Gervautz, 1996), and allows them to be more aware of the spatial context (Azarby & Rice, 2022; Zhang et al., 2021). The more closely a virtual experience resembles real life, the more intuitively and naturally a participant will be able to interact with the virtual space (Campbell & Wells, 2003; Nisha, 2019). For example, Coburn et al. (2020) found that spatial awareness within a virtual environment is heavily impacted by the way in which participants move around in the environment. Gradual movement is the most natural way of moving around, and was subsequently shown in their research as being the way of movement in which participants retained the strongest sense of space.

The way one moves in, and interacts with, the immersive virtual environment influences the way the human vestibular system reacts to the visual stimuli. A common occurrence in immersive simulations is that the user can experience negative side effects in the form of nausea, dizziness, headaches or eye strain (Rebenitsch & Owen, 2016). These effects have collectively become known as Virtual Reality Induced Symptoms and Effects (VRISE) (Cobb et al., 1999). The main cause of this occurrence is a mismatch between the perceived stimuli from the virtual environment and the expected stimuli from the real world (Rebenitsch & Owen, 2016). Other factors include the level of control the user has over their movements and perspectives (Sharples et al., 2008), as well as the quality of the virtual environment (Mazuryk & Gervautz, 1996), which will also be discussed in section 2.5.

2.4. The added value of VR technology in the design process

Many authors see potential in virtual reality (VR) technology to alleviate the lack of immersion that hampers the iterative design process as mentioned in the introduction (Yan & Tamke, 2021). As the capabilities of virtual reality (VR) technology are growing rapidly, so do its possible uses in various societal domains, including urban design. Effective use of VR technology can greatly contribute to learning and active engagement throughout the design process. Nisha (2019), in the domain of spatial design education, recognizes VR as a potentially valuable tool for immersive and experiential learning for individuals, as it allows for participants to gain a strong sense of scale and spatial awareness. These skills are considered important in many scientific fields (Lee-Cultura and Giannakos, 2020).

Sharing experiences in virtual space helps create a common understanding, even for untrained participants, of the space under study and its complex internal relations (Fröst & Warren, 2000). VR can create an opportunity for experts in different fields to come together by putting urban projects in a wider context. The effects of new developments on other aspects of urban systems, such as transportation and the environment, can be visualized. New traffic patterns can be simulated and assessed before implementation. By allowing for these domains to be taken into account in an accessible manner, virtual modelling provides both an individual and shared learning platform and allows for better cooperation between multiple stakeholders across different disciplines (Jamei et al., 2017). Digital city models more accurately represent the actual scale of objects, and allow for easier adjustments to the model itself compared to physical models. Their digital format also allows for easier access without having to be at a certain location, which saves time. This high level of flexibility and ease of access permits a wide range of stakeholders to become involved, depending on the scale and scope of a project (Thompson et al., 2006). The feedback participants give on designs is based on a ground-level view, thereby constantly using the expected lived experiences of a new design as a guiding principle for the next iteration. This feedback is useful already in the earliest stages of the design process (Campbell & Wells, 2003). Al-Douri (2010) mentions that VR can play an important role in “increasing designers' cognitive and communication capabilities and providing a platform for communicating design ideas among and across design teams that lead to wider involvement in the decision making” (p. 75), and specifies that the technology is particularly useful in the design phases where initial concepts are developed and refined into workable solutions, i.e. phase 4 and 5 in the model from Abd Elrahman & Asaad (2019).

Using VR in spatial design also has great potential for allowing the general public to more effectively participate in the design process. The possibility of adding, removing or in any other way flexibly adjusting a virtual model assists participants in comprehensively expressing and sharing their desired spatial vision (Fröst & Warren, 2000). The visual and sensory method of studying an area allows experts to better express their design ideas (El Araby, 2006), which reduces confusion and lowers entry barriers for participants who are not trained to interpret design documents and abstract models (Simpson, 2001). This more accessible and attractive communication method can be more enticing for community members to express their ideas, resulting in higher degrees of participation overall. The added level of transparency VR offers helps in creating trust and social acceptance among citizen participants towards the design, reducing the risk of conflicts and cautious attitudes during the process (Wanarat & Nuanwan, 2013).

2.5. The effect of model quality

The extent to which the benefits described above can be achieved is highly dependent on the technology used, as well as the context and purpose. A key aspect is the overall quality of the virtual environment and the capacity of the available technology to provide a simulation that sufficiently resembles a real-life experience (Azarby & Rice, 2022). VR technology is becoming increasingly affordable and accessible (Simpson, 2001), but higher-end systems and software that can more accurately and smoothly render large quantities of data might yet be unaffordable for smaller design firms (El Araby, 2006). The technology may be finicky, requiring carefully set up workstations, software and data to even function properly. Small errors may result in a negative experience that achieves the opposite of the aforementioned benefits, as well as increase risks of VRISE occurring due to the inaccuracies between expected and actual visual feedback (Rebenitsch & Owen, 2016). These technical issues are expected to become of decreasing prevalence as the technology becomes ever more sophisticated, but the social reluctance to use such technology might still linger (Wang, 2007).

Another issue in the necessity for high-quality virtual models is the effect that the level of detail (LOD) of the virtual environment has on the extent to which digital models can effectively aid in spatial design. The concept of LOD can be described as a means to "define a series of different representations of real world objects, and to suggest how thoroughly they have been acquired and modelled." (Biljecki et al., 2014, p.1). Zhu et al. (2021), in comparing preferences for street renewal plans using both VR and conventional rendered images, concluded that a lack of realism of the digitally built environment can negatively affect the extent to which design participants see the virtual experience as a realistic one, which subsequently decreases the sense of spatial presence. Conversely, higher detail can stimulate more imaginative thinking. VR has been shown to be uniquely able to deliver such high levels of detail (Campbell & Wells, 2003). There are, however, drawbacks to maintaining such a high LOD. More detailed models can cause great strain on the machines used to operate them, particularly when moving around in them or adjusting the objects in it, which can cause crashes (El Araby, 2006). Additionally, polished models may give off a 'finished' look, which affects the extent to which designers perceive them as still being open for adjustments. Working with a lower LOD might stimulate more experimentation among users (Štefancová et al., 2020). Finally, a thesis by Hoeckner (2016) suggests that high levels of LOD can actually detract from useful discussions about spatial design when prioritizing the volumes of built objects rather than their appearance. The appropriate LOD needs to be chosen depending on context and purpose.

2.6. Spatial data analysis and VR in design

Murayama and Thapa (2011) describe how GIS and spatial analysis came to be in the realm of geography and spatial planning. GIS mostly took off in the '60s as a means to utilize spatial data to inform and support spatial decision- and policy-making. Quantitative analysis for exploring and determining spatial patterns and processes was particularly important. Compared to statistical or mathematical analysis tools, GIS was uniquely suited for efficiently handling georeferenced data. The most distinguishing features of GIS are performing large numbers of geographical calculations (e.g. mass, distance, area), determining patterns and causal relationships, creating and manipulating digital objects and their relations, and visualizing them with high degrees of flexibility (Murayama & Thapa, 2011).

Although GIS became widely used at higher levels of abstraction and geographical scale, the design side of spatial development was significantly slower in adapting to such data-driven analyses and meaningfully incorporating them into the design of smaller residential and commercial projects at the urban level (Sipes, 2006). For a long time design decisions have mostly been based on aesthetic considerations and the intuition of the designer, rather than data and past experiences (Gehl, 2010; Nisha & Nelson, 2012). This way of thinking tends to sideline the perspective of the prospective users of the space in favor of the goals of the client or the artistic vision of the designer (Nisha & Nelson, 2012). Gehl (2010) argued that this narrow-minded focus is not sufficient in effectively tackling challenges in the changing urban fabric, such as regeneration projects. The need to substantiate design decisions with data and opinions collected from end users is becoming more apparent (Dyer et al., 2017). This approach to designing has become known as 'evidence-based design', which Hamilton & Watkins (2008) define as "*a process for the conscientious, explicit, and judicious use of current best evidence from research and practice in making critical decisions, together with an informed client, about the design of each individual and unique project*" (p.9). In other words, it means using results from scientific research and experiences from practice in the designing and construction of a physical environment to achieve the best possible results. Both qualitative data, e.g. opinions and values, as well as quantitative data, e.g. wellbeing indices, can be considered useful data. With the advent of the Smart City concept, large quantities of user-generated and automatically collected data from urban residents can provide deep insights in the patterns of urban life, and how to optimize for them (Batty et al., 2012). This approach can better account for the subjective values of end users and directly connect them to the design by collecting public opinions in an early stage of the process. It is also useful for assessing the effects of physical determinants of the urban space, such as density, on its inhabitants using post-occupancy interviews (Dyer et al., 2017). This is a marked departure from the aforementioned focus on aesthetics and intuition, and introduces a design culture shift that planners and designers have oftentimes been reluctant to adopt (Nisha & Nelson, 2012). Utilizing new technological and pedagogical innovations in spatial learning early on in a designer's career can alleviate this adoption issue in the long term (Nisha, 2019).,

VR has potential for being used as tool for evidence-based design. City models are mainly being used for visualizations, but are also increasingly employed for a variety of end goals, which oftentimes require additional spatial information to be added to the 3D environments (Kolbe, 2009). Big data is becoming more relevant and sophisticated, and researchers are looking to VR to meaningfully visualize these potentially massive data sets and perform spatial analyses with it in an immersive 3D setting (Chandler et al., 2015). Because of this, the concept of VR-GIS has received much attention, particularly in the fields of geography and urban planning (Ma et al., 2010; Wang et al., 2018). HMDs have been the dominant utility for such endeavors since 2012, but as a result of the still volatile technology of VR, the full development of the integration of VR and GIS is still struggling (Fonnet & Prié, 2019). While existing VR-GIS systems are capable of performing spatial analysis functions, this has historically been underutilized in favor of merely revealing and visualizing the data (Ma et al., 2010). Zhao et al. (2019), in the field of earth science, used satellite imagery, terrain elevation data and a LiDAR data point cloud to recreate a volcanic system in an immersive and interactive format. They note that 2D data analyses do not utilize the full potential of 3D geodata sets, and recognize the usefulness of not only visualizing spatial data, but also allowing for active interaction and manipulation of such data, and performing quantitative analyses with it.

For urban and architectural design, a tool has been designed to bridge this gap in the form of the CityGML data format. CityGML is an internationally used standard managed by the Open Geospatial Consortium, especially adept at covering large spatial scales, i.e. the urban scale. It also prescribes certain standards for 5 different LODs (see Figure 2), and allows for GIS analyses in 3D objects (Kolbe, 2009; Ohori et al., 2018a). These standards make information easily exchangeable with other parties adhering to the same standards (Döllner et al., 2007). However, Biljecki et al. (2016) criticized the limited demarcation of 5 LODs, stating that the boundaries between them are too ambiguous. They expanded upon the framework with 16 unique LODs, incorporating the exterior geometry in the buildings to more strictly define the difference between one LOD and the next (Figure 3).

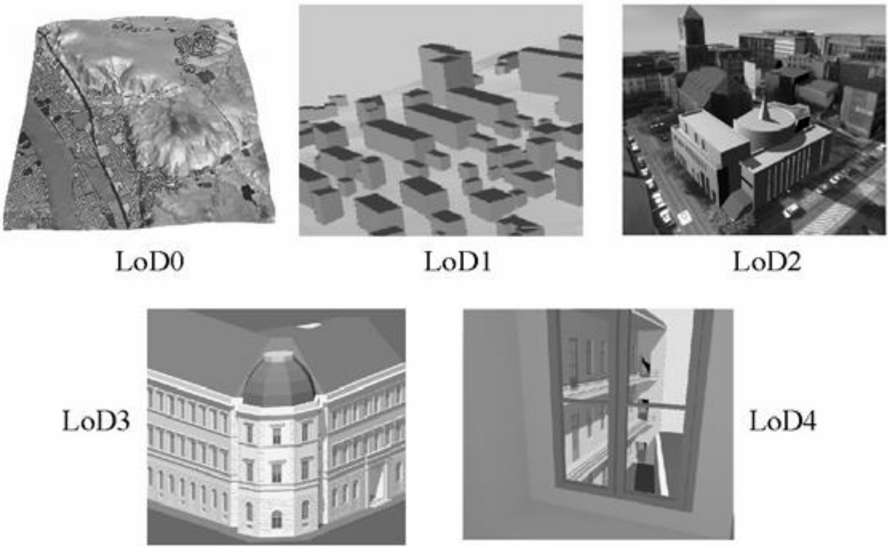


Figure 2: graphic representations of the 5 different LODs utilized by the CityGML format. Source: Kolbe (2009).

