The Use of Virtual Reality in Urban Planning

Review paper on the (dis)advantages and a new perspective for future research

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REVIEW PAPER ON THE (DIS)ADVANTAGES AND A NEW PERSPECTIVE FOR FUTURE RESEARCH

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Abstract

Albert Einstein once said 'The only source of knowledge is experience'. Virtual reality fits perfectly within this statement. The experience in a virtual world helps to give knowledge to urban planners, to other parties they work with and even non-expert stakeholders.

The availability of various virtual and augmented reality devices enable multidisciplinary work and generates a higher involvement of stakeholders in different stages of the urban process. Because the generation of knowledge happens in an understandable way, virtual reality is able to facilitate several decision-making processes.

However, there are also some disadvantages such as technological problems, the required knowledge, the costs and psychological, social and physical side effects.

Empirical research confirms results obtained during an extensive survey of relevant literature. However, the empirical studies are still incomplete and not very systematic. Recommendations in the conclusions state that it would be of great value to carry out new studies, making use of current technology and comparing the different devices for the different scales and purposes within urban planning and design.

Keywords

Virtual reality, augmented reality, VRISE, city model, urban planning, urban design, decision making, urban studies, construction, multidisciplinary working, participation processes, risk perception, social acceptance, disaster planning.

PREFACE

With great pleasure, I present this master's thesis. When I had to make the choice for a topic, the option to choose for the combination of urban design and virtual reality immediately stood out. For me, this review paper contains the perfect combination of my different interests.

At first, I would like to thank the University of Antwerp who have given me high-quality education and have broadened my horizons. My thanks go out to the professors from the bachelor in Architecture and the master in Urbanism and Spatial Planning. Special thanks to my promotor Tom Coppens, for assisting throughout the entire process, the useful insights and for guiding me in the right direction. I would also like to thank Guy Vloebergh for the co-supervision of my thesis.

Next, I am very grateful to Reynaers Aluminium for all the opportunities they gave me. Because I am an employee, I had the opportunity to work in their virtual reality team and to get a good basic knowledge about the topic. This practical experience, with both a head-mounted display (HTC Vive pro) and a CAVE (AVALON), is of great value to raise my master's thesis to a higher level. From my own experiences, I have been able to get a lot of input. In addition, I want to express special thanks to my manager and other close colleagues, because they have given me all these opportunities and have always been a support throughout the entire process.

Finally, a word of thanks to my family, friends and acquaintances who kept believing in me and gave me confidence. This support has been of countless value.

Thanks also to those who helped me with providing input or proofread my master's thesis. These things have ensured that I can share this review paper with you all.

TABLE OF CONTENTS

1 INTRODUCTION 01

2 VIRTUAL REALITY 03
2.1 Virtual reality 03
2.1.1 What is it? 03
2.1.2 Devices 04
2.2 Augmented reality 06
2.2.1 What is it? 06
2.2.2 Devices 07
2.3 VRISE: Virtual Reality Induced Symptoms and Effects 08

3 VIRTUAL REALITY AND URBAN PLANNING 11
3.1 City model 11
3.1.1 What is it? 11
3.1.2 CityGML 14
3.1.3 Intellectual property 15
3.2 Project scale 16
3.2.1 Design phase 16
3.2.2 Studies 17
3.2.3 Construction phase 17
3.3 Advantages of using virtual reality 18
3.3.1 Multidisciplinary working 18
3.3.2 Participation processes 20
3.3.3 Disaster planning and urban behavior studies 22
3.4 Disadvantages of using virtual reality 23
3.4.1 Technology 23
3.4.2 Social and physiological side effects 24

4 EMPIRICAL RESEARCH ON THE APPLICATION OF VR IN URBAN PLANNING 26
4.1 Overview empirical research 26
4.2 Discussion research 33

5 CONCLUSION AND RECOMMENDATIONS 37

6 REFERENCES 39

1.
INTRODUCTION

Virtual Reality, abbreviated VR, is one of the most discussed and trending topics of the moment. The technology of VR has it basis in the 15th century, when Leon Battista Alberti gave insight in the mathematics of linear perspective rendering. The first use of VR goes back to the 19th century with the use of Sir Charles Wheatstone's first stereoscope (Sherman & Craig, 2003). In 1956, Morton Heilig wanted people to feel like they were actually 'in' a movie and patented 'Sensorarma', a head-mounted display device, four years later. But also Ivan Sutherland is seen as one of the founding fathers of VR because of his 'Ultimate Display' in 1965, which he concieved as a window where everything was real (Mazuryk and Gervautz, 1996).

Ever since, virtual reality is a booming technology that is evolving fast. VR can be used in countless sectors: the gaming industry, the medical sector, product development, educational purposes and training, real estate, interior design, etc. Virtual reality also found its way to the domain of urbanism and spatial planning.

In this review paper, the central topic is the relationship between urbanism and the use of virtual reality. The paper will start with a literature study, which will give information about virtual reality and augmented reality and the different devices. Next there will be a short part about VRISE, which are virtual reality induced symptoms and effects.

Next, the literature review will focus on the link between VR and urbanism. The different scales will be discussed, namely a city model for planning and a project scale for urban design. The advantages will be highlighted, such as multidisciplinary work, participation processes and the option to use VR for studies about urban behavior and disaster planning. Disadvantages such as technological problems and difficulties as well as side effects will be discussed. These will be about the technological problems and difficulties, as well as about the side effects of using virtual reality.

The next chapter compares the results of the literature review with the results from empirical studies. There is a selection of twenty empirical studies, first presented in a table and afterwards discussed in detail. The issue of whether or not they support the views of the literature review is the main question, but there is also a detailed examination of the studies themselves. This to see where the gaps and shortcomings are and if general conclusions can be drawn.

Finally, the conclusion formulates the central ideas of this study, as well as the gaps and recommendations for studies in the future.

2.
VIRTUAL REALITY

There are different forms of physically immersive media. This part of the paper will examine virtual reality (VR), which is a synthetic, computer-generated environment, and augmented reality (AR), which is a mix of the real physical world with synthetic elements that are computer-generated. Augmented reality is sometimes stated as a soft version of VR that is less immersive (Sherman & Craig, 2003).

The information in this chapter is based on a theoretical literature review. Articles were obtained on Google Scholar based on the keywords that are the same as the titles in this chapter, namely: virtual reality, augmented reality, the devices for both media and VRISE. The aspects covered are based on the available literature and on my own working experience inside the field of virtual reality.

2.1 VIRTUAL REALITY

2.1.1 WHAT IS IT?

Virtual reality creates a new world that is completely isolated from the real world. It is easy to experiment in here with the not-existing (Chavan, 2016).

VR creates an interactive and immersive experience in a simulated environment generated by strong computer systems. The type of VR environment and the quality will influence the feeling of the users. The level of immersion is very important for the feeling in VR (Mazuryk & Gervautz, 1996).

Immersion is the feeling of being present in an environment. There are two different forms of immersion: mental and physical. Mental immersion is the principal goal of the creators of VR. It is the state of deep involvement in the environment. Then there is physical immersion where the body is inside the medium and can be used or followed to have a better virtual reality experience. There are options on how many senses and how much of the body immerses, depending on the VR environment (Sherman & Craig, 2003).

There are three groups of VR systems, based on their grade of immersiveness. First, desktop VR, which is also called 'window on world'-system. It is a basic VR application that uses a monitor for displaying the VR image. The user only needs to watch to a screen. Second, there is fish tank VR, which is a second step in the VR experience. There is the support of head tracking in this version of VR, which improves the level of immersiveness. It still makes use of a monitor and most of the time there is no sensory output. The last step is an immersive system where the user really feels to be in the environment. The system follows the user's position and orientation. There is the possibility to add audio, haptic and sensory interfaces to these immersive VR systems (Mazuryk & Gervautz, 1996).