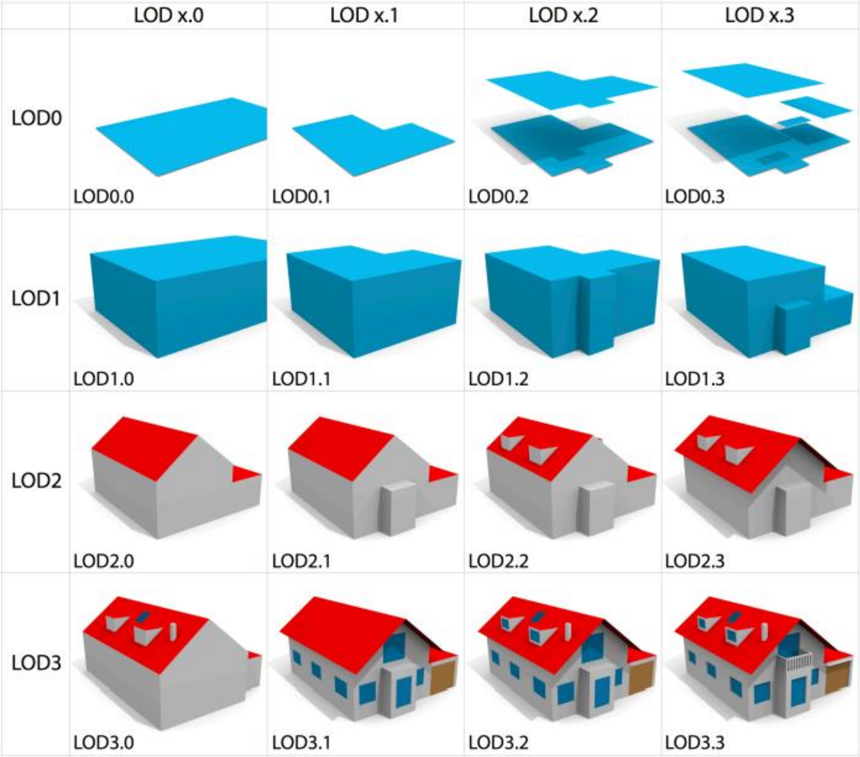


Figure 3: expanded LOD definition, incorporating the exterior geometry of the building. Source: Biljecki et al. (2016).

CityGML only represents a semantic definition for the basic entities of a city model and their relations, and allows for experts from other disciplines to add their own information to it (Kolbe, 2009). On the level of the individual building, Industry Foundation Classes (IFC) provide a similarly basic definition of building information modelling (BIM) data. Currently, research is being done on integrating these two formats to allow for GIS data analyses on individual buildings, and to make it easier for BIM experts to analyze individual buildings alongside their immediate context (Ohori et al., 2018b).

2.7. Conceptual model

Table 1 provides an overview of the tools discussed in this chapter, including what qualities they offer (interactivity, adjustability, realism, data accuracy and immersion). Figure 4 on the subsequent page depicts a conceptual model showing how designers use their interactions with a virtual model to iterate on design ideas. Based on the human-model interaction model by Robinett (1992, see Figure 1), a designer acts upon the virtual model, consisting of a city model with geodata sets attached to it (Kolbe, 2009). These actions either concern adjustments to the model itself (Thompson et al., 2006), or analyses and queries to the data in the model (Ma et al., 2010). The results of these actions are then processed by the model and displayed back to the designers (or other relevant stakeholders) who then express their opinions and provide feedback for additional adjustments or analyses (Moughtin et al., 1999; Yan & Tamke, 2021). Finally, once all involved parties are satisfied, the ideas are converted into plans to be implemented in the real world (Abd Elrahman & Asaad, 2019).

Tool	**Interaction**	**Adjustability**	**Realism**	**Data accuracy**	**Immersion**
Printed map	-Users can only look at the data provided on the map	-Hard to adjust once printed -On-the-spot drawings are possible, but often irreversible	-Limited to top-down view -Potentially highly realistic	-Suitable for exact measurements	-No immersion
Digital map	-Users can look at the data provided on the map -Zooming in and out is possible	-Visualizations and data sets can be changed	-Limited to top-down view -Potentially highly realistic	-More complexity as data amount increases -Suitable for exact measurements	-No immersion
Geographic information systems (GIS)	-Users can display spatial data in maps -Zooming in and out is possible	-Spatial data can be added and manipulated -Maps and layouts can be created	-Mostly limited to graphical representations of data	-Highly accurate spatial data derived from measurements -Complex spatial analyses can be performed -Accurate scale and geographic projection	-No immersion
Physical 3D model	-Users can look at the model from multiple perspectives from a bird's eye view	-Hard to adjust once constructed	-3D modeling possible -Potentially highly realistic -More detail means more costly to produce	-No data attached to model	-No immersion
Desktop digital model	-Users can look at the model from multiple perspectives -Users can move through the model as they see fit -Users can look around freely using buttons	-Users can adjust objects freely (scale, rotation, position)	-3D modeling possible -Potentially highly realistic -Higher LOD means more processing power needed	-Data can be attached to digital objects	-Limited immersion; user looks at design from a screen -Head movement not tracked
Immersive (VR) digital model	-Users can look at the model from multiple perspectives -Users can move through the model as they see fit -Users can look around freely using head movement	-Users can adjust objects freely (scale, rotation, position)	-3D modeling possible -Potentially highly realistic -Higher LOD means more processing power needed	-Data can be attached to digital objects	-Users are immersed in the model through HMD which tracks head movement -Immersion depends on level of realism and quality of technology

Table 1: summary of design tools discussed in chapter 2. Source: author

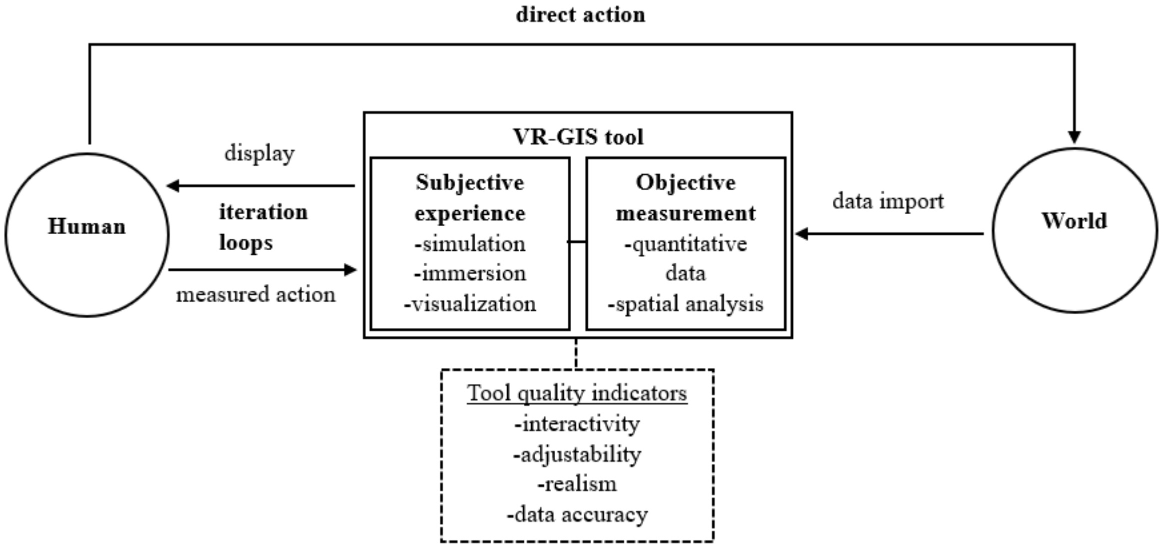


Figure 4: conceptual model showing how designers can combine VR and GIS in a single tool for use in the spatial design process. Source: author, based on Abd Elrahman & Asaad (2019), Azarby & Rice (2022), Campbell & Wells (2003), Fröst & Warren (2000), Hermund et al. (2019), Kolbe (2009), Ma et al. (2010), Moughtin et al. (1999), Robinett (1992), Thompson et al. (2006), Yan & Tamke (2021), & Zhu et al. (2021).

The immersion provided by the model helps the designer obtain a sense of spatial presence, which helps assess the actual size and scale of the design (Azarby & Rice, 2022). The extent to which the VR tool aids in this, however, is highly dependent on the designer's capability to naturally interact with and adjust the model as they wish (Campbell & Wells, 2003; Fröst & Warren, 2000), the adequate level of realism (Hermund et al., 2019; Zhu et al., 2021) and the accuracy of the model and its spatial data (Thompson et al., 2006).

2.8. Debates on measured and perceived urban density

This section will delve into the concepts of density and openness, and the discourses on how they are perceived differently by different people. Density is a prevalent theme within discourses on 'good' spatial design. In debates on how to make cities more sustainable and prevent urban sprawl, increasing density to reduce the need for polluting transport is an oft-proposed solution (e.g. Fisher-Gewirtzman, 2018; Khavarian-Garmsir et al., 2023). However, merely looking at certain density measures does not give a proper indication of what the urban form will look like. Alexander (1993) notes that density measures are an important asset in a spatial designer's toolset for guiding and measuring their designs, but that their assumed connection to urban form has become unclear. Berghauser Pont and Haupt (2005) support this, stating that there are multiple possible interpretations of how density is supposed to be calculated. For example, the popular measure of "Floor Space Index", i.e. the ratio of total floor area to total plot area, says little about how much space there is for every person living in a certain area when taken in isolation (Shirish et al., 2007). It also does not provide a meaningful insight in how people will experience the area once it is completed. Even small adjustments to the urban form can have effects on how the density of the area is perceived, and subsequently, to what extent people find an area desirable to be in (Fisher-Gewirtzman, 2018). Tang et al.

(2019) found that the mechanisms of how humans interact with their space tend to be chronically oversimplified by spatial planners and designers.

Density as interpreted and calculated by experts can differ greatly from what lay people experience as a 'dense' urban area. Zacharias and Stamps (2004), in their study on perceived density as a function of building layout, found that similar levels of built surface area are perceived differently based on the cumulative gaps between each building. Even if larger gaps resulted in taller buildings, density was generally perceived lower as cumulative gap increased. Hur et al. (2010) confirmed this, saying that physical density is less of a determinant factor of neighborhood satisfaction than people's perception of openness. It should be noted that they did not include building height in their analysis. Mousavinia et al. (2019) determined that form, design and layout of the buildings play a more decisive role in perceived density for non-experts than quantitative measures. It seems that although many authors have attempted to capture the idea of density in numerical values (e.g. Berghauser Pont & Haupt, 2005), those indices do not appear to be sufficient in properly assessing the concept of density in a way that will yield desirable results for prospective visitors of an area down the line. Despite this, urban design researchers still recognize the value of quantitative density indicators, and are continuously coming up with innovative ways to make them less opaque and link them to perceived density (e.g. Bolton, 2021; Steurer & Bayr, 2020). Supplementing such quantitative measures with qualitative data on perceived density can create a better understanding of how spatial interventions influence people's experiences, which Hur et al. (2010) deem important.

3. Methodology

3.1. Purpose and approach

As this thesis serves to understand how VR can aid in creating and evaluating spatial designs, the data collection method should reflect this. Based on the elements of the VR tool that affect its capacity to assist in the design process, the data collection method aimed to simulate such a process in which VR is used as the primary design tool. A qualitative research approach was taken, considering the importance of human perception and opinions in this experiment, and how qualitative methods are uniquely suited for these types of research settings (Punch, 2014).

3.2. About the tool

The VR system used for this research was a head-mounted display of the model Oculus Rift. This model supports the creation of a fully immersive experience by limiting the vision of the user exclusively to the digital environment presented in the screen. Internal accelerometer, gyroscope and magnetometer track the movements of the user's head, which are matched by the movement seen in the display. Users could interact with objects in the environment using the two wireless controllers provided with the HMD.

The software used for this research was a concept version of a program developed at the University of Groningen, using the Unreal Engine. This program allowed for importing data sets in OBJ file formats, generating individual objects which could be worked with. Users were able to move and teleport through the area using the controllers provided with the Oculus Rift system. Users could zoom out for a bird's eye perspective, or zoom in all the way to ground level to experience the design from a perspective closely resembling a pedestrian. Using the controllers, users could select individual objects and adjust their rotation, scale, height and location at will. Objects could also be deleted completely. The software was also connected to an instance of ArcGIS Pro for spatial analysis to run in the background. Users could make an export of the objects, and set a floor height to determine how many floors each building approximately has. Once an export was made, an area needed to be selected to perform calculations on. Users could create their own selection polygon within the VR environment, or load a pre-saved selection polygon from the software files. For the purpose of this research, a predefined selection polygon was used to reduce inconsistencies between participants' experiences. Once the area was defined, users could opt to calculate GSI, which only takes the footprint of the building into account, or the FSI, which also incorporates the floor height determined when exporting the objects. For this research, a floor height of 3 meters was assumed.

The OBJ data set imported into this tool was derived from the 3D BAG, which is an open data set containing 3D models of every building in the Netherlands. The data can be downloaded in tiles, which cover small or large sections of an area, depending on whether they represent city centers or more sparsely populated rural areas (3D Geoinformation, 2023). This data set is available in multiple data formats, making it flexible to be used in a variety of software applications (3D Geoinformation, 2023). The objects are also available in multiple LODs, using the expanded LOD classification system by Biljecki et al. (2016). For the purpose of this research, LOD 2.2 was chosen, because this level was deemed a proper balance between being abstract enough to minimize the distraction for participants, while still being able to distinguish different building types (e.g. single-family home vs. apartment building). It was also the highest LOD that the 3D BAG supports (3D Geoinformation, 2023). This has consequences for the achievable level of realism in this experiment: while LOD 2.2 defines some of the exterior features, it remains a rather abstract representation of what the actual building will look like in real life. The conceptual nature of the building means that this specific tool is less useful in the later, more detailed design phase (Abd Elrahman & Asaad, 2019), and is most likely more suitable for the conceptual design phase where volume and mass are important considerations (Hoeckner, 2016). Furthermore, this affects the extent to which the virtual space represents a real-life situation, and subsequently to what extent the participant can obtain a sense of spatial presence (Zhu et al., 2021). This aspect will have to be taken into account when the results are discussed, particularly when put in the broader context of the design process as a whole.

3.3. Participants

Because quantitative expressions of density are rather specific knowledge that only specialized people are expected to know about (Alexander, 1993), this experiment was performed by students and academic staff (teaching and research) in the field of spatial planning and design. Having background knowledge of the concepts was also expected to more educated and confident design choices (Dobbins, 2009). A downside is that the data will not be representative for the entire population. Experiments that specifically include the opinions and experiences of laypersons in their research design are more suitable if representativeness is desired. As mentioned before, density measures are specialist concepts (Alexander, 1993); therefore, representativeness was not a priority in this specific research. This will be elaborated upon in chapter 7. A total of 5 people participated in this research, of which 3 were students, and 2 were scientific staff, all studying or working at the Faculty of Spatial Sciences of the University of Groningen where this research was conducted. Details of the participants are shown in chapter 4.

3.4. Data collection methods

For setting up the VR environment and its objects, tile number 3007 was imported from the 3D BAG data, which corresponds to an outer city area of the Dutch city of Delft. This tile was deliberately chosen for the following reasons. First, as this research is performed by people who live, work and/or study in the city of Groningen, it was deemed desirable that there are no preconceptions regarding the study area that could influence the participants in their decision making (e.g. recognizing a historic building that is perceived to be of cultural value and therefore should be preserved). Second, as the current tool does not provide a way to add new buildings into the environment, having a variety of building types already present in the area and its surroundings gives the participants more design options when creating their own vision, rather than being restricted to a small selection variety. Third, it was preferable that the buildings were simplistic enough to be workable. Due to inaccuracies in the generation of the 3D BAG data, inner city buildings are oftentimes represented as oddly shaped objects that could be difficult to realistically fit in an area other than where it was originally located. Additionally, inner city layouts have a ‘finished’ appearance that might deter participants from interfering with it. A building’s shape could also hint towards a specific function; e.g. industrial buildings are easily recognizable by their large footprint, or the presence of high smokestacks. This might give participants certain preconceptions about where a specific building should go, or to what extent it can be adjusted. Therefore, an area was selected that has identifiable housing blocks, but with relatively simplistic objects that can easily be detached from one another without breaking apart the entire urban fabric.

Before the session had started, a survey was provided to the participants via Google Forms, in which they could state their age, gender and current occupation in the field of spatial planning and design, being either student or researcher. Additionally, a number of questions regarding previous expertise in the domains of VR, 3D modeling, spatial analyses in GIS, geodata, spatial design and density measures were asked (Appendix A). This information will be used to compare the results within their occupation groups and levels of expertise, and reflect on how they approached the design session.

The session consisted of two major parts: in the first part, the participants experimented with the VR tool to explore the practice of designing in virtual reality, as well as getting a feeling for perceiving and measuring density. The second part consisted of a focus group in which the researcher and the participants discussed their experiences from the design session.

3.4.1. Design experiment in VR

The participants received an introduction to the research topic, as well as a quick tutorial on how to use the HMD to navigate through the virtual environment and make adjustments to the buildings. After this demonstration, the participants were assigned a computer to work on, and simultaneously started with the design tasks (Appendix B). The design session can be divided in 4 parts, which will be described below:

Exploration phase (7 minutes): the participants were provided with a pre-built design concept within a predefined study area. The participants were able to explore the environment and become familiar with the VR technology and the virtual environment, as well as the contents, layout and scale of the study area and its surroundings. In this phase, no adjustments were made to the area. While they were exploring and getting used to the environment, they were tasked with making an estimate of the FSI of the study area, and providing a score for the perceived openness of the area. This score could range from 1 to 10, where 1 represented a very confined area and 10 represented a very spacious area. After the 7 minutes, participants filled in their FSI estimate and openness scores (Q1 and Q2), after which they used the built-in FSI calculation tool to accurately measure the FSI of the study area (Q3). This exercise served to highlight the difference in perceived versus measured density as discussed in chapter 2.8.

Design phase (20 minutes): In the design phase, the task of the participants was to increase the study area's density to 1.5, while preserving a similar sense of openness. To this end, participants could manipulate buildings' size, height, position, and orientation. The FSI calculation tool aided participants in receiving feedback on the target of a value of 1.5. Participants had to record its usage frequency (Q4). At the end of the phase, participants noted their final FSI value (Q5) and rated the openness of their new designs (Q6). These variables served to compare the different designs. The final design was saved and used for feedback in the next phase.

Feedback phase (5 minutes): directly after this, the participants evaluated the design of one of the other participants, and once again made an evaluation of the openness of the area (Q7). They were also asked to compare their colleague’s design with their own, and provide some comments on the differences between their approaches and results (Q8). This resulted in two different opinions and perspectives for every design, which allowed for comparisons to be made in how people perceive density differently from one another.

Evaluation phase (5 minutes): after finalizing their comments on their colleague's design, the participants were asked to fill in a review form. This form served to inquire the participants on the extent to which the tool enabled them to carry out their assigned tasks. The questions were aimed towards evaluating the concepts as mentioned in the conceptual model, in terms of interactivity (Q9), immersion (Q10), spatial awareness (Q11-Q13), data measurement and accuracy (Q14) and, crucially, the feedback function of VR (Q15-Q17). Answers were rated on a Likert scale ranging from "strongly agree" to "strongly disagree", similar to the questions in the pre-participation survey. While this method of ranking would allow for statistical tests to be carried out on the given answers, the low number of participants raises representativeness issues. Instead, the answers given to these questions served as supportive input for the focus group session.

3.4.2. Focus group

The second part of the experiment was a focus group session, in which the researcher conversed with the participants about how the design tool aided them in expressing their spatial vision. The quality indicators and the feedback function of VR, described in the conceptual model and addressed in the evaluation phase of part 1, were the focal point of this discussion, while also allowing for overall experiences to be shared. The question guide used by the researcher can be found in Appendix C. This guide was not a strict order; the conversation was allowed to flow freely, and the question guide served as a general guidelines of topics to be discussed. Discussions were recorded and transcribed to create a textual dataset. Then, they were deductively coded based on predefined criteria, in this case, tool quality indicators and feedback mechanism from the conceptual model. Other reoccurring topics were then inductively coded. Coding was done using ATLAS.ti software, according to the coding system found in Appendix D. This approach allowed the systematic categorization of data into themes or groups, facilitating the identification of patterns and trends during the analysis phase. It was a clear and structured way to distill complex qualitative data into meaningful insight, from which relations, patterns and trends can be discerned during the analysis phase (Punch, 2014). The discussions will provide useful insights in how VR can be utilized in a design process, which will be reflected upon in the light of the literature discussed in chapter 2.

3.5. Ethical considerations

Before the experiment starts, participants were asked to sign a consent form which explained the purpose of the research and confirmed their explicit written consent to participate in the research. The form also stipulated their rights to withdraw from the research at any point and have all their personal data deleted if they so desired. Contact details to the researcher and their supervisor were provided, through which participants could ask any questions. The designs created in the experiment were saved, and the discussions from the focus group session recorded, solely for the purpose of this research, and were handled anonymously in the writing of the research report. All personal data is to be deleted once the research is concluded. The participant information sheet and consent form can be found in Appendix E and F respectively.

Additionally, as HMDs are known to contain a higher risk of causing VRISE compared to other virtual environments (Sharples et al., 2008), participants were warned of these effects before being allowed to work in the VR environment, and were occasionally reminded of this. Participants were reminded that they could take off the HMD at any point, should these effects occur. After such an event, participants were asked whether they wanted to immediately continue, take a small break, or end participation altogether.

4. Results

This chapter will show the results from the digital forms filled out by the participants, and the discussions from the focus group sessions. Discussions regarding these results will be handled in chapter 5.

4.1. Data from participant survey

The following section will go into the data generated by the participant survey that was sent to all participants to be filled in prior to the design sessions. In total, there were 5 participants over 2 sessions: 3 students (R1, R2 & R3) and 2 staff members of the University of Groningen (R4 & R5). One participant (R1) did not fill in this survey due to communication errors, so apart from gender and occupation, no data is available for their age or previous experiences. Table 2 below details the personal data from the participant survey.

Participant	*R1*	*R2*	*R3*	*R4*	*R5*
Age	?	22	23	31	41
Gender	M	F	F	O	F
Current occupation	student	student	student	staff	staff

Table 2: participants' age, gender and current occupation within the field of spatial design. Source: author

Table 3 shows the scores that the participants gave regarding their previous experiences with VR, 3D modeling, spatial analyses in GIS, geodata, spatial design and density measures (1 = strongly disagree, 5 = strongly agree). As seen in this table, none of the participants score above 3 (neutral) when it comes to feeling comfortable with using VR devices, and most participants answered 'disagree' on this statement. This is further highlighted by the fact that all participants answered 'strongly disagree' on the statement of having used VR often in their study program or work. This accentuates the fact that VR technology has not yet become a widely integrated method in the toolkit of spatial designers and education.

Quantitative building density measures are a familiar concept to most participants. While R5 responded with 'strongly disagree' and asked during the session what Floor Space Index meant, one other participant mentioned it also being known as Floor Area Ratio (FAR), to which R5 appeared to show more familiarity with the concept.

Participant	*R1*	*R2*	*R3*	*R4*	*R5*
I feel comfortable using VR devices	?	2	3	2	2
I have often used VR in my study program/work	?	1	1	1	1
I am experienced with using 3D models in my study program/work	?	4	1	5	2
I know how to perform spatial analysis tasks with GIS software, e.g. ArcGIS or QGIS	?	5	4	5	3
I am familiar with geodata such as the Dutch BAG	?	5	1	5	1
I am a professional in spatial design	?	2	1	5	5
I am familiar with building density measures such as Floor Space Index (FSI)	?	5	3	5	1*

*Table 3: previous experience of participants in relevant fields. Source: author. *: showed more familiarity once FAR was mentioned as an alternative term for FSI.*

4.2. Data from design sessions

The following section is an analysis of the data derived from the answer form filled in by the participants during the design session, separated by the different phases of the session as described in chapter 3.4. The results from the evaluation phase will be supplemented with the focus group session data.

4.2.1. Exploration phase

The answers to questions 1, 2 and 3, related to the discrepancy between perception and calculation discussed in the theory, are displayed in Table 4 below.

Participant	***R1***	***R2***	***R3***	***R4***	***R5***
Q1: estimated FSI	1,2	0,5-1,0	1,5	1,2	0,95
Q2: openness score	7	8	8	5	9
Q3: calculated FSI	0,752	0,734*	0,712**	0,752	0,752

*Table 4: answers given by participants on questions 1, 2 and 3. Source: author. *: unusual outlier of which the cause is unknown. **: due to unexpected technical issues, the calculations on R3's computer were faulty.*

For question 1, answers range from 0,5 to 1,5, with the lower end being part of a ranged answer rather than a singular answer. When looking solely at single-point answers, all participants estimated FSI to be above its actual value of 0,752. Of note are the outlying answers given to question 3, that being 0,734 from R2 and 0,712 from R3. Regarding R2, it is unknown how this error was caused. Regarding R3, an unexpected technical issue made her unable to perform proper calculations. Regardless, the differences between the erroneous calculations and the expected value are not considerably large, and are therefore deemed not detrimental to the research.

Regarding openness scores given in question 2, answers range from 5 to 9, with most participants considering the neighborhood to be rather spacious. Only 1 participant (R4) graded the openness of the area on the lower half of the spectrum, considering it a little confined. Interestingly, the participant with the lowest singular FSI also has the highest openness score, but this pattern was not consistent across the sample.

4.2.2. Design phase

Moving on to the designing phase of the workshop. Table 5 shows the results of questions 4, 5 and 6. Relating the number of calculations to the final FSI levels and the target FSI level of 1,5, it becomes clear that more calculations correspond to more closely reaching the target. The largest difference is found with R3, who was unable to perform any calculations at all, and overshot the target by a wide margin (1,392). The second-largest difference is found at R4, who only made one calculation at the end of the allotted time, and ended up with a difference of 0,668. After that is R2, who made 2 calculations and ended up with a difference of 0,379. R1 and R5 both made 4 calculations, and ended up with differences of 0,122 and 0,01 respectively.