To have a VR experience, three basic components are necessary. First, there are the input devices, which allows the user to communicate with the computer. If the input device works in a natural and intuitive way, this will increase the feeling of immersiveness. The second component is the output device that is responsible for the presentation of the environment. This can vary from visual, auditory to haptic output and again, the feeling of being immersive depends on this. If the gear is heavy, has a low quality or low resolution, this will have a negative impact on the experience of the user. The third component is the needed software to make the devices work properly. The software needs to work very precise and must manage to send large quantities of data in a quick time, to have a good output in the devices and a feeling of immersion (Mazuryk & Gervautz, 1996).

2.1.2 Devices

There are different options for experiencing projects in Virtual Reality, divided in three groups of paradigms: head based, stationary and hand based.

With the head based version, there is the need for a head based display. This can be a helmet, glasses, but even a display held in the hands can be head based. There is the option to allow the view of the real world, or only show the virtual one. The virtual reality images are on one or a pair of screens in front of the eyes. There are sensors that tracks where the user is looking, so the images moves simultaneously when the participants moves or look somewhere else. Additional devices are possible to make the user interact more with the virtual world and not only by looking around. Secondly, there is the stationary version, where the user does not wear or carry the hardware. Instead, it is at a fixed point and uses projectors and displays to show the virtual environment. Last option is the hand based variant, where the user literally hold something in his hand. Think off a smartphone or a tablet. This medium will show the information to the user (Sherman & Craig, 2003).

There are multiple devices and VR environments inside these three different paradigms of virtual reality, with all their own level of immersion.

Inside the first paradigm of desktop VR, there is the use of 3D glasses when looking at a monitor. There is a very low level of immersion or interactivity. The next option is surround displays or the room-based system, which is an evolution on the standard monitors. Large projection screens are used, which give a better quality and also a wider field of view. An example is the CAVE, which stands for cave automatic virtual environment. Here, the screens surrounds the user, which give a higher grade of immersion. In an ideal situation, the CAVE gives a full 360° field of view. The last option is the head mounted display (HMD) which can be fully immersive. The screen is in front of the user's eyes and the images change accordingly by tracking the position of the head. The ergonomic requirements are very important to make it comfortable to use it (Muhanna, 2015).

In this review paper, the focus will be on head mounted displays in general and on the CAVE. These two options are, at this moment, the most useful ways for using VR into urban planning. It is also very interesting to see how these options compare themselves to the more traditional desktop VR.

All VR environments have positive as well as negative aspects. Only limited research is available to compare these options with each other.

In the conference paper of the Construction Research Congress of 2016, an interesting overview table gives the general characteristics for the different options.

Table 1. Comparison of General Characteristics of Environments

Main Features	Non-Immersive Desktop VR	CAVE VR	Oculus VR	Cardboard VR
Resolution	High	High	Medium - High	High
Scale of surroundings (perception)	Low	Medium - High	High	High
Field of regard	Low	Medium	High	High
Sense of immersion	None - low	Medium - High	Medium - High	Medium - High
Multiple concurrent users	Yes	Yes	No	No
Head tracking	Yes	Yes (if single user)	Yes	Yes
Primary input device	Hand controller	Hand controller	Hand controller	Gaze
Portability and setup	Hard	Hard	Medium	Easy
Initial cost	Medium	High	Medium	Low

Source: Kasireddy, Zou, Akinci, & Rosenberry, 2016

There are multiple benefits of using a CAVE environment. The resolution is much higher than most available HMDs because it works with multiple projectors behind the screens. Users will feel like they are really 'in' the environment when they are standing in a CAVE, which gives it a more natural feeling of space and scale. Another very big advantage is that it is possible to be in the room with multiple people, which makes interaction with each other possible. On the other side, there are also some difficulties linked to the installation of a CAVE. The biggest problems are the needed space, the fact that it is at a fixed location and the high cost for integrate the room and buying the projectors (Havig, McIntire, & Geiselman, 2011).

HMD's have several advantages. Equipment wise only a computer capable of running the appropriate software is needed. HMD's are mobile tools that can be used on location and the space needed is much more limited compared to a CAVE solution, which makes the use much more accessible. A big disadvantage is the interaction and communication with other users. The user is alone in the virtual world or can only communicate with avatars, which feels rather unnatural. If a good and fast head tracking is required, the HMD needs a connection to the computer with cables. The use of these cables often leads to discomfort for the user (Havig et al., 2011).

The discussed environments are output devices controlled by different input devices, which lead to different experiences. Only tracking eyes and movements will give a natural feeling. There is the option, depending on the purpose of VR, to add extra input devices. The most common is the 'wand' or controller, which can have different shapes and forms. An infrared sensor defines the position of the controller and makes it possible to navigate through the virtual world. The use of cameras can be an important input device to register movements of people (Boas, 2013).

Next, there are options to link the virtual world to devices that make it possible for the user to feel like really doing something in the virtual world (Boas, 2013). In addition, other devices are possible to link to the virtual reality system. This makes it possible for example to walk, drive or ride your bike through the virtual environment (Bayer, 2018).

2.2 Augmented Reality

2.2.1 What is it?

Augmented Reality (AR) uses the existing world and adds or changes something to it. The real environment is used together with an overlay with new or extra information (Chavan, 2016). This makes augmented reality a variant of virtual reality, where there are added supplements to the reality, instead of really making a new world with new elements. AR can provide information to a person in a better and more satisfying way than traditional approaches, such as maps and handheld displays (Chou & ChanLin, 2012).

Augmented reality is closer to the real world than VR. To goal is simplifying the life and work of a user by bringing virtual information to the person, while working for example. The work process can continue the whole time, instead of stopping every time to go and look for information in a traditional way. There is the option to apply AR to different kind of senses, depending on the purpose of the use: sight, hearing, smell and touch (Carmigniani, Furht, Anisetti, Ceravolo, Damiani & Ivkovic, 2010).

There are three different ways of visualizing for augmented reality. The first option is video see-through where a camera films the real world and shows this to the user, combined with the virtual part. This way the glasses or helmet is still opaque. It is the cheapest version and the easiest to implement. Brightness and contrast are also matched easily to the reality. The disadvantages are low resolution of reality, a limited field-of-view and user disorientation.

The second form of see-through is the optical one where the users really see the reality, added with virtual information or graphics. This display shows the real world, so the resolution will not be a problem. It is also relative cheap, safe and there is no eye-offset due to camera positioning.

The third option is projective display. It does not require wearing devices for the user, which is the biggest advantage. The display of the images is directly on the surfaces in the real world. The use is limited to indoor use only, because of brightness and contrast problems of the projections. Reflections on the surfaces can also cause problems (van Krevelen, 2007).

2.2.2 Devices

For augmented reality, there are three important types of devices that can be used: head mounted, handheld and spatial displays.

The head mounted display is of the same type as for virtual reality, but depending on the way of visualizing, it can be see-through or opaque.

Handheld displays are small devices with a display that the user hold in his hands. It makes use of the video-see-through technique to film the real environment and add the virtual parts as an overlay on the filmed scene. At this moment, there are two different kind of displays that are often used for handheld augmented reality: smartphones and tablets. The advantage of the smartphone is that it is widespread and easy to carry along everywhere. The technology is evolving quickly, which makes it a good and powerful device. The negative aspect is the size of the display, which makes tablets much more interesting. They are more powerful and the screen size is bigger. Negative side-aspects are that they are more expensive and often too heavy for single-handed use.

Last is the spatial display, which makes use of video-projectors, optical elements, holograms, radio frequency tags and other tracking technologies. It will display graphical information directly onto physical objects. The users do not need to wear or carry a device anymore, which gives a very natural experience.

There are three different forms of spatial AR. The first option is the video-see-through display that is screen based and similar to the version with the HMD. The second option is optical-see-trough, which has also a similar way of working to the HMD. The created images are aligned within the physical environment. The last option is direct augmentation, which is projector-based. It applies front-projection of images directly onto the physical surface of the objects (Carmigniani et al., 2010).