Participant	*R1*	*R2*	*R3*	*R4*	*R5*
Q4: how often did you calculate the FSI?	4	2	4*	1	4
Q5: final calculated FSI	1,378	1,121	2,892**	0,832	1,51
Q6: openness score	6	7	6	5	7

*Table 5: answers given by participants on questions 4, 5 and 6. Source: author. *: no actual calculations were performed; participant instead provided estimate number of checks. **: calculated by author at a later time for completeness.*

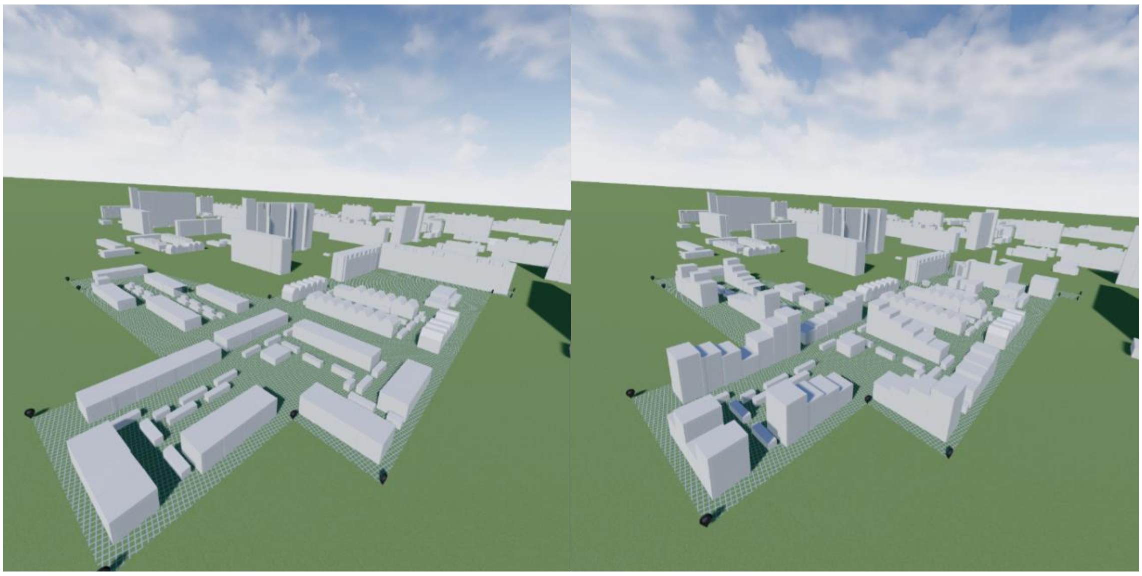
Figure 5 on the next page shows an overview of the different designs the participants came up with, together with the base design and their respective FSI levels. The Figure shows a multitude of different approaches to the design task, but some recurring patterns can be discerned. The participants tended to adhere to the original layout of the area, and resorted mostly to increasing or decreasing heights of certain buildings to adjust density and create variation. Some buildings have been replaced with other buildings from the surrounding area, but were oftentimes put in the same location as the original to retain the general layout. While the participants had full creative freedom to redesign the area as they saw fit, this potential does not seem to be utilized in full. The most variation can be found in the section with the large apartment building, which also contains the largest section of unbuilt area. Figure 6 on the subsequent page shows how an overlap count of all the buildings in the area. On this map, it becomes clear that the most overlap is found among the small row houses, whereas the area with the apartment building shows more variety.

R3 and R5 opted to raise the apartment building to increase density, while R1 removed one section and added new buildings instead. R2 and R4 left the building as is, but filled in the open square with additional buildings. From these observations, it would appear that open, unbuilt areas are more inviting to work with than areas which already have buildings placed on them, despite having the ability to move or delete those buildings at will.

At the same time, openness scores generally decreased across the board, with the sole exception being R4. Table 6 shows and the changes of both FSI and openness scores per participant. Again, a clear pattern appears: the 2 largest increases in FSI also produce the largest decrease in openness score (R3 and R5), and the same goes for the smallest changes (R4), with R1 and R2 having moderate changes to both. This is not a linear pattern, however, as the decrease in openness score for R3 is only -2, whereas a much higher decrease is to be expected were it a linear trend.

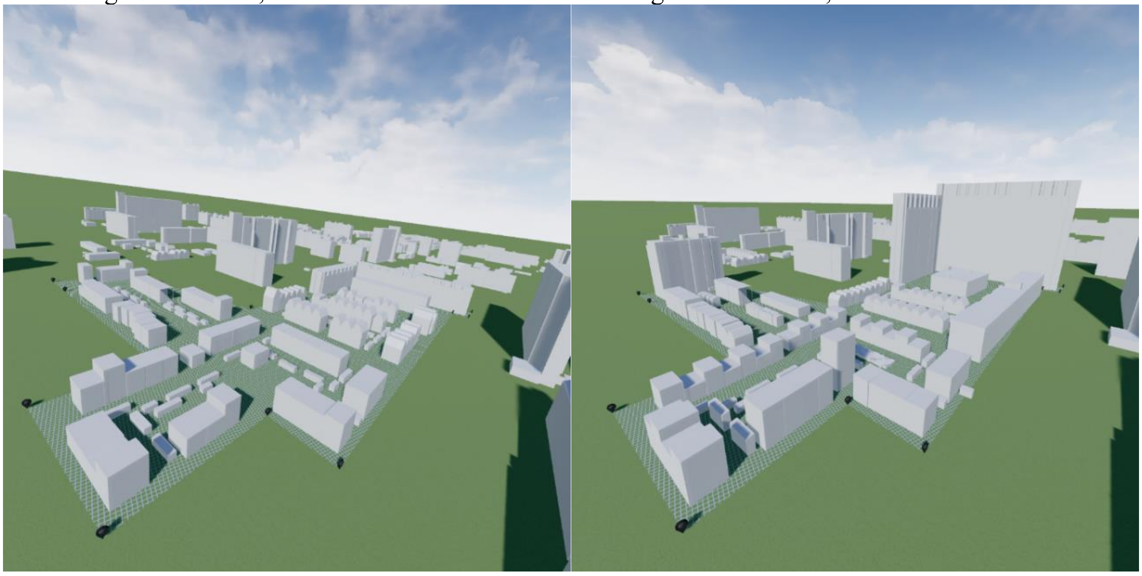
Participant	*R1*	*R2*	*R3*	*R4*	*R5*
Q3: FSI original design	0,752	0,734	0,712	0,752	0,752
Q5: FSI new design	1,378	1,121	2,892	0,832	1,51
difference	**0,626**	**0,387**	**2,180**	**0,080**	**0,758**
Q2: openness score original design	7	8	8	5	9
Q6: openness score new design	6	7	6	5	7
difference	**-1**	**-1**	**-2**	**0**	**-2**

Table 6: changes in both FSI and openness scores. Source: author



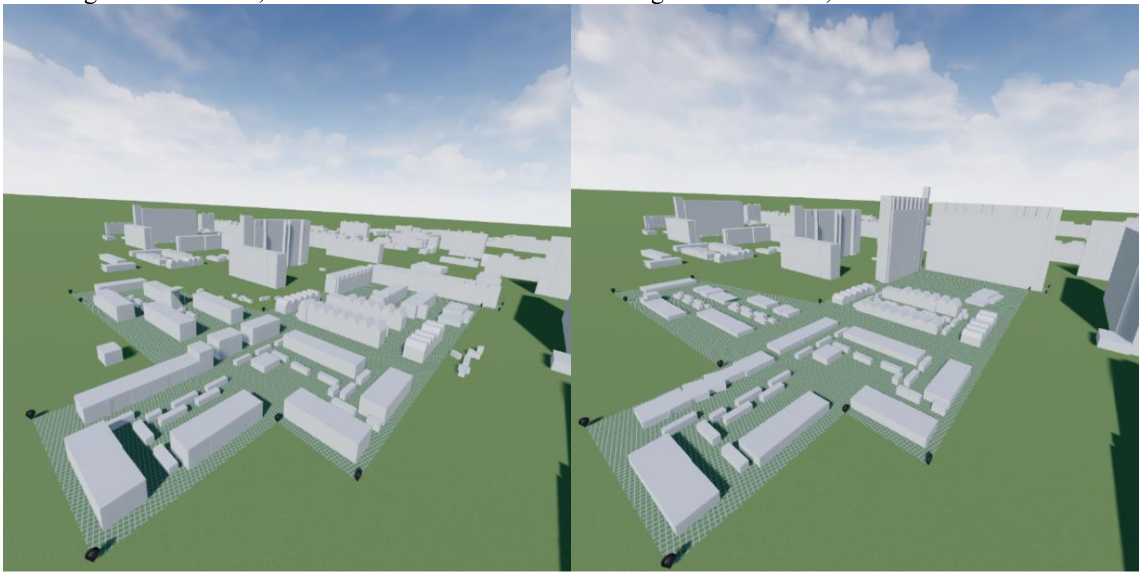
Base design FSI: 0,752

R1 design FSI: 1,378



R2 design FSI: 1,121

R3 design FSI: 2,892



R4 design FSI: 0,832

R5 design FSI: 1,51

Figure 5: all designs with their FSI levels, including the base design. Source: author

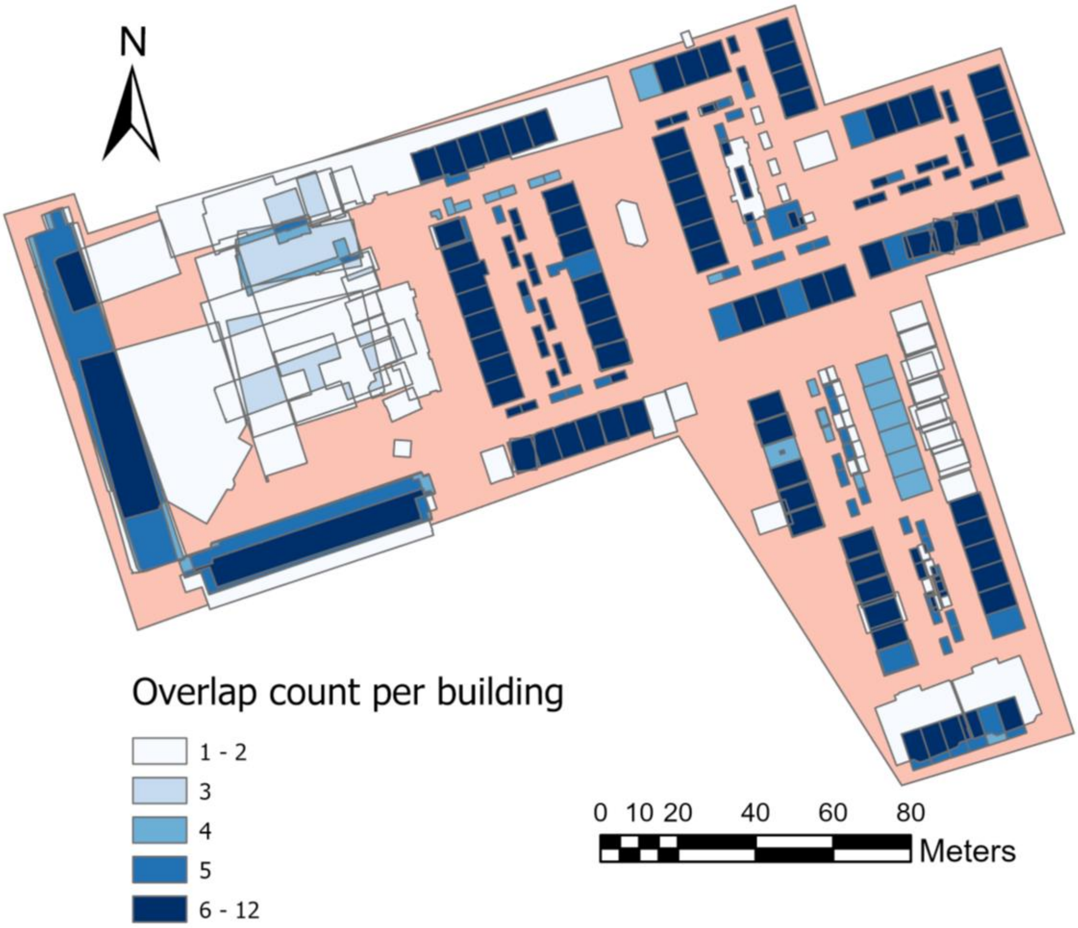


Figure 6: overlap count per building section. Source: author

4.2.3. Feedback phase

During the feedback phase, participants evaluated the openness of each other’s designs, the results of which can be seen below in Table 7 compared to the original designer’s score. While no clear relation between these openness scores and those given on each participant’s own designs can be discerned, it does serve to indicate how openness is a matter of perception that differs per person.

Participant	***R1***	***R2***	***R3***	***R4***	***R5***
Q6: openness score new design	6	7	6	5	7
evaluated by	R2	R3	R1	R5	R4
Q7: openness score from colleague	4	9	8	6	6
difference	**-2**	**2**	**2**	**1**	**-1**

Table 7: differences between self-scored openness and scores from colleagues. Source: author

4.2.4. Evaluation phase

Table 8 below shows how the participants evaluated the various benefits that the VR tool was hypothesized to provide, using a Likert scale ranging from ‘strongly disagree’ to ‘strongly agree’. The answers to these questions will be discussed in the following sections, together with the focus group results.

Participant	***R1***	***R2***	***R3***	***R4***	***R5***
Q9: I was able to freely interact with the objects in the VR model as I saw fit	3	3	3	2	3
Q10: I experienced a sense of immersion in the virtual environment	5	5	5	2	4
Q11: I was able to get a feel for the actual scale and size of the spaces and objects	5	5	4	4	4
Q12: I could get a good sense of the density of the built environment	4	4	5	3	5
Q13: I could get a good sense of openness of the built environment	4	5	5	4	4
Q14: I was able to make accurate measurements using the tool	3	4	2	4	4
Q15: After making changes in the design, the feedback of spatial measurements (FSI score) helped me to make decisions in the design process	5	4	1	1	5
Q16: After making changes in the design, the feedback from my experience in the virtual environment (perception of density and openness) helped me to make decisions in the design process	4	5	4	3	5
Q17: The interplay between experiences in virtual reality and spatial analysis of the built environment helped me to make decisions in the design process	5	4	4	4	5

Table 8: evaluation of benefits of VR in spatial design. Source: author

4.3. Focus group

Here, the discussions from the focus group sessions will be analyzed, using the organization of quality indicators discussed in the conceptual model and according to the code book in Appendix D. These will be used to reflect upon the answers to the evaluation phase questions summarized in Table 8. Additionally, participants’ overall experiences with working in VR will be discussed.

4.3.1. Interaction (Q9)

Participants were not very positive on the extent in which the tool enabled them to freely redesign the area, with most participants answering ‘neutral’ and one person answering ‘disagree’. In general, participants appreciated the ability to easily change the heights of each building to adjust the density of the area. Many participants opted to raise the existing buildings rather than importing new ones, as can be seen in Figure 5 and Figure 6.

The reluctance of participants to bring in new buildings from the surroundings appears to stem mostly from the limited controls of the software. For example, multiple participants commented on the lack of precision for moving buildings in the specific spot:

> *“I think it’s not super precise; I had trouble moving stuff in their exact spot that I wanted it to be; I don’t know, maybe there was a ‘place’ button but I’m not sure; but that also felt slightly limited if you want to make the most precise thing.” -R2*
>
> *“I totally agree that it was very wobbly to put it somewhere. I didn’t follow the lines of the roads or the buildings, for example.” -R3*

Moving buildings relies on hand movement, which is difficult to keep perfectly still to place a building in a very specific spot. There was no function to move a building along a certain axis or by certain increments using a button, which R2 and R3 suggested would greatly help in making more precise designs.

The extent to which a building could be moved in one motion was also limited compared to the freedom of moving oneself around. This could make bringing in new buildings from the surrounding area rather cumbersome, especially if they were located along the edges of the tile.

> *“The one thing that I found really difficult that would’ve really changed my ability to design is moving things and teleporting. I felt like I wanted to often go quite a bit further than the software would allow me.” -R4*

This was exacerbated by the lack of a function for creating new objects, whether by copy and pasting an existing object or generating an entirely new object, or editing the general shape of existing objects.

> *“I think what would be great to see…like, in SketchUp there is a tool where you can place a square and just extend it or just place it…yeah, more flexibility in creating figures or something.” -R1*
>
> *“In terms of the tool, I think copy-paste options or [...] being able to modify the shapefile in terms of adding instead of just grabbing from the sides, [...] I think that makes the process easier.” -R2*
>
> *“I wanted to play around more with the blocks, for instance, it would be nice to open punctures in these big blocks in the MVRDV style. So more can be done with the design.” -R5*

Another common criticism was the inability to adjust or move multiple buildings at once, making adjustments to long rows of houses a lengthy task and thereby disincentivizing participants from working with these sections:

> *"What I'd also like is to select more things, so if I want to move this whole row of houses or delete a whole area I have to do it individually, which is time-consuming."* -R3
>
> *"Not being able to make multiple selections was a limitation."* -R5

If such a function were available, it could encourage participants to make more adjustments to the sections of the area where row houses are prevalent. Instead, as can be seen in Figure 5, these areas have almost exclusively had their individual heights adjusted, with their overall layout generally being left as is.

As mentioned before, the most variation in building arrangement was found in the empty space close to the large apartment building. One participant mentioned how in past experiences, working with empty space rather than already existing objects inspired more creativity:

> *"In the atelier, you start from scratch, so we choose areas that don't have so many buildings, or maybe none, even. So it's not really about modifying the current environment, maybe a couple buildings, but you have a lot of freedom creating completely new buildings."*

This could indicate that having a pre-built area limits creativity, because people are more inclined to stick to a layout as it is presented to them, despite being able to clear out this original layout entirely if they so desire.

4.3.2. Immersion (Q10)

Scores for Q10 ranged from 2 to 5, with 5 being the most chosen answer. Overall, participants appreciated the feeling of seeing the buildings around them as a pedestrian would. One participant, relating to past experiences in 3D modeling and design exercises, commented on how it is hard to make judgments on livability when there is no way to experience the built environment from a pedestrian point of view:

> *"The exercise was to make a livable, dense city, and the livable part means: how does it feel like to be there? But because many people are not familiar with the 3D modeling, they would just say: okay, we put a 12-floor building over here, and then it was hard to…without a tool like this, to actually say: hey, but imagine being there and you're looking to your left, then you have the farm, and then you're looking to your right and you have the tiny coffee place and then you have this giant tower."* -R2

R4 commented on how the easily attainable sense of immersion could help students make more realistic design decisions, rather than assuming the unrealistic position of an all-knowing designer who automatically assumes that all design interventions would be received well by the public:

> *"You're like: I want to do this, and then you're like: okay wait, but what actual impact on the ground does that have? So I think being able to just… *makes a sweeping motion* and you're there and you're in it, it helps to change that…you know: 'oh, this will work, this will work and this will work', because you can immediately see when it doesn't."* -R4

For both, it appears that the sense of immersion that VR can provide aid in making more informed and realistic design decisions. However, both staff members remarked that this added experience would be most beneficial to beginner-level students and designers, because they believe professionals are more experienced in making designs suitable for end users even with traditional design methods:

> *"If you are a professional designer, then you'll see it doesn't matter much to work in SketchUp, VR or even with hands-on modeling, but maybe for students who are experiencing this for the first time, really being inside the environment really helps. I think in its current form, it's more beneficial for beginner level students and designers; that would be my first reaction."* -R5

> *"I think for me, the key difference between this and something like SketchUp is that I could just more easily stand in the middle of the space and exert, right? So I think the fact that you can shoot something and just be like *shooting noises* and you see it and you feel it go up around you, I think that's the key difference. But in terms of who that's more beneficial for, I think definitely someone starting out more than someone a little more developed."* -R4

R5 later added to this, stating how an immersive experience provides a better feeling for the area and its size than a desktop monitor can provide, and once again reiterated how this is especially useful for beginners:

> *"Maybe one more difference with SketchUp or similar software, which is: there you have the limits of the screen, which is quite problematic, especially to get the early or beginner level design students to get the feeling of the scale. But now you have a more realistic human-eye, horizontal kind of view, so that definitely helps to get a grip of what they are doing, so I think that would be the main difference that I would like to address."*

The relative lack of detail, both in the data itself and in the supporting graphics implemented in the VR software, tended to break the sense of immersion for some. R3 mentioned how some objects did not appear to be the size one would expect from real life:

> *"If I zoomed in completely and put myself in the position of a pedestrian, I don't think it was very presentable, like, the height, because I compared it to the bike sheds and I could look over them."* -R3

However, R4 remarked that this low level of detail is actually beneficial for experimentation purposes. They mentioned that already having a high-quality impression of what the area could potentially look like might set certain expectations, inhibiting creative freedom.

> *"The benefit to having it lower-poly is that you're a lot freer to move stuff around, you don't have roads in your way so you can just plonk buildings, and just mess stuff up. [...] if things already look perfect and neat, then you don't want to interact with that because you don't want to mess it up, or you think you have to make something of the same quality. The lower quality it is, I personally feel, the more likely you are to just be like: oh, what if I just…[try different things]." -R4*

R1 noticed that some of the buildings seemed to float above the ground plane. R4 remarked on how that affected their feeling of the built area as a whole:

> *"The hovering above the ground plane makes it kind of difficult, because also that moment where the building meets the ground plane and how that heaviness can make you feel, and especially when it's a very tall building, that's really important to the feel of it. So having that image that it was sort of floating was less beneficial." -R4*

4.3.3. Experiencing the space (Q11-Q13)

Participants were almost unanimously positive about how the VR environment allowed them to obtain a feeling for the scale and size of the objects, and to perceive and estimate density and openness. For Q11, answers given were either 4 or 5, with 'agree' being the most chosen. R2, who had experience working with 3D models before, mentioned how she pays attention to the human scale when designing and that VR is better equipped to provide that sense of scale. She also related this to the aforementioned sense of immersion:

> *"I like doing 3D models and I always, like, through my laptop, run through them, like I'm in them to get the hands-on of what we were doing with the human-scale part and everything. And with the VR, it makes a huge difference." -R2*

R3 did mention, however, that she would have liked some extra details in the environment, such as infrastructure or street objects, as a means of reference:

> *"Maybe if I saw a lamp next to it, then I think I would be able to compare it more, but if I don't see the floors or windows, then I don't know how high I actually am." -R3*

Density and openness were usually discussed together, as they are closely related concepts. For Q12, answers ranged between 3 and 5, with most participants being above neutral. For Q13, the answers were either 4 and 5. 3 out of 5 participants had different answers for Q12 and Q13, indicating that these concepts were evaluated differently.

R2 remarked that the added ground-level perception and personal feeling of the area that this tool provides makes it more useful than GIS in terms of making assessments regarding openness.

> *"Definitely more useful than GIS, because you see it, and you can be like: I don't feel like this is open, or I do feel like this is open." -R2*

R5 mentioned that VR fares better than other design software because you are not fixed on one specific perspective, and instead have more freedom to look at the area from multiple perspectives with ease:

> *"In terms of guessing the density, I think it gave me a good sense. For instance, I'm thinking about other design software, I haven't used them for a while, by the way, but I call these 'distorted perspectives' that you use in SketchUp or 3ds Max or whatever, so it was quite distant and helped me to come up with an estimate, and that's an important part of design, you know, the kind of mass that you are suggesting or the density you're suggesting." -R5*

Despite that, it became clear that there is more to assessing density and openness than just the buildings. R3, returning to her previous argument of adding infrastructure or street objects for size reference, mentioned how this reference can aid in assessing whether an area could be considered open or not:

> *"It was just a green space, right? And I was like: OK, but how representative it is, there is no measure. [..] Because you just see white on the side and green here and blue up, so if there was at least a possibility to make a pavement or make a one-lane or something and then you see: this is quite open, two lanes can fit here, or just one. Some kind of reference." -R3*

Coinciding with this somewhat is an argument made by R4, who stated that not all open space influences the sense of openness in the same way, whereas the VR software displays all unbuilt space as a flat and empty field. They stated that having an idea of the different functions of the open space could be of assistance in assessing openness.

> *"I think something that would be key to at least understanding the environment is having an idea of the fabric, so: where do the roads go, where are parks, where are open spaces? Because I think that's also really important when you talk about the relationship between built and open form, it's also important to realize that not all open form is the same, and that changes the way we perceive our environment." -R4*

Another common topic was how light and shadow influence perception. In this version of the software, there was one singular light source (the sun) which could not be moved, meaning that all shadows were static. Being able to view the change in lighting throughout the day and seeing which places get more light than others were seen as important when trying to assess density and openness. Multiple participants agreed that this would be a useful additional feature.

> *"We were adding tall buildings and we weren't really sure how much shade it would create. So I think here, even though there was a shadow…I don't know what time of the*

> *day it was, or if it was summer or winter, so also it would be nice to see in future projects if this is used to like: okay, throughout the day, this is how the sun moves, so this is how the shade moves, so for example, these units will never have sunlight. [...] That would be my openness perception." -R3*

4.3.4. Data analysis (Q14)

The key aspect of the specific tool that has been used in this research is the ability to perform spatial analyses inside a VR environment, rather than having to resort to external programs. Opinions on this aspect were predominantly positive, ranging between 2 and 4. R3 was the least positive, owing to a lack of access to an instance of ArcGIS running the calculations in the background. R1 and R2 did have working calculations, and mentioned how this method of calculating is rather fast, as compared to previous methods where they had to calculate manually or set up a formula themselves in GIS. They viewed built-in calculation functions as comparatively more beneficial when the area under study is rather complicated.

R5 saw potential for other spatial analyses to be performed in this way, that could better utilize the immersive view that VR provides. She gave the examples of heat island effect analysis, which would require additional data on building materials, and accessibility analysis, in the sense of a spatial syntax.