Van Krevelen (2007) gives a clear overview of the advantages and disadvantages of the different types of techniques for augmented reality.

Positioning	*Head-worn*				*Hand-held*	*Spatial*		
Technique	**Retinal**	**Optical**	**Video**	**Projective**	**All**	**Video**	**Optical**	**Projective**
Mobile	+	+	+	+	+	−	−	−
Outdoor use	+	±	±	−	±	−	−	−
Interaction	+	+	+	+	+	Remote	−	−
Multi-user	+	+	+	+	+	−	Limited	Limited
Brightness	+	−	+	Limited	+	+	Limited	Limited
Contrast	+	−	+	Limited	+	+	Limited	Limited
Resolution	Growing	Growing	Growing	Growing	Limited	Limited	+	+
Field-of-view	Growing	Limited	Limited	Growing	Limited	Limited	+	+
Full-colour	+	+	+	+	+	+	+	+
Stereoscopic	+	+	+	+	−	−	+	+
Dynamic refocus (eye strain)	+	−	−	+	−	−	+	+
Occlusion	±	±	+	Limited	±	+	Limited	Limited
Power economy	+	−	−	−	−	−	−	−
Opportunities	Future dominance	Current dominance			Realistic, mass-market	Cheap, off-the-shelf	Tuning, ergonomy	
Drawbacks		Tuning, tracking	Delays	Retro-reflective material	Processor, memory limits	No see-through metaphor	Clipping	Clipping, shadows

Source: Van Krevelen, 2007.

2.3 VRISE: Virtual Reality Induced Symptoms and Effects

VR might be very popular now, it is not all positive. Many people suffers from nausea and other side effects. Already in the twentieth century, there was an investigation into this problem. A 20 minutes' study with 150 test persons gave the following results: 61% were reporting some symptoms during or after the test period and even 5% had to withdraw from the study because of their symptoms. (Regan, 1995).

The question whether the use of VR outweighs the symptoms arises. The answer is different for every user, but it leads to new studies about the topic. It is important to understand which forms of ‘simulator sickness’ can occur.

Multiple studies learn that it is possible to divide the symptoms into three groups: oculomotor dysfunctions (for example: eye strain, difficulty focusing, headache), mental dysfunctions or disorientation (for example: difficulty concentrating, dizziness) and last physiological dysfunctions or nausea (for example: discomfort, headache, sweating, vomiting) (Rebenitsch & Owen, 2016).

There are multiple causes for VRISE. The main reason is sensory mismatch, where the stimulus from the virtual reality are not the same as the expected stimulus in the real environment (Rebenitsch & Owen, 2016).

Different aspects have an influence on this sensory mismatch. First, the quality of the images and the naturalness of the simulation are the most important. Secondly, the frame rate variations are very important. When the user moves around and the view moves to slow, simulator sickness will appear because our brains will be disoriented (Mazuryk & Gervautz, 1996).

A third important impact on the symptoms the user may experience is the impact of user control. If the user can control his views and movements himself, he will experience less symptoms because the brains knows which movements to expect (Sharples, Cobb, Moody, & Wilson, 2008).

From the different aspects that facilitate VRISE, it can be deduced that the occurrence of cyber sickness is different for various VR devices. The feeling of immersion, the different experiences and differences in user control will have a big impact. With a HMD, the user will determine his own movements. In a CAVE, there is the possibility to see your own body and other users. This will lead to a more realistic feeling. Only the person who’s controlling will have a similar control experience as with an HMD. The other people will have more difficulties with focusing and orientating, what will result in experiencing more symptoms.

Measuring cyber sickness during studies is not that easy. The most common way is with a questionnaire containing several questions on the three categories mentioned above, but the answers are very subjective (Rebenitsch & Owen, 2016).

Another option is a pre and post questionnaire, but again these are subjective. Last option is the objective psychophysiological measurement, where the researchers try to detect VRISE based on heart rate, blink rote electroencephalography and stomach upset (Davis, Nesbitt & Nalivaiko, 2014).

3.
VIRTUAL REALITY AND URBAN PLANNING

The implementation and use of virtual reality can happen in different ways and on different scale levels in urban planning. Going from city models on a macro-scale to urban projects on a mesoscale, and even on microscale the design and evaluation of architectural projects in the environment.

This chapter will discuss the use of VR on all these different levels of urban planning and in addition, there is attention for the opportunities and barriers. The information from this chapter is collected based on a theoretical literature research. Again, Google Scholar was the main source and the keywords for the first search were 'VR and urban planning/design'. Next to that searches were the term 'virtual reality' is combined with keywords similar to the titles in this chapter such as city models, CityGML, urban studies, urban design, construction phase, multidisciplinary working, participation processes, technology, side effects and methodology were used.

3.1 City Models

3.1.1 What is it?

A VR city model is a digitally generated graphical visualization of a city and its components. Traditionally, local authorities use cardboard models to look at their city and experiment with different options, changes and possibilities. The disadvantages are that it is not a flexible tool to make changes and the only way to look at it is through the 'bird's eye view'. Because of the evolution of computer and virtual reality, a change from cardboard models to 3D-models is possible. These models will give a better perspective on a human scale, are more accurate and are flexible to make changes inside the model. Where there was always the need for multiple documents, such as databases, maps, models and visualizations, there is now the possibility to integrate them into one VR model (Thompson, Horne & Fleming, 2006).

A city model can offer advantages for technical, environmental and commercial purposes. Therefore, both public authorities and private companies want to use city models for very diverse applications such as tourism, architecture, town planning, navigation systems and to do research on climate, noise and environment (Brenner, 2000).

A city model contains different city objects. The most important objects are the following: terrain and sky, buildings, landmarks, vegetation and landscape, streetscape and street furniture. There is the option to add pedestrian and traffic networks to the model as well (Thompson et al., 2006). Everything that was in GIS before can now have a visualization in a VR City model. All the symbols on a GIS map are displayed in VR as they are in reality. The main advantage is that it becomes possible to add and see height differences of elements (El Araby, 2006).

Because of the wide scope of application, many different and very varied stakeholders are interested in using city models. City authorities, the built environment sector and the academic world are the three main domains where they can be used. Underneath is a schedule that gives a more detailed view on who uses the models and for which purpose (Thompson et al., 2006).

CITY AUTHORITIES	
Planning and Design Related Activities	Urban planning scenarios Planning and decision support Spatial analysis What if scenarios GIS applications Development control Planning permission applications Contextual modelling Traffic simulations Transportation modelling Public participation Environmental impact assessments Visual impact analysis
Infrastructure and Facility Services	Climate, air quality, fire propagate, public safety studies Emergency planning Facilities and utilities management Property management and analysis
Commercial Sector and Marketing	Marketing and advertising E-commerce
Promotion and Learning of Information on Cities	Tourism and entertainment City portals

BUILT ENVIRONMENT SECTOR	
Base data resource	Architectural Planning Landscape architecture and planning Construction Surveying Real Estate etc. companies
Maintenance and development plans	Gas Electricity Phone Internet/broadband/TV companies
Marketing and advertising	

ACADEMIA	
Teaching and learning activities	Use and creation of city models City segment models for students projects Context analysis, mass analysis Experimenting ideas etc.
Research	
Consultancy	
Archiving	

Table with interested stakeholders.

Source: Thompson et al., 2006

Depending on the purpose and use of the 3D model, there are three different ways of visualization. First, there is the photorealistic visualization, where the aim is to give a realistic impression of the environment. Possible uses are for tourism, entertainment or public participation, because photorealism makes it possible for non-experts to understand how it will look once realized. The disadvantage is that the complexity of the geometry needs reduction to enable a good real-time rendering of a large-scale city model. Especially the modeling of plants and vegetation will easily give problems because of the high geometric complexity. File sizes will increase rapidly and files will become impossible to work with or will not run fluently.