> *"The combination of spatial analysis with the 3D model is quite promising. If you want to do more with, for instance, heat island effect or other analyses like accessibility, if you could have more layers, I think that would be quite impressive." -R5*

R5 also referred to how a similar method is used in the field of architecture using BIM. She felt being able to do quantitative analyses becomes especially important when taking into consideration guidelines and building codes. A requirement would be that the analyses can be carried out at a sufficient speed so as to not interrupt the workflow.

> *"There are, of course, rules that you have to comply [with] in the real world, [...] especially if you are working with building codes, then it becomes very important to calculate such measures. And this was quite handy, as you said. If it were 10 minutes or so, then you become distracted, but I think it works quite well in terms of the workflow between design and calculation." -R5*

R4 suggested adding functions for visibility analyses using isovists, but was otherwise more conservative in the kinds of analyses that would be useful to perform in VR. They mentioned that the accuracy of the data is vital in properly performing such analyses, and felt like this was hard to achieve within a VR environment compared to GIS.

> *"Honestly, to do a lot of those things, I would rather do it in GIS. You mentioned yourself, the building height scale was a little bit finicky, and it was very hard to be precise, and I feel like with some of these things you want to be quite precise about what kind of analysis you're performing. Personally, I wouldn't think too much in there, but I do think the relevance of isovists for example could be really cool."-R4*

Visibility analyses could potentially provide some calculable measure for openness. R2 was more reserved about this idea, however, stating that it could reduce an evaluation of the openness of the space to revolve solely around quantitative measurements. She felt this approach could potentially dehumanize the design process, if decisions regarding the quality of the space can be relayed to calculation tools rather than the informed perception of designers. While recognizing the importance of quantitative analyses for meeting certain requirements (e.g. how many people can live in a certain area), thereby coinciding with R5, she felt that analyses of openness should mainly resort to qualitative measures, which is where the experience that VR provides was considered beneficial.

> *"I think, honestly, the cool thing about this is that it really makes a point of the fact that it's not just about numbers to plan a space but how people perceive it, and sometimes you can't translate that into a number, and I think that for openness, it's really more a qualitative thing: does it feel open, does it not feel open? How does it feel to walk around here? [...] For the 'feeling' part, I really think that this is a cool part of the project, that you can add this extra human-level experience without inserting too many numbers in it, otherwise you just make a chart and then you're like: OK, to make it this open we have to add this much building, and then you make a robot do it." -R2*

4.3.5. Feedback (Q15-Q17)

Feedback is defined here twofold: either the feedback generated by the tool itself via calculations or visuals that provide information to the user on which to act, or generated by others through sharing designs with one another and making comparisons.

For the feedback provided by calculations, R3 and R4 strongly disagreed with their usefulness in informing new design decisions. R3's technical issues did not allow for calculations to be made, and she stated that this affected her sense of density and her capacity to carry out the design task.

> *"I also started with increasing the height and also just putting some tall buildings, but it was difficult to know without actually seeing any predictions at least, if I'm on the right track or if I'm exceeding. So I went all in." -R3*

R1 agreed that it was difficult to assess their progress towards the goal without making calculations. They also mentioned how the calculations affected their design choices, predominantly by opting to move new buildings into the area rather than trying to meet the target using small adjustments to the buildings already present.

R4 only performed one calculation at the end of the allotted time, due to struggles with getting used to the program itself (more on that in the next section) but also opted to perform a GSI analysis for personal reference.

The visual feedback appeared to be more useful in informing new design decisions, due to the reasons described in the previous sections regarding interaction, immersion and experience. R4 remarked on how this immediate feedback, combined with freedom of movement, helped them keep the original sense of openness in mind while designing:

> *"Every move you make, you can go back into it and really quickly assess whether changes in the building height and the density…precisely what impact they have had on the openness of the area. […] So when you're in there and you're like: if I put this up 2, does it still give me that same feeling of openness that I had before, or is that going to be too much of a change and I need to focus density elsewhere? So that was helpful." -R4*

With comments made earlier, e.g. by R2 regarding a possible quantified measure for openness, and R5's evaluation of the workflow and the potential of combining spatial analysis and immersive experiences, it can be said that there are benefits to combining the two, but it is highly dependent on what kinds of data is being used and for what purpose.

The feedback other participants gave on each other's designs served to make explicit the different perceptions that people can have on the same area. R1 agreed that it was insightful to see different interpretations of density and openness.

> *"It always shows how people create it differently. Yeah, there is a lot of options for how you can increase FSI, what a person perceives as an open space, and it was good to compare." -R1*

Using VR to experience an area allowed participants to more quickly gain insight into the thought processes behind a design compared to other methods, according to R2. She believes this method can help bridge the gap between the difference in interpretations of a designer who has spent a long time on a project compared to someone viewing it for the first time. R4 agreed with this, saying how they could see the differences in their approach and that of their colleague in a short time. R5 specifically pointed out how VR can provide a first end-user experience.

> *"When you work on your own design, you do it for so long that you really have a good understanding of it, and maybe even without the VR tool, you looked at it so much from SketchUp, from GIS, you thought about it a lot so you have this perception. But then if somebody sees it only for 10 minutes when they come to your table and give you feedback, they don't have the same hours that you spent on it, so to have something like this, it would really give them immediately, like: this is how it looks like."*

> *"Even from that short little time, I can see the different thought processes we had moving into it. It was very clear that you [R5] were like: okay, big density. And I want to try to get that balance. So it's nice to see that difference." -R4*

> *"Of course, it's always nice to see how other people are approaching it with entirely different solutions. And of course, being able to…yeah, that is where VR steps in, you really experience it as almost like a first end user, so maybe that's the difference. So that's particularly interesting."*

In relating to experiences in her studies, R2 also thought that this deeper understanding could potentially improve the feedback given by others.

> *"[The teachers] always walked to the tables and then look at the people's designs, but then, again, they weren't there for the 3 hours beforehand that brought to this result. If they could just look at it VR-wise, I think that the quality of the feedback would improve." -R2*

4.3.6. Overall experiences

Finally, after having discussed the individual characteristics of the VR tool, it is important to evaluate whether VR is actually an attractive and engaging method of designing for people to actually use it. This section, therefore, will go into the overall experiences that the participants had, which can be useful for gauging how inclined prospective users will be in implementing this tool in their design process.

In general, the students were quite appreciative of the technology, and unanimously agreed that it was fun and engaging to work in such an environment. While the students experienced some VRISE in the beginning, they mentioned that they wore off quickly and did not affect their engagement with the task at hand. Repeated exposure to the environment, one participant mentioned, might also reduce the occurrence of these effects.

> *"In the beginning it was hard to get used to the controls and I was feeling a bit dizzy, but after like... 10 minutes it's...it's all good, yeah. I could sit there for hours probably (laughs). Yeah, I really enjoyed it." -R1*

> *"I also really liked it and since I already used it a couple months ago, then I was already familiar with it so I didn't have the uneasy feeling anymore, so...quite fun." -R3*

In contrast, the staff members were less positive about their experience, mostly due to the effects of VRISE compromising their ability to comfortably use the tool. One staff member mentioned that moving through the area and zooming in and out, while beneficial for understanding the space and being a more accessible function than in other spatial design software e.g. SketchUp, also caused the most issues with VRISE:

> *"I feel quite sick (laughs). I think it was a little much for me in some instances. I found zooming up and down really hard, so I closed my eyes when I did it. So I really see the benefit of it and I would love to get comfortable with it, but currently I am not." -R4*

> *"I think the setup to get to eye level and at a very particular point in SketchUp is a little bit more of a process than it was here, because you can just very, very quickly do that. So I think it is, in terms of that, a little bit easier. In terms of my personal emotion...not so much." -R4*

The other staff member agreed, saying that this way of working should be avoided by people vulnerable to health issues. These initial reactions are in line with the previous experiences participants had in VR (see Table 3): with the exception of R3 who had worked with an earlier version of this software before, none of the participants had much, if any, prior experience with working in VR. This explains how R3 had the easiest time getting used to the controls and did not experience VRISE anymore, while most others seemed to have some initial problems with getting used to the technology and controls.

It was also mentioned how VR could lower entry barriers for designers to work with 3D models. This appears to be especially important in education, where such skills are not sufficiently developed yet.

> *"I think it's a quite interesting tool for people who are not just interested in downloading SketchUp and sitting there for 9 hours, but this is more interactive and more fun." -R1*

> *"Many people don't put the effort into making it 3D, not because they don't want to, but also because it's not something we are taught. [...] Maybe actually, this would inspire people to embark on it because it's cool, so maybe: oh cool thing, VR, then I can work on the 3D model." -R2*

R5 agreed that VR holds a lot of promise, and could help students be more engaged in getting into design.

Finally, the participants made some comments on what purposes this tool could serve in their opinion. R2, remarking on the lack of accuracy in designing, pointed out that she would not use this to make a complete design, and instead suggested using VR as one tool in the process.

> *"But I think the purpose is not to make the design in that; it's that you make the design and then you test it in this thing, right? Like, you make it 2D and then you import it and then you test it and then you change stuff? [...] To have a design, test it in there, change heights and sizes and stuff and see that if it works well as a human, then I think it's great and then maybe you put it back into GIS or SketchUp and then you change stuff and then you put it back and then you're gonna use it as an extra." -R2*

She later reiterated on that statement, imagining a situation where a designer is working on multiple monitors and exports the data from SketchUp or GIS into VR multiple times to get the immersive feeling as they are working on the design.

> *"I think in the process it can be very useful. I imagine ideally you would have multiple monitors and you're working on the 2D or SketchUp on one side and then it can be very fast how you export into the other program and then you look at it." -R2*

R5 agreed with this, and also stated that the effect of VRISE could prevent smoothly transitioning from one program to the other.

R2 also mentioned that the lack of details in the VR environment itself could be compensated by making screenshots and editing them in a graphics program e.g. Adobe Illustrator for presentation purposes.

> *"And then with the screenshot option, actually I was imagining you'd make a screenshot and then put it into Illustrator and then add the details on it then, like really have a chain of tools, so like: SketchUp, VR, SketchUp, VR, screenshot it, Illustrator…and then you can make nice renders out of it, I think." -R2*

R1 believed that VR would be more useful towards the end of a design project, but could also be used in the early stages to explore the area if it is impossible to be present physically. R3 shared this sentiment, stating that she would prefer a more finalized model as a means of reflecting upon the design. R4 agreed that a highly developed model would be useful for presentation purposes and community participation, but also saw more potential for this tool to be used in the earlier stages, suggesting that it holds a similar function to massing models used to study volumes on a conceptual level. They also mentioned the LOD here, stating that it should go even lower than it was to properly use it as a massing model.

> *"I could see it working in the very initial, rough stages. I wouldn't use it to push a more finalized version of a design, but I imagine it holds quite a similar space as a massing model or something like that. So for initial ideations. And in that case, I would have it even more low-poly than we had it in this. Because I found that to be kind of distracting to the feel of it, personally. […] I find it sort of counterintuitive to the whole thing. So if you're engaging with citizens in a public participation project, I wouldn't go that route, but I think less detail is better." -R4*

R5 also thought this tool would be more useful in the conceptual stages. She believed more tools are necessary in this phase.

> *"This would be something that I would recommend in the early to mid-stages of a studio. With the analysis and early design decisions, but after that…yeah, you definitely need more tools at the very first stages, both in 3D and 2D, and more detailed drawings." - R5*

5. Discussion

5.1. Evaluating the tool quality

After having dissected the main themes discussed in the focus group sessions, some key advantages and drawbacks can be discerned. These have been summarized by tool quality indicator in Table 9. These will be further discussed in comparison to the theory outlined in chapter 2.

	Advantages	**Disadvantages**
Interaction	-Possibility to change size of buildings -Low LOD and freedom of movement encouraged experimentation	-Limited precision in controls -Limited distance for moving objects in a single motion -No creating, copying or adjusting objects -No multiple selection of objects -Pre-built area limited creative freedom
Immersion	-Pedestrian point of view -Better judgment of livability -More realistic decision-making -Better understanding of the area compared to desktop view	-Not very useful for experienced designers -Errors in data accuracy (e.g. objects not appearing true to life or floating above the ground) broke immersion
Experience	-Good feeling for scale and size of objects -Beneficial for perceiving and qualitatively assessing density and openness (compared to GIS) -Special attention to human scale -Dynamically change perspective	-No reference objects for scale in the environment -No observable differences in types of open space (roads, parks etc.) -No dynamic lighting for assessing light and shadow coverage throughout the day
Data analysis	-Quick analyses without having to use another program -Useful for complicated study areas -Potential for additional analyses -Useful when having to adhere to building codes and guidelines	-Data inaccuracies can make analyses unreliable -No function for calculating openness, e.g. spatial syntax or isovists
Feedback	-Quantitative analysis useful for assessing progress towards a goal -Informing new design choices -Immediate visual feedback helps retaining a sense of openness -Potential for combining quantitative analysis with immersive visual experiences -Provide deeper insights into thought processes of other designers, subsequently improving feedback	-Assessing density is difficult if data analysis is not possible -Usefulness of feedback is highly dependent on data quality
Overall experience	-Engaging and enjoyable method of designing -Accessible way of working with 3D models -Complementary tool to other digital designing software (e.g. SketchUp, GIS) -Useful for early exploration and conceptual design, similar to a massing model	-Occurrence of VRISE severely affects the extent to which users are willing and able to use VR -Not suitable for making highly detailed designs -Should not be used as the sole design method -LOD still too high for mass modeling purposes

Table 9: summarized results from the focus group discussions. Source: author

5.1.1. Interaction

Freely and flexibly interacting with the individual objects is considered a key advantage of VR over traditional methods of designing in terms of enabling users to express their design ideas (Chavan, 2016; Döllner et al., 2007; Fröst & Warren, 2000). Having this feature functioning well is therefore crucial to making VR a valuable tool in spatial design and give it a unique place in the toolset of designers. The relatively low scores for this category given on Q9 indicate that this aspect of the tool does not adequately support users in expressing their spatial vision. The possibility of exploring and experimenting in an artificial world was overall well-received, which was the expected unique advantage of virtual environments (Chavan, 2016). The main drawbacks are found in the limited controls: moving objects around was imprecise and cumbersome to do over larger distances, and only one object could be adjusted at a time. Furthermore, participants were strictly limited to what was already present in the environment: no new objects could be created, nor could existing objects be copied or reshaped. These technical barriers limited participants in (re)designing the area as they saw fit. The key insight here is that the availability and intuitiveness of ways for manipulating data must be carefully taken into account when developing specialized software for VR.

The existence of a pre-built area appeared to limit creative freedom: participants were less inclined to work in areas with many pre-loaded objects. This is supported by the Figure 6 that shows that the most open area near the apartment building had the most variety between the different designs. While this could mostly be due to the lack of a means to move multiple buildings at once, this behavior is also in line with the findings of Štefancová et al. (2020), who state that a more polished and ‘finished’ look of a design deters users from making adjustments to it. It must be carefully considered whether to provide users with a pre-built area or with empty space; this will ultimately depend on the purpose of the design.

5.1.2. Immersion

Being immersed in the virtual experience is relevant for obtaining the feeling of spatial presence (Mazuryk & Gervautz, 1996). This immersion gives the participants a pedestrian point of view, which is better suited for making realistic design decisions (Campbell & Wells, 2003) and stimulates users to naturally interact with their environment (Hermund et al., 2019). The immersion and the ground-level view provided the participants with a deeper understanding of the design, which enabled them to make experience-based assessments of the environment. Most participants reported that they did experience this spatial presence to an extent, and appreciated the added experiential value. The feeling of being present inside the area and experiencing the effects of their adjustments as would a pedestrian was considered useful in informing their decisions.

The sense of immersion appeared to be strongly tied to the perceived realism of the environment, as was expected based on Zhu et al. (2021). The experience in the virtual environment must appear to the user as realistic in order for them to obtain spatial awareness. High quality input data is required to provide that sense of realism (Azarby & Rice, 2022). This aspect was deemed lacking in this tool. The low LOD of the objects, combined with data inaccuracies, made for an experience that was difficult to perceive as realistic. The ground-level view might actually emphasize these data imperfections, as it makes users observe them up close, whereas a more distanced view can obfuscate these errors.

Ultimately, though, some participants, particularly the staff members, felt that this kind of immersion would not be very beneficial to experienced planners and designers, and instead is most suited for beginner-level designers or students in the field of planning and design, because professionals are expected to have the knowledge and expertise to circumvent errors in judgment stemming from distorted perspectives in designing. However, the long-standing trend of aesthetics-focused designing that is inadequately oriented towards end-user experiences would suggest that a new perspective is necessary specifically at the professional level (Gehl, 2010; Nisha & Nelson, 2012; Tang et al., 2019). Immersive designing can steer this trend in another direction, where the effects of design interventions on the end-user experience become a focal point (Dyer et al., 2017).

5.1.3. Experiencing the space

The immersive way of viewing an environment is expected to provide a stronger feeling for the space, the scale and size of the objects and the relative locations and distances between buildings (Azarby & Rice, 2022; Nisha, 2019). Digital 3D models are well-suited to provide viewers with dynamic perspectives (Ajene & Sylvester, 2014), as well as a deeper understanding of the human scale (Thompson et al., 2006). These elements were picked up on and appreciated by most participants, stating that they were more acutely aware of the relative scale and size thanks to these multiple perspectives. The lack of extra details to fill in the environment counteracted this, due to the lack of reference material to estimate sizes compared to other objects. There was also no distinction between different types of open space. It would appear that the appropriate level of realism in an environment does depend on the purpose of the environment (Hoeckner, 2016): the lower the realism, the harder it is to estimate relative sizes and distances, but the more encouraged one is to experiment (Štefancová et al., 2020). The purpose of using VR in a design process must therefore be carefully considered.

Perception and understanding of the three-dimensional nature is strongly related to feelings of density and openness (Hur et al., 2010; Mousavinia et al., 2019; Zacharias & Stamps, 2004). It was generally appreciated how the virtual environment enabled better qualitative assessments of these aspects. However, a recurring issue was the lack of dynamic lighting, which to many was a key aspect in assessing openness. Ajene and Sylvester (2014) recognized the option for dynamic lighting as a major advantage of 3D models, and Zacharias and Stamps (2004) concluded that perceived density is affected by the presence of gaps in the built environment for light to come through. The lack of a function to change the position of the light source hindered the extent to which participants could make judgments on openness, and appears to be a clear priority when looking at suitable VR software for design tasks.

5.1.4. Data analysis

Data analysis is an essential tool for informing and supporting spatial decision-making (Murayama & Thapa, 2011). The design focus has been shifting from a solely aesthetic perspective to a quantitatively substantiated approach (Nisha & Nelson, 2012). Exploring and analyzing these data in a VR setting is expected to have great potential for the future (Chandler et al., 2015). Overall, the participants saw this potential as well, although the relative infancy of this integration of methods mentioned by Fonnet & Prié (2019) was also recognized. Participants had many different suggestions for future analyses that could be particularly insightful to explore in a VR setting. One participant also commented that such analyses are also being performed at architectural level using BIM and might be similarly useful on a larger scale. The flexibility with which spatial data can be applied to BIM and CityGML means that multiple data sets on architectural level can serve as input for data on larger scales (Döllner et al., 2007; Kolbe, 2009; Ohori et al., 2018b).

Its perceived use for more complicated areas also mirrors Sipes' (2006) comments regarding the adaptation of this method on different geographical scales. The neighborhood scale can already be too large to make manual calculations feasible, as one participant mentioned doing on small plots. Calculating density was also perceived as useful when adhering to codes or guidelines, which helps explain why quantifiable density measures are still relevant (Alexander, 1993).

The differences in perceived versus calculated density is made apparent by the data from Table 4. The participants' tendency to overestimate the density shows that basing a design off of density measures alone can result in widely differing experiences for people. It is the perception of openness and density that is required to substantiate quantitatively informed decisions, because density can hardly be assessed properly only by looking at the numbers (cf. Hur et al., 2010). This idea, which was remarked upon many times in chapter 2.8, was also recognized by a participant, who stated that design should not be reduced to numbers and instead need to have human perception incorporated in them. The data from Table 6 shows that calculated density and perceived openness are inversely related. While this is not surprising, it does confirm that quantitative measurements of density have some meaning in discussions regarding openness. These results further stress the necessity of including human perception early on in the design phase, where discussions regarding openness and density are most relevant. It also confirms that height is an important factor in these discussions. This might put into question some of the results by Hur et al. (2010) who omitted building height from their analysis. Physical density might impact neighborhood satisfaction more than previously thought, although it is unlikely that it will become a more decisive factor than perception, considering the other results discussed in chapter 2.8.

5.1.5. Feedback

Finally, after the individual tool quality indicators have been discussed, it is important to evaluate how the tool as a whole was suited to provide qualitative and quantitative feedback to the user, driving the production of new design iterations. This feedback is deemed lackluster in traditional design methods (Yan & Tamke, 2021); therefore, the instant feedback function that VR provides through a continuous cycle of acting upon and viewing a virtual model (Robinett, 1992) is anticipated to help alleviate this issue. Informing new design decisions with the constant feedback that VR provides is expected to be a main driver of its usefulness in the practice of spatial design (Campbell & Wells, 2003), both for the user and the other stakeholders involved in the process (Moughtin et al., 1999). This unique feature of designing in VR was considered by the participants to be very beneficial in making more informed decisions. Quantitative data provided measurable progress, and the visuals helped participants to continuously take density and openness into account while designing. The combined effects of qualitative and quantitative data analysis within a single environment is still rather unexplored (Ma et al., 2010), but even in this conceptual tool did most participants see its potential. A critical note here is that the data used must be accurate and reliable for spatial analyses to be more viable in a VR setting than switching to GIS.

5.2. Overall experiences

Nisha (2019) concluded that VR is an engaging method that inspires users to be involved and stimulates higher spatial learning capacity. El Araby (2006) ascribes the engaging effect of working in VR to its visual and sensory nature. In general, participants enjoyed working in VR. They saw potential in this method of designing, and came up with many suggestions on what else could be possible with this tool. Simpson (2001) noted that this method could lower entry barriers for working with 3D models. A number of participants shared this idea, stating that this method could inspire people to work with it thanks to its ease of access and intuitive controls.

A major issue that participants encountered was the occurrence of VRISE. These negative symptoms discouraged some from working with the tool as much as they would have wanted. This was especially prevalent among the staff members; the students showed markedly fewer symptoms. This occurred despite the participants being in full control of their movements and vision, which, according to Sharples et al. (2008), should help avoid these from occurring. A more probable cause is the low data quality of the environment and the occasional stuttering or glitching of the screen (Mazuryk & Gervautz, 1996). While much research has been done on this topic, the exact causes are still relatively unknown, as is the question whether these effects will ever be fully avoidable (Rebenitsch & Owen, 2016).

Most participants agreed that this specific tool is most useful in the conceptual design phases, where exploration and early mass modeling are relevant. This would coincide with the 4th phase of the design process outlined by Abd Elrahman and Asaad (2019). This is also in line with the statement by Al-Douri (2010), although this specific tool is most likely not useful for the later design stages. For mass modeling, however, Štefancová et al. (2020) suggested to use a low LOD, which one participant argued was still too high in this research. If experimenting with mass and volumes is the primary function, then it might indeed be effective to go to as low an LOD as possible while still retaining visible height. In the ordering by Biljecki et al. (2016), the minimum of LOD 1.0 would suffice.

Based on the comments by the participants, it is uncertain if higher quality data and software would eventually lead to a tool which could effectively replace other designing software like SketchUp. As seen in Table 2, this experience was quite novel for most participants, so they had little reference material for the other uses that VR might have. Results on the effectiveness in later stages of the design process are therefore inconclusive.

6. Conclusions

This research has attempted to evaluate the usefulness of VR in the spatial design process, with a particular focus on assessing openness and density. VR is a rapidly expanding technology, and its potential in urban design is still very much undiscovered. Researchers and professionals have been looking for ways to implement its distinctive feature of providing immersive experiences to use in the field of spatial planning and design. Most of these endeavors, however, have focused on data visualization, and less so on immersive spatial data analysis. These two aspects together are vital in properly informing design decisions that focus on the end user rather than the personal perspective of the professional.

VR has the potential to encourage experimentation and creative thinking, but this is not something that is automatically granted when working in a virtual environment. The controls and built-in features need to support the user in expressing their design vision by providing options for precise placement and modification of objects.

The immersive experience is key in giving the user more insight in the size and scale of their environment and its individual objects. A ground-level pedestrian view simulates an end-user experience that is hard to replicate with other methods. The feeling of immersion heavily affects the experience a user will have, and how they will interact with the environment. As this is connected to realism, the overall level of realism in the environment must be carefully considered when deciding to use this method, as different levels serve different purposes.

Density and openness are related concepts, but they are not to be approached solely on a quantitative level. The immersive experience is a unique way of obtaining a feeling for desirable levels of density. Dynamic lighting appears to be crucial in assessing these.

Performing data analyses in VR is relatively unexplored, but shows decent potential. It can aid designers in steering away from an aesthetics-focused design approach and instead take real-life data into account. As the concept of evidence-based design expands, it appears that VR presumably can play a big role in making more informed design decisions.

Altogether, while there is still plenty to be uncovered, this research has attempted to show that there is potential for quantitative and qualitative analysis to be combined in a single immersive tool to allow designers to understand their designs on a deeper level than was possible before; at the very least on a conceptual level. With the overall process of spatial designing becoming increasingly more digital and multiple design programs becoming ever more integrated in a designer's toolkit, there appears to be an experience-focused niche for VR to fill. This research evaluated this through the lens of quantitative density measures, but there are many more avenues to explore. Based on the common issues raised by the participants of this research, some relevant topics could be immersive data exploration along the themes of visibility, light and spatial syntax to deeper analyze the concept of openness and possibly make it quantifiable; and better understanding of the causes of VRISE to find ways to prevent them from occurring, as they heavily affected (and will affect) engagement.

7. Reflecting on research quality

While this research has revealed many insights on the potential of spatial design in VR, it must be noted that there are limits to the research design that affect how conclusive and generalizable the statements made in this report are.