Next, there is the option for the visualization of information and data. The visual feedback is not primary, because the 3D model is only the medium to give clear and comprehensive information. For example, it is possible to link information about vacancy, ownership, year of construction, etc. to the city model.

The third option is an illustrative, non-photorealistic visualization. It can have different purposes such as giving urban information, helping in the decision-making process, giving a first visualization of a design, helping in city and landscape planning, etc. It can combine principles out of cartography, geographic information systems, visualization and arts. This form can replace the traditional cardboard models, because of the interactivity and flexibility (Döllner, Baumann & Buchholz, 2007).

Three different ways of visualizing.
Source: Döllner et al., 2007

A city model can be made automatically where 2D straight-line segments and regions of an image are extracted and converted to 3D forms using an algorithm. The automatic technique changes rapidly because of the evolutions in hardware and software. It has great potential for a first design phase or an overall view. When there is need for a more detailed model, this can be done semiautomatic, where the computer will handle the large amount of data and the operator will interpret this afterwards. This will result in a more reliable and detailed city model (Förstner, 1999).

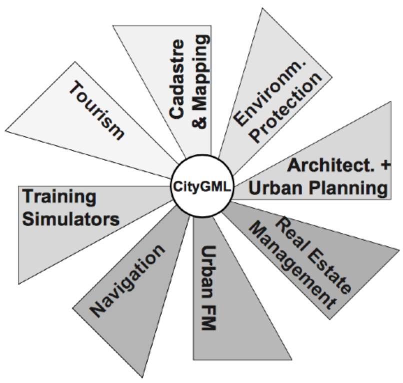
City models becoming more used and many cities already developed them. Berlin, London, LA, Beirut, Newcastel upon Tyne and Helsinki are some examples of cities that are using a city model already (Thompson et al., 2006).

3.1.2 CityGML

For creating city models, there was no worldwide-accepted standardized convention for a long time. CityGML is an initiative developed by GDI NRW, Geodata Infrastructure Nort-Rhine Westphalia. The realization is through an application schema for GML 3 and the data model is based on the ISO standard family 191xxx (Kolbe, Gröger & Plümer, 2005).

Today it is an open standard, of which the further development and maintenance is in hands of the OGC, Open Geospatial Consortium (Ohori, Biljecki, Kumar, Ledoux & Stoter, 2018).

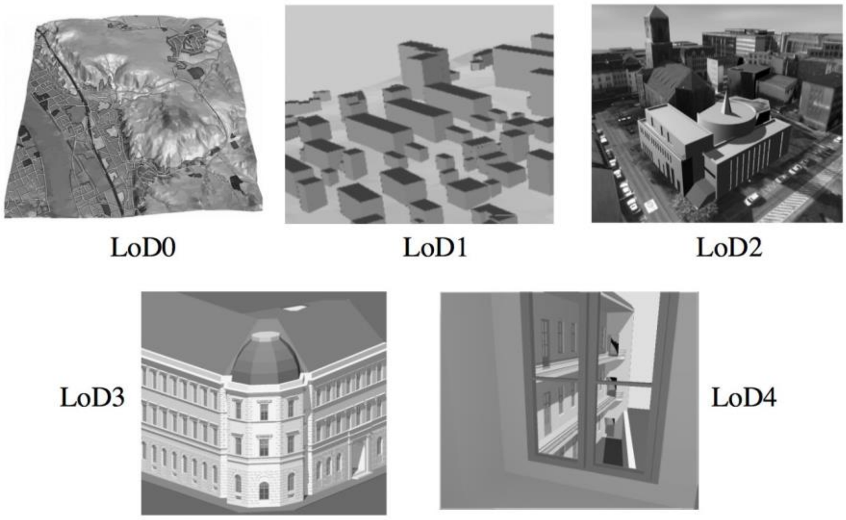
CityGML simplifies cooperation between different stakeholders (Döllner et al., 2007). It provides a core model with entities that can serve as a central information hub by different disciplines. It combines a semantic data model with a virtual 3D city model. Each stakeholder can attach their own domain specific information to complete the model and optimize the information exchange between parties (Kolbe, 2009).



Source: Kolbe, 2009

The use of GML is a help as well as a problem for urban planners, because of its often unknown coding language. The choice to base on the international ISO standard does provide a clear structure and equality in the CityGML models.

The CityGML model has five different levels of detail (LOD). LOD0 is the coarsest model and is a two and a half dimensional terrain model. In the CityGML there is specific attention for the topology of the terrain. LOD1is a model that contains blocks, without any further structure of texture. LOD2 has already roof structures and textures, in some cases there is also vegetation presented. LOD3 contains architectural models with detailed structures and elements. LOD4 is the finest level. Next to the architectural model, it also shows furniture, stairs, doors and other interior structures (Kolbe et al., 2005).



Visualisation of the five levels of detail

Source: Kolbe, Gröger & Plümer, 2005

A comparison between CityGML and GIS is often made because of the geo-information that is present. Also for the construction or architectural world and for facility management, there is a lot of information included. In CityGML there is the representation of all the 3D elements with the spatial properties and data (Kolbe, 2009).

In the building industry, BIM (building information model) is becoming very important. On a project scale, an IFC-model (industry foundation classes) contains all the data of a project combined with the 3D model. This makes the communication between different stakeholders better and easier. It would be a big advantage to combine IFC, which is on a project scale, with the bigger scale of a city model to have a complete and correct BIM-story on all the different scale levels.

It is possible to import an IFC model into CityGML, but the derivation is not yet possible because IFC only contains buildings and sites, and not yet topographic elements (Kolbe, 2009). The amount of detail is very different in both file formats, which leads to the fact that researchers are still studying on how to share the information and bring both models together (Ohori et al., 2018).

3.1.3 Intellectual property

There is one major disadvantage associated with the use of City Models and that is the aspect of intellectual property. It mainly concerns organizational and legal problems on this subject: who is the owner, what about copyright, who manages the model, what about security and privacy, who pays for the model and who can use it? It is a difficult issue involving different stakeholders, which are different for each city and each project. Bringing together the separate models of the different stakeholders, might help to get a shared ownership. Still this involves time, money and effort of someone to make this possible (Thompson et al., 2006).

It is important to understand that the boundary between authorship, creatorship, ownership and usership is very unclear. If there is no clear set of rules around this topic, clear agreements are necessary about who is responsible and who will be using the virtual city for which purposes.

Since CityGML, maintained by OGC, became an open standard, many of these uncertainties are solved. If cities decided to make and maintain the models privately, the different questions still stand.

3.2 Project scale

The use of virtual Reality is possible through the complete urban process, with different goals and benefits in each phase. If wanted, the model of the urban project can be loaded into the concerned City Model if it exists, what can offer an enrichment in every phase.

3.2.1 Design phase

Virtual reality can be useful in various ways in the design phase, whereby it can support the traditional plans and can replace scale models. Starting from the schematic development stage, where there are only rudimentary shapes to show the concept and see how it fits in the existing environment (Campbell & Wells, 2003).

Next, there is the design development where virtual reality helps to give a good idea of scale, order and proportions. Research has shown that forms of VR where the users walk on the ground will give a better perception of space and scale as it will be in real life. The version of VR where it is possible to fly through the design, to have viewpoints that are not possible in the real environment. This is useful for evaluating specific connections and details, which will lead to a strong reduction of faults and problems in the design. The level of detail will increase in each phase of the design process, which makes it possible to have a higher level of detail in VR than is possible in any other way of working (Campbell & Wells, 2003).

Through the design phase, VR can be helpful in the decision-making process, because it makes it possible to experiment, make multiple versions of a design and compare them. In an ideal world, the

3D-model in VR has a link with other software that provides immediate information about aspects as cost and performances of different design proposals (Petric, Maver, Conti & Ucelli, 2002).

3.2.2 Studies

Virtual reality can also help in the permit application phase. There is often a demand for various studies about the impact of a new development. VR can be helpful to show this impact on traffic, transportation patterns and on the environment (Jamei, Mortimer, Seyedmahmoudian, Horan, & Stojcevski, 2017).

When it comes to transportation and traffic studies, VR can also be very helpful for the development of intelligent transportation systems and automated highway systems. Virtual reality can help in the testing and evaluation phase, before bringing it to reality. Computer simulation for traffic is a good way to experiment with different algorithms in different traffic situations in a safe way. Virtual reality can help in the visualization of transportation, the modelling and simulation of new traffic systems and has many options for driving simulators. In VR, it becomes possible to see the interaction between the traffic model and the environment. When extra aspects of the environment are added, such as wind and number of lanes, it will give a lot of information about the driving speed and time delay (Yu, Kamel, Gong & Li, 2014).

Especially interesting on doing traffic studies in VR are all the different options and viewpoints that can be evaluated. It is possible to see the impact of transportation on the environment and vice-versa. When there is a new urban project, virtual reality can help to investigate what the consequences will be in terms of traffic.

Current shadow studies can be replaced by showing the impact immediately in VR (Kakuta, Oishi, & Ikeuchi, 2005).

3.2.3 Construction Phase

VR also has a function in the construction phase of the project. When problems arise, it can help to see how to tackle them. A big advantage is the possibility to look from perspectives that are difficult or impossible to see in real life (Campbell & Wells, 2003).

Also in terms of communication with the workers on site, it offers a great value. Whereas in the traditional way only information was exchanged based on CAD plans and verbal information, VR can create a clearer picture (Woksepp & Olofsson, 2008). If the VR-model is enriched with the aspect of time and information about the construction and costs, it can be used to make a good planning and to follow up the whole process (Issa, Flood, & O'Brien, 2003) .

Virtual reality can help with the planning of a construction worksite. Different parties need to work together here and not everyone is capable or trained of understanding 2D-plans and translate them by themselves in 3D to see the entire planned scene. It is important to have a good idea of spatial impression to organize the active areas and safety margins. VR offers the possibility to build the complete worksite in advanced. On the worksite itself, augmented reality can be of greater value. The user still looks at the real site as it is, but with the extra information about how everything should become. This can help creating an easy and quick setup that is understandable for everybody on the site, reducing mistakes and improving safety (Wang, 2007).

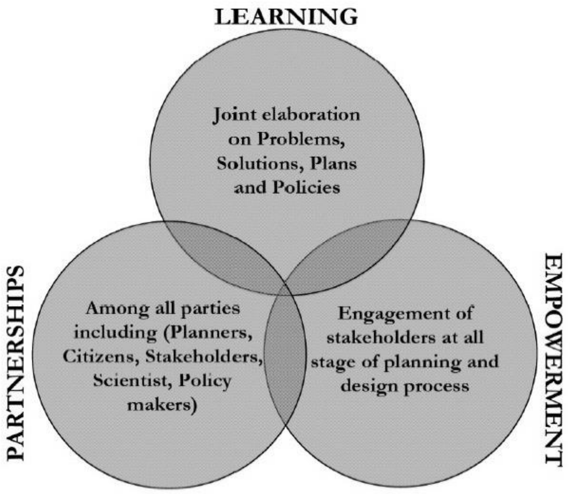
3.3 ADVANTAGES OF USING VIRTUAL REALITY

3.3.1 MULTIDISCIPLINARY WORKING

Often it is assumed that VR is a way of visualizing and has a great value for the designer, but VR can also be a tool that helps with working in a collaborative way.

In the traditional way of working, there is a clear and strict planning, which says when all different parties are involved in the process. Certain persons or organizations can work on or give their opinion about the urban project at set times. Nowadays, collaborative design is becoming increasingly important, so the exchange of information is better and design decisions are made in dialogue with all different parties involved (Fröst & Warren, 2000).

Because of participatory planning, we are evolving from a top-down hierarchy to a collaboration that will give a better result. Different parties such as planners, stakeholders, policy-makers, neighbours, scientist, etc. can be involved. VR can be helpful to create a platform for this active interaction between different disciplines. The focus in no longer on the designer, but on the mutual learning, the partnerships and the empowerment of stakeholders (Jamei et al., 2017).



Source: Jamei et al., 2017

The big advantage of this active interaction is the saved time compared to the traditional way of urban planning processes. The fact that VR models are 'portable' makes it possible to open and use them everywhere. Parties can see the model everywhere and there is not always the need to go physically on location. This makes collaboration easier and reduces waste of time (Thompson et al., 2006).

In the traditional urban planning process, a lot of time is lost because designs are passed back and forth between designers and other involved parties. The current technology, makes it possible to immediately involve all parties, which lead to a stronger, better and faster way of design decision making (Petric et al., 2002).

Another big advantage of collaborative design in VR is that every participant can be involved. When non-experts, such as clients and users, are confronted with traditional blueprints, the communication is sometimes difficult because these participants are not used to reading plans. This means that the collaboration will be difficult because some parties will not understand everything, which leads to mistakes in the communication or a big difference in the amount of influence between the different parties. To solve this problem, different presentation-tools are used such as perspectives and scale models, but virtual reality can be of much greater benefit in this case because it offers the feeling of scale, the possibilities to make it very detailed and look real and the option to walk around (Fröst & Warren, 2000). Because VR can give a very realistic image in comparison with scale models and perspectives, it is the most effective tool to use for offering the respondent the best result and satisfaction. This way researchers or designers can also reach parties without a deep knowledge of the design and is not adept at processing the abstract, traditional documents. Virtual reality makes it possible to include everybody in the collaboration process in an understandable manner (Simpson, 2001).

Virtual reality can be a tool that enable the designers to show their intentions and thoughts to the clients. By using VR, it is no longer a case of guesswork how the design is going to look like, which will make the communication between both parties a lot easier (El Araby, 2006).

For collaboration, the level of immersiveness will be important. The different VR environments will have different influences on the degree and manner of cooperation between parties. If there is an immersive usage, a HMD can be used to let people watch the VR-model on their own and discuss it afterwards. Another possibility is the semi-immersive CAVE (Petric et al., 2002). The CAVE solution seems like the best option because multiple people can watch the same VR-model at the same time on a real scale and in a good quality. The advantage of the CAVE on the HMD is that the all parties can be in the model at the same time and still see each other. Seeing the other parties is important for pointing at aspects in the model and having a good dialogue. With the HMD, the users will find themselves in their 'own world', which makes the discussions harder. The fact that the CAVE environment is the best solution is only an assumption.

Augmented reality with see-through displays are also a good idea to use for collaboration because it makes it easier to interact with each other when it is possible to see the other participants. The main use is on a worksite, but is also possible in an office. To avoid confusion or mistakes about what someone is pointing at, physical or VR pointers can be used (van Krevelen, 2007).

Depending on the scale and scope, stakeholders in the virtual reality collaboration process can vary widely (Thompson et al., 2006).

3.3.2 Participation processes

The use of virtual reality improves the communication between stakeholders because it is a clear and understandable medium. It can reduce confusion and improves trust. This is also a very important factor in participation processes for including citizens in a project. VR offers the option to develop and experiment with multiple alternative scenarios and discuss these with the citizens to see their reactions (Simpson, 2001). Because people see a completely modeled and visualized neighborhood where they can walk around, they will have a good experience of the proposed design scenarios. Creating this total experience where everything is clear, will help in participatory planning (Jamei et al.,2017).

What exactly makes VR better than the traditional ways of participation? Virtual reality will help in attracting the attention of community participants because of the visual way of communication. VR models are therefore a strong tool in participatory planning because they attracts community residents to public meetings in an easy way, which will lead to a higher number of participants and participation. (Wanarat & Nuanwan, 2013). Traditional documents are passive, but VR gives the users the option to navigate freely inside the environment and pick the wanted perspectives. In addition, the feeling of immersion is much higher, which gives citizens a better idea of the simulated situation. If wanted, there is the option to link comments to the VR-model. This way it becomes possible to give very specific remarks and 'pin it' to specific points in the model. Before this was difficult and the comments were more general (Howard & Gaborit,2007).