Immersive experience and the usefulness of the data analyses are highly dependent on the quality of the input data and the software used for handling it. This tool used 3D BAG data, which is based on LiDAR data and may therefore not be entirely accurate, particularly when it comes to complex building shapes. Because of inaccuracies, some buildings appeared to float, or were not to the scale one would expect from a realistic setting. This hindered the immersive experience somewhat. While more detailed data would have helped in simulating a more realistic setting, and subsequently have users interact with it more naturally, this was not possible with the data available for this research. There is also the trade-off of realism versus experimentation mentioned before. Ultimately, providing the participants with the room to experiment was also a large factor in this decision.

The overall scope of this research was rather limited. There was a limited timeframe, which made scheduling a challenge at times. Only 5 participants were able to attend on the dates on which the experiments were conducted. More participants would have been preferable, but the aforementioned scheduling issues, together with last-minute cancellations, made obtaining a larger participation base difficult. One participant (R1) also had missing data due to communication issues. This small test group makes the results less generalizable. A larger test group could reveal more similarities and patterns between multiple users, and would also be more able to compensate for no-shows. Repeated experiments are also useful to diminish the engagement hampering effect of VRISE.

There were also some technical issues regarding the tool. As mentioned in section 4.2.1, R3 was unable to make calculations, which makes her FSI calculations unreliable. This issue was later discovered to originate from a lack of access of the VR tool to the ArcGIS Pro application necessary for running the calculations. This unexpected issue also caused a large delay in starting the design sessions, which prompted one of the student participants to leave before any data could be created. More extensive testing and troubleshooting beforehand could have revealed this issue earlier.

In this research, assessments of openness were limited to perception, but quantitative measurements for openness could also be implemented. This was also a suggestion made by some of the participants, although some others were more reluctant to express openness in quantitative measurements due to the importance of human perception. For this research, it was decided to emphasize the qualitative nature of assessing openness and density.

Lastly, the software itself is still in development. Many features, like dynamic lighting or isovists analyses, are potential improvements for the future, but could not be implemented in the timeframe of this research. Adding additional features to the software would greatly enhance its potential. The results from the focus group analyses could provide a good starting point on what features people are looking for in a VR design tool.

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Appendix A: participant form

Workshop to test the interplay between virtual reality and spatial analysis in spatial design

Participant Information

Gender:

○ male ○ female ○ other

Age: ______

Current occupation in the field of spatial design:

○ student ○ scientific staff ○ other

Name of organization/company:

Expertise in VR, GIS and spatial design (fill in where applicable)

I feel comfortable using VR devices

○ strongly disagree ○ disagree ○ neutral ○ agree ○ strongly agree

I have often used VR in my study program/ in my work

○ strongly disagree ○ disagree ○ neutral ○ agree ○ strongly agree

I am experienced with using 3D models in my study program/ work

○ strongly disagree ○ disagree ○ neutral ○ agree ○ strongly agree

I know how to perform spatial analysis task with GIS software, such as ArcGIS or QGIS

○ strongly disagree ○ disagree ○ neutral ○ agree ○ strongly agree

I am familiar with geodata such as the Dutch *Basisregistratie Adressen en Gebouwen* (BAG)

○ strongly disagree ○ disagree ○ neutral ○ agree ○ strongly agree

I am a professional in spatial design

○ strongly disagree ○ disagree ○ neutral ○ agree ○ strongly agree

I am familiar with building density measures such as Floor Space Index

○ strongly disagree ○ disagree ○ neutral ○ agree ○ strongly agree

Appendix B: design tasks

Workshop to test the interplay between virtual reality and spatial analysis in spatial design

Introduction about the aim of the research and the workshop, and a demonstration of the VR tool. – 10 min.
Write down your PC number (red sticker on top of the PC), then go to the next section
Task 1 (7 minutes): Explore the VR tool, and the 3D model. Move through the designated area to familiarize yourself with the technology and the virtual environment. You are free to move through the area as you wish. Take a look at the different buildings and their layout, and get a feel for how it is built up. While you are doing this, try to estimate the Floor Space Index of the area without calculating it yet, and think about the perception of openness of the area. Once the time is up, make an estimate of the FSI, and provide a score for the openness of the area from 1 (very confined) to 10 (very spacious). Write down the answers in the Google form on the second monitor.
Answer Q1 and Q2
Next, use the predefined selection polygon under "Load selection", and then the "Calculate FSI" function in the VR tool to calculate the real FSI, and write the answer down in the form.
Answer Q3, then go to the next section

Task 2 (20 minutes):
Use the VR tool to redesign (parts of) the study area in such a way that the total FSI ends up as close to 1,5 as possible, while keeping the perceived openness as close as possible to the original situation. Assume that all the buildings in the area are residential buildings (single-family homes, apartment buildings etc.) You have full freedom over how you want to design the area. You can use any building for whatever purpose you wish, regardless of what you might think the building's original purpose was (e.g. expanding a shed into an apartment building). Use the VR controls to change the size, rotation, position and height of a building. Whenever you want to measure the FSI to gauge your progress, you have to use the "Export Buildings" feature under the "Analysis" tab (this can take about 1 minute). Keep track of how often you calculate the FSI as you work on this.
Once the time is up, export the buildings one more time, calculate your final FSI, and write the results down in the form. Then, make another assessment of the perceived openness of your final design using a score from 1 (very confined) to 10 (very spacious).
Answer Q4, Q5 and Q6, then go to the next section

Task 3 (5 minutes):
You will now assess the openness of the design of one of your colleagues. Move over one computer to the right of you, and use the VR tool to move around in the study area designed by your colleague. Once the time is up, score the openness of your colleague's design with a score from 1 (very confined) to 10 (very spacious). After you have evaluated the openness, compare your design to the one you have evaluated just now and write your thoughts in the form.
Answer Q7 and Q8 on your colleague's computer, the go to the next section

Task 4 (5 minutes):
While you are adjusting back to reality, move back to your own computer and take a look at the questions on the last page of the Google form asking about how you experienced working with this

tool. The possible answers range from “strongly disagree” to “strongly agree”. These answers can serve as a starting point for the discussion session following this part.
Answer Q9 till Q17 on your own PC, the send the form

Task 5 (30-40 minutes):
You will now discuss your experiences with working in the VR model in a focus group with the other participants and the researcher. The discussion will follow along the lines of the questions you answered in the form. During this discussion, you are free to say anything that is on your mind.

Appendix C: focus group question guide

Introduction

-How did you experience the exercises?
-How did it feel working in a VR environment?

Working in the VR environment

-How free did you feel in changing the environment as you saw fit?
-To what extent did you feel as if you were actually there in your design (immersion)?

Assessing the built environment

-To what extent did you feel like the model represented a realistic setting?
-How did the tool help you get a feel for the true shape and scale of the buildings?
-How did you experience openness and density in the virtual environment?

Feedback from the VR tool

-How did the visuals affect the design decisions that you made?
-How did the calculations affect the design decisions that you made?
-How do you feel that these two elements work together to affect your decisions?

Evaluate/compare/feedback on other design

-What did you learn from the design of the other person you evaluated?

Closing questions

-Anything else you wish to comment on?

Appendix D: coding system

Category	Sub-category	Description	Method	Example words/phrases
Accessibility	Controls	Working with the controls and controllers of the HMD system	Inductive	Copy/paste, selection, buttons, move in straight lines, interface, wobbly/finicky
	VRISE	Getting used to the VR environment and the associated negative side effects	Inductive	Dizziness, nausea, uneasy feeling, familiar, (un)comfortable
Interactivity	Viewing the environment	Moving through and observing the VR environment	Deductive	Zoom in/out, look around, move (self), perspective, view, screen
	Making adjustments	Feeling enabled by the VR tool to make adjustments to the objects in the environment and their layout/arrangement	Deductive	Modify, move (objects), change (height, size), create, place
Experience	Realism	Whether the virtual environment represented a realistic setting	Deductive	Representative, details, resolution, abstract
	Immersion	Feeling like being immersed/actually present inside the environment	Deductive	Being/standing there/in it, feel around you, human-eye view, experience as an end-user
	Density	Experiencing the density of the objects placed in the virtual environment, and how to assess this	Deductive	Density, height, FSI, shadow, mass
	Openness	Experiencing the openness of the virtual environment, and how to assess this	Deductive	Spacious, open space/form, (sun)light, feeling, visibility
	Scale and size	Getting a feeling of the scale and size of objects	Deductive	Human scale, small/large (contrast), high/low, context, massing model, 3D
Measurement	-	Making accurate measurements and data analyses using the VR tool	Deductive	Precision, calculating, accuracy, analysis, data (layers)
Feedback	Visuals	How observing the objects in the environment and their relation to one another	Deductive	Perception, ‘how does it feel’, impact, seeing, assess, inform, guess (density)

		affected the participant's design decisions		
	Calculations	How the results from the calculations affected the participant's design decisions	Deductive	Check, calculate, numbers, decisions, precision, guidelines, rules, requirements
	Evaluating other designs	How observing another participant's design provided new insights on approaching a design task	Deductive	Other people, compare, feedback, approaches, differences
Overall experiences	-	General opinions on working and experimenting in VR, and performing the design tasks	Inductive	Fun, enjoyment, want to play it with, intense, interactive

Appendix E: participation information sheet

Workshop to test the interplay between virtual reality and spatial analysis in spatial design

Participant information sheet

Introduction

Thank you so much for considering getting involved in my master thesis research at the University of Groningen, Faculty of Spatial Sciences. My research revolves around testing the usefulness of using the combined technology of virtual reality (VR) and spatial analysis through GIS in a spatial design process. Thanks to ongoing advancements in this technology, designers can now visualize their design ideas in virtual space and conduct data analyses in VR. This is expected to enable designers to make more informed decisions that are evidence-based and consider the human experience in a way that traditional methods of designing (e.g. 2D plans or physical 3D models) cannot support. This is an as of yet relatively unexplored domain, which is why experimentation with this technology is necessary to evaluate how useful it can be.

Confidentiality and anonymity rights

As a participant, you are entitled to certain rights pertaining to confidentiality and anonymity, which are listed below:

- The data generated in the design phase will be saved and analyzed;
- The focus group session will be audio-recorded, and notes will be taken afterwards;
- All data from the design sessions and the focus group recordings will be saved in a secure location on a computer, and will be deleted after the research has been completed in full, or up to five years after completion if further research is necessary;
- You may ask to have the recording of the focus group turned off at any time;
- You may opt to quit participating at any time during the design phase or the focus group session at any time;
- If you wish, you can ask for a copy of the notes taken during the workshop, and request any amendments to the notes, or have parts that you do not wish to be used, erased.
- You are free to ask any questions about the research before, during or after the workshop;
- You are free to decline participating altogether.

All data derived from this workshop will be mainly used for furthering my master thesis, which will be made publicly available online. The data may also be used in further research. All personal data will be handled anonymously, and no personal identification will be mentioned in the research report or any future research unless you have given explicit permission to do so.

Again, thank you so much for taking the time to learn about my research. If you have any remaining questions, you can contact me or my supervisor via mail, the details for which I have provided below.

Master thesis student:	Supervisor:
Maarten Holsappel	Gerd Weitkamp
m.t.holsappel@student.rug.nl	s.g.weitkamp@rug.nl

Appendix F: consent form

Consent form for: Workshop to test the interplay between virtual reality and spatial analysis in spatial design

The purpose of my Master's Thesis research at the Faculty of Spatial Sciences, University of Groningen, is to test how spatial analysis in virtual reality can help make more informed decisions in the spatial design process. This form serves to record your given consent in participating in this research, as well as how your personal data are to be processed by the researcher. Please carefully read the statements below before signing:

- I have read and I understand the information sheet of this research project;
- I have had the opportunity to discuss this study with the researcher and/or their supervisor, and I am satisfied with the answers I have been given;
- I understand that taking part in this research is voluntary and that I have the right to withdraw from the study up to three weeks after the exercise;
- I understand that my participation is confidential, and that no personal identification will be mentioned in the research reports or any further research, unless I have given my explicit permission to do so;
- I understand that the data recorded during the workshop and collected via the survey may be used for further research and publication purposes but only in an anonymized form.;
- I understand that all data derived from this workshop will be stored on a secure location on a private computer.

<u>Please circle YES or NO to each of the following:</u>

I consent to photos being taken during the VR workshop for the purpose of using them as illustrations of the tool in presentations and publications	YES/NO
I consent to the audio recordings of the focus group session	YES/NO
I wish to remain anonymous in the research report	YES/NO

"I agree to participate in the workshop, which includes completing a survey, completing design tasks with a VR tool and participating in a focus group discussion. I also acknowledge that I have received a copy of this consent form and the research project information sheet."

Signature of participant: __________________________ Date: _____________

OPTIONAL: If you would like to receive a copy of the notes taken during this workshop or research, in order to review, suggest amendments, or request their erasure, please provide your email address below.

E-mail: _______________________

For the researcher:

“I agree to comply with the conditions outlined in the information sheet and I will ensure that no harm will be done to any participant during this research.”

Signature of researcher: __________________________ Date: ____________