The use of VR-models may help the planning facilitator to get more feedback and information of the citizens. Compared to traditional ways of working, technology makes it possible to have quicker discussions and decisions. Because the participants are visually informed, there is a reduction in the time talking about the physical characteristics of an area. Also conflicts among participants will be reduced or solved quicker because of the use of virtual reality (Wanarat & Nuanwan, 2013).

Insufficient or late citizen participation often leads to complaints and appeals, and too long and expensive procedures. This is the main reason why citizens need to be involved in an earlier phase. There is the need for clear and comprehensible information (Bayer, 2018).

The clear communication is very important for the risk perception of people, because it will influence their opinion and decisions. If citizens cannot predict the outcome of a project, they will interpretate it as a risk. This helps them cope with the dangers and uncertainties that it brings along. Emotions are also playing an important role, when it comes to risk perception and social acceptation of a project. Changes in the environment of citizens evoke many emotions and thus a feeling of fear and risks (Slovic & Weber, 2002). Because traditional plans do not give enough information, citizens' reaction will often be negative out of fear of the unknown. Virtual reality can help reducing this fear and increase social acceptance by breaking down some of the psychological barriers in public meetings or hearings (Wanarat & Nuanwan, 2013).

Multiple environments of VR can help in the participation processes. There is the option to organize a moment where citizens can come and look at a project, with the HMD or in a CAVE. Similar to the current situation where people go and look at 2D plans.

There is also the option to use internet-based VR, what gives interested people the option to look at the project regardless their situation. The number of reached people will be higher, but there will be less control over who is watching the project and their remarks (El Araby, 2006).

An important side-note is that virtual reality is a good medium to communicate with citizens, but it does not guarantee the success of urban planning and a good participation process. This requires debate, negotiation, grouping opinions and come to a consensus. Virtual reality can help in this process to make ideas understandable, but only showing a project in VR is not enough to have a public participation process (Wanarat & Nuanwan, 2013).

3.3.3 Disaster planning and urban behavior studies

Having detailed, up-to-date and flexible virtual reality models, especially city models, is a big plus when it comes to safety and disaster planning. A virtual 3D model can provide planners and the government with important information for disaster management. All spatial objects and information about the terrain needs to be available by their geometry, topology, appearance and properties (Kolbe et al., 2005).

If this is the case, a VR model can help with the simulation of risks but also with the reconstruction after a disaster. GIS was a helpful tool to use after a disaster because of the 'after-action report'. Virtual reality can even give a better idea about the impact and how to react because of the clear visualization. It also helps in the communication between all the involved stakeholders in the disaster planning (Simpson, 2001).

A city model can also help in understanding the influence of an urban environment on the human behavior. One of the main application areas is the investigation of how people react when there is a potential dangerous situation. The prevention of crime is an important issue when it comes to urban planning. Narrow passageways without escapes, hidden spaces at the side of a road, big garbage dumpsters, etc. Those are all examples of a situation that can cause fear. When a city model is build, virtual reality can help with the examination of a design. If it contains places or situations that can feel scary for citizens, they have the option to make changes before breaking ground on site (Park, Calvert, Brantingham & Brantingham, 2008).

Also in case of a fire, fear and panic are important factors in the reaction of an individual. VR can help again with simulation of their movements. Especially in public spaces, it is important to know how the crowd movements works, to adapt the design of buildings and sites, and to improve fire evacuation procedures (Li, Tang & Simpson, 2004).

3.4 Disadvantages of using virtual reality

3.4.1 Technology

The biggest disadvantage of virtual reality is the high cost of adopting the technology. Hardware and software are necessary. Depending on the chosen devices and software programs, the price can be very high. This makes it sometimes almost impossible for small firms or urban designers to use VR daily in their designs and projects (El Araby, 2006).

Because of the quick evolution in technology, the prices are much lower today compared to a couple of years ago, which leads to a transformation. The use of VR becomes possible and more affordable to use in all the environmental design fields (Simpson, 2001). When looking at the hardware, the HMD is now an affordable tool to show a project in VR. More advanced technology, such as a CAVE, is still expensive due to the many projectors and computers that are necessary. A bigger problem is the need for software. The price of licenses can be very low or very high, depending on the chosen software. For some software, people with specific knowledge are necessary to program the virtual environment, but in other cases the standard design programs are sufficient for showing a project in VR (Hilfert & König, 2016).

Technical problems are the next big problem, such as low sensitivity trigger to recognition, GPS errors, problems with file sizes, etc. (Akçayir & Akçayir, 2016). The computational power needs to be high, which leads to the high cost mentioned before, and even then, there can still be display problems and limitations of hardware. When a VR model is too detailed, it will be difficult to render it at a good speed and de technique may crash (El Araby, 2006).

Virtual reality needs highly accurate trackers. Even a tiny fault or error can cause problems for having a good VR experience. If the technical part is not walking or looking around at the same time or in exactly the same direction as the user, then VR is not working properly and will not be useful (Wang, 2007). By a slow rendering time or slow trackers, this can lead to VRISE, mainly nausea, as mentioned before.

The needed space for some of the virtual reality devices is a disadvantage. For example, a CAVE solution needs a big, fixed surface where it can be build. This makes it more difficult to bring it to the field of urban design. There is also a mobile CAVE from Barco, but it takes half a day to build the CAVE and the cost is very high.

For the other forms of VR, the portability and outdoor use is a limitation. Most of the systems requires a lot of heavy material to carry, which makes it hard to bring it to every wanted space. Outdoor use is limited and often not possible because the equipment is not weather resistant. Aspects of brightness, contrast and resolution causes many problems with outdoor use (van Krevelen, 2007).

Next, there is the time needed to make the VR model. Especially in a design phase this may take a lot longer compared to hand sketching. This is one of the reasons why urban designers will stick to the traditional design methods (El Araby, 2006).

To receive a good VR model, all the information needs to be prepared and registered accurately and very precise (Wang, 2007). Most of the time, urban designers do not have enough technical knowledge to build good VR-models as this is not part of their expertise. For example, for a CityGML knowledge of the GML coding language is necessary (Kolbe et al., 2005).

3.4.2 Social and physiological side effects

For some people, there is a lack of motivation or stubbornness to switch from the traditional way of working to a new way with the use of virtual reality. Many people active in the construction industry are conservative and, accordingly to Wang (2007), reluctant to change especially in the aspect of moving toward new technology. A mindset shift is neede. It is important that social concerns are not ignored to make the switch possible. For example, if workers think that the lasers might implement a health risk, it is important to make them understand that the lasers are eye safe. It needs to be clear that virtual reality is a tool for them to make the job easier and does not replace them as human workers (Wang, 2007).

The concerns lead to the fact that social acceptance of VR might be a bigger challenge than expected. The appearance of people is also a big problem. The helmets, glasses, gloves, etc. are not very fashionable, which leads to the fact the people do not want to wear them. Privacy concerns are another problem for some people if they are filmed (van Krevelen, 2007).

The way of using the tools for VR will have a big influence on the social acceptance. If it feels natural and easy to work with, people will use it quicker than when they must learn something new.

People do not want to look awkward in front of other people or in public places because they do not know how to interact with the devices (Carmigniani et al., 2010).

Virtual reality will cause a shift in the way of communicating from personal to electronic. The principles of environment behavior are fundamental for the perception of space and place for someone, and are getting lost right now. But also issues as social-cultural perception, symbolic meanings and how a space can influence someone’s mood and behavior are aspects that are not so clear and sometimes forgot in the virtual realm instead of physical (El Araby, 2006).

4.
EMPIRICAL RESEARCH ON THE APPLICATION OF VR IN URBAN PLANNING

4.1 OVERVIEW EMPIRICAL RESEARCH

An analysis of the empirical research and experiments around this topic has been done. The main source for this empirical research was Google Scholar. Keywords were the same as for the literature study, but now combined with keywords as 'study' or 'empirical research'. The most used combination of keywords was 'VR in urban design – empirical study', which gave almost 70.000 hits. Next, there was a selection based on evaluating the title and source of the article. Many of the articles only discussed a very small study on a very specific topic, making it irrelevant for this review paper. Subsequently, the number of times there was a reference to the source also played a role in investigating how important the empirical research is. Finally, there is the year of publishment that was important. The focus was on articles as recent as possible due to the rapid changes in the field of VR. If recent research did not exist for a certain topic out of the literature study, it was decided to look at older studies because of the interesting assumptions in it. These studies are the basis for the use of VR in urban planning.

Twenty articles were selected in the end, based upon the different criteria. All the studies are discussed in the table and categorized with keywords. These keywords link the studies to the titles of the literature review.

The table explains all the necessary information to have a good idea of what the research is about and which are the results. First the source is given, together with the information and questions that were investigated in the study. Next, there is a brief explanation of the methodology, how many parts there were and how the evaluation happened. Information is given about the participants and the form of virtual reality or visualization that is used. Then there is extra information about the practical aspects of the study: where was it, was there a specified timing and what was the task and procedure for the empirical study?

Last, there are the findings and remarks about the study, based on what is relevant to this paper. If the researcher had recommendations for further research that is useful for the discussed topics, then it is also included in the table.

	Empirical study			Method			Participants		Virtual reality	Study			Evaluation/results	
	Keywords	Title and source	Information about study	Method	How many parts in the study	How evaluated	Amount	Selection criteria	Form of VR	Location	Timing	Task and procedure	Results	Further research
1	**Virtual reality**	Virtual reality as an empirical research tool — Exploring user experience in a real building and a corresponding virtual model Kuliga, S. F., Thrash, T., Dalton, R. C. & Hölscher, C. 2015	- Comparison of an existing building with a virtual model: examining differences in experience - Is VR a valid environmental representation?	Multi-method approach	3 - 1: investigation of the correspondence of building users' experience in a real conference centre and a virtual model. Does the order of presentation has an impact? - 2: Investigation of the correspondence of building users' experience in a real conference centre and a virtual model: with self-navigation - 3: Study that virtually implemented systematic redesigns to the existing building layout	- Study 1: Questionnaire with a bipolar 6-point semantic differential scale for different items - Study 2: Same questionnaire as in study 1 + evaluating how much the user felt involved in the virtual experience - Study 3: Informal comments during walkthrough	- Study 1: 23 - Study 2: 20 - Study 3: 8	- Study 1: Students of an international spring school in cognitive science - Study 2: Students of an international spring school in cognitive science - Study 3: Students of the same spring school that did not participate in study 1 or 2	- Study 1 and 2: Laptop - Study 3: Large projection screen	- Real building: Heinrich-Lübke House in Günne am Möhnesee - Virtual environment	No information	- Study 1: Half of the participants first experience the real building and than the virtual one. The other half had the reversed experience. - Study 2: Same study as study 1, but self-navigation is possible. - Study 3: Users could give comments on the differences between the real world and the changes that are made in the virtual world.	- VR has a strong potential to be used as empirical research tool in psychological and architectural research. - Participants who first experience the virtual building rate the virtual environment more positively than the participants who first saw the real environment. - User experience is vital to studies about human-environment interaction.	- Further study can prove the potential of VR for behavioural validation.
2	**Virtual reality**	A comparison of active navigation and passive observation of desktop models of future built environments Conniff, A., Craig, T., Laing, R. & Galan-Diaz, C. 2010	- Comparison of passive observation of walkthrough with a user-controlled, active navigation	Experiment	2 different versions of the same place	- Participant viewed one monitor and a digital video camcorder was pointed at another monitor, to simultaneously record video output and subjective commentary from the participant whilst preserving anonymity - Participants could make notes on paper during the session - Questions based on three main themes: opinions on versions of the model, perception and sensations on differential scales and sense of presence - Four open-ended questions relating to overall experience	81	- Between ages of 18 and 40: mean age was 28,5 - Normal or corrected-to-normal eyesight - Had not been to the Faroe Islands - Non regular players of computer games - Variety of educational backgrounds	- Computer VR - Navigation with mouse and keyboard	Photorealistic computer model of Tinganes	No information	- Participants were shown two versions of the same place and at the end they need to report which version they preferred and why. - There were two groups: a group with self-navigators with instructions of the researcher and a group observers that watched walkthroughs. - Self-navigators were given a brief training session before the experiment on how to move around. - Participants needed to think aloud during the experiment.	- Observers of walkthroughs tend to be more observant of architectural detail. - Self-navigators tend to notice bigger structural and layout alterations. - Passive observation may be better if the purpose is to compare design alternatives, since it gives a better feeling for what it's like to be there.	- Repeat the study with a population that is already familiar with the area that is presented in VR. - Would the participants focus to a greater extent if the rendering was more realistic and less artificial? - Is there an added value in adding realistic auditory background sounds?
3	**Virtual reality**	Psychological and physiological human responses to simulated and real environments: A comparison between photographs, 360° panoramas and virtual reality Higuera-Trujillo, J. L., Maldonado, J. L.-T. & Milan, C. L. 2007	- Comparison of the psychological and the physiological responses to the environment - Analyse of presence	Set-up of four environments	2 - 1: Focus on analysis of the psychological and physiological responses - 2: Analysis of presence	3 methods - 1: SMB scale for environmental assessment - 2: PAD emotional state model - 3: SUS presence questionnaire - Afterwards: statistical analysis	100: 25 participants for each set-up	- Between age: 23-51 year - 54% male, 46% female - Not be familiar with the scenes - Not suffer from claustrophobia, epilepsy or nausea	- 1: Physical environment - 2: Photograph (viewed with HMD) - 3: 360° panorama (viewed with HMD) - 4: VR (viewed with HMD)	- 1: Study environment - 2: Physical environment	3 minutes time in the environment	- Brief explanation of the experiment. - Need to sign informed consent. - Instructions on how to use the technology. - Participant for VR: practise time to get used to navigate in VR environment. - Start experiment: same starting point and angle of view. - After 3 minutes: questionnaire while still looking at the stimulus.	- VR and 360° panorama approach the physical environment more closely. - Interactivity in VR has a influence on the sense of presence. - 360° panoramas have the best results for psychological measurements - VR has the best results for physiological measurements. - Photograph format is the most different from the real environment, but still the most used format. - In 360° panorama format: some dimensions are overestimated; for photograph format: some dimensions are underestimated. - VR format scores the highest in the 'arousal' dimension, probably caused by the format's stereoscopy or by motion sickness.	- Interesting results for research into the advantage of the visualisation technologies. - It is possible that the results are different if another system or device is used instead of HMD. - Add augmented reality in a next study. - Neuroscientific methods (for example EEG) would expand the objective responses.

	Empirical study			Method			Participants		Virtual reality	Study			Evaluation/results	
	Keywords	Title and source	Information about study	Method	How many parts in the study	How evaluated	Amount	Selection criteria	Form of VR	Location	Timing	Task and procedure	Results	Further research
4	**Virtual reality**	Assessment of path choices on a country walk using a virtual environment Bishop, I. D., Wherrett, JA. R. & Miller, D. R. 2001	- Experiment to answer questions about validity and about local landscape preferences - Model is based on a section of the Dee valley in northeast Scotland	Experiment	2 - 1: Virtual environment - 2: Validity test	- Study 1: Subjects' choices were monitored and recorded from a remote computer - Study 1: Questionnaire - Study 2: Subjects' choices were registered	- Study 1: 42 - Study 2: No information	- Study 1: Volunteers who are employees of the Macaulay Land Use Research Institute in Aberdeen, Scotland 2: No information	- Study 1: Virtual environment - Study 2: Still images on the internet	- Study 1: Virtual environment in Scotland - Study 2: Internet	- Study 1: Maximum 15 minutes - Study 2: No information	- Study 1: Participants were given a set of instructions and also shown a map of the area. - Study 1: Participants were left alone in the room for the experiment. - Study 1: During the experiment: participants needs to make choices between different paths. - Study 1: After experiment: short questionnaire. - Study 2: Participants needs to chose between the same paths as in experiment 1, but now based on still images.	- Participants made choices in the virtual environment which fitted their stated preferences and were different from the choices other subjects made on the basis of still images. - People will make deliberate choices in a virtual environment.	- No further recommendations.
5	**City model; studies**	Investigating the Role of Virtual Reality in Planning for Sustainable Smart Cities Jamei, E., Mortimer, M., Seyedmahmoudian, M., Horan, B. & Stojcevski, A. 2017	- Potential of VR in visualizing pedestrian thermal comfort in cities - Potential of VR in visualizing smart transportation in a city - Potential of VR in data management - Potential of VR in visualizing the cognitive behaviour of urban dwellers - The whole experiment is based on a VR city model for Melbourne	Experiment of a real case study	4 - 1: Study examined the thermal consequence of implementing 'Plan Melbourne' at the pedestrian level at a neighbourhood scale - 2: Information on real-time data on traffic, pedestrian and parking conditions and diverse available transportation systems to reduce the traffic issues and the incidence of major accidents - 3: VR assist in aspects of spatial information management and urban development - 4: VR used as basis for the cognitive movement in cities and to analyse and stimulate people's interaction with their surrounding environments	Evaluate the model	No information	Urban planners, researchers, stakeholders and community developers	No information	VR city model of Melbourne	No information	- Looking at the models. - Going into dialogue. - Share the project.	- VR can help with the dialogue between different parties. - VR can increase the level of awareness. - Communities will feel highly engaged in the policy-making process by using VR. - VR can help creating a clear vision on what-if scenario's. - VR can help in the traffic problem. - VR can help linking the government to the society and enable planning professionals to take appropriate decisions during approval processes. - VR creates a link between theoretical and practical frameworks. - VR has the capability to assess design ideas in real time during the design and planning phase. This saves time by excluding guesswork. - VR makes integration of all aspects in the design possible. - VR promotes participatory planning. - The key challenge for implementing VR in urban planning is the cost.	- No further recommendations.
6	**City model**	Visit VR Glasgow: Welcoming multiple visitors to the Virtual City Ennis, G. & Maver, T. 2001	- How interact participants with the existing system under different conditions? -What benefits perceive the participants on entering the environment via the multi-user interface? - Information is based on the city model of Glasgow	Real use of the city model	3 - 1: Registered members who gives feedback - 2: Follow-up of the use - 3: Visitors who looked at the exhibition at a public gallery were observed	- Study 1: Feedback forms - Study 2: Automatic counting system - Study 3: Observation	- Study 1: 300 visitors registered to test the system in 1999 - Study 2: 10.000 visitors each year - Study 3: No information	- Study 1: Everyone could register - Study 2: Everyone can visit the website - Study 3: Everyone can visit the public gallery	- Study 1 and 2: City model on the internet - Study 3: Screen with projector	- Study 1 and 2: Online - Study 3: Exhibition of the city model in a public gallery	- Study 1 and 2: 15 minutes - Study 3: 20 minutes	- Study 1: People need to register. Next they are able to look at the city model online. Afterwards they give their feedback. - Study 2: The visitors on the website are counted and the time they spend there. - Study 3: Users are observed to see how they use the city model.	- Visitors tend to navigate in the central zone of the area. Even the participants who are not familiar with the 'real' Glasgow. - A tour guide helped the users to explore the virtual city. - Users had problems with finding each other in the city model.	- The system would be better if there is the possibility to identify the location of other participants.

	Empirical study			Method			Participants		Virtual reality	Study			Evaluation/results	
	Keywords	Title and source	Information about study	Method	How many parts in the study	How evaluated	Amount	Selection criteria	Form of VR	Location	Timing	Task and procedure	Results	Further research
7	Design phase; participation processes	An Analysis of Usage of Different Types of Visualisation Media within a Collaborative Planning Workshop Environment Gill, L., Lange, E., Morgan, E. & Romano, D. 2012	- Which type of visualization helps to engage with stakeholders in a collaborative planning workshop? - Research to familiarity with the usage of different media types for communicating planning proposals - Research to suitability for understanding and facilitating of each media type	Experiment	8 different presentation options	- Discussion of the proposal that is video recorded - Duration of usage of each media type was recorded and analysed - Questionnaire	11	Six members of the SWSG and five researchers	- A1: 1:1000 scale plan view - 5 x A3 image views - 1:500 scale model - 3D CAD: sketchup - 3D walkthrough with game controller - 3D walkthrough with game controller and stereo glasses - A1 1:1000 scale current situation map - A1 1:1000 scale Sheffield Council 'master plan' plan view	Reflex studio: virtual reality laboratory at the University of Sheffield	No information	- Each media type was introduced at the beginning. - Participants could examine all the different media types. - For the interactive 3D media: participants could chose to navigate themselves or have a facilitator navigate for them. - Participants were left after experiment to discuss the proposal. - After discussion: questionnaire was filled in by each participant.	- Coding of a video timeline is a complicated and time-consuming process. - Most used media type was the mapping containing a wider context. The reason may be that the proposal was related to flood defence and a wider context was needed. - Isolated areas of visualisation are not seen as useful in comparison with the ones which contain contextual spatial information. - Software tools for participatory planning workshops needs to be able to switch between mapping and 3D easily.	- It is a limited group so it is hard to form conclusions out of it. It is interesting to see if the results can be replicated and how different group sizes or other participant mixes may effect them.
8	Design phase	Application of Human-scale Immersive VR System for Environmental Design Assessment - A proposal for an Architectural Design Evaluation Tool Ryu, J., Hashimoto, N., Sato, M., Soeda, M. & Ohno, R. 2007	Experiments related to urban environmental design verification and evaluation	Experiments	3 - 1: Evaluation and verification of public space design - 2: Human behaviour in public open spaces concerning seat preference in public squares and the distribution of the surrounding people - 3: Several basic psychophysical experiments on human distance perception in virtual space	- Study 1: In percentages - Study 2: Subjects had to evaluate the positions resting, reading and eating on a scale of 0 to 20 - Study 3: Comparison of the estimated distance in real and virtual environment	- Study 1: No information - Study 2: 19 subjects - Study 3: No information	- Study 1: No information - Study 2: 8 male, 11 female - Study 3: No information	- Multiprojector display system (D-vision): 180° viewing angle - Turn-table as locomotion interface	- D-vision at university - For study 2: Also real urban environment - For study 3: Also real hallway at the university	No information	- Study 1: Users can navigate freely through the environment. - Study 2: Human seat presence was observed in virtual and real environment. - Study 3: Subjects had to walk 2, 5, 10, 15 and 20 meters in the real and virtual hallways while looking straight ahead. The estimated distance is compared to each other.	- Human-scale immersive virtual system can help to assess urban environmental design and to perform experiments on human behaviour. - The distance in virtual space is underestimated by about 20% - 40% compared with the distance in a real environment. - Insufficiency of information in VR causes a different distance sensation than in a real environment.	- The research is still on going to realize more complete VR applications. - Human factor issues, for example sensory perception and psychological cognition, must be examined in greater detail. - Start using this application for disaster preparedness training.
9	Design phase	Design and evaluation of a real-world virtual environment for architecture and urban planning Drettakis, G., Roussou, M., Reche, A. & Tsingos, N. 2007	Study about the design and evaluation of user activity in virtual environments: user needs analyses and usability evaluation	Experiments and evaluation of real use	4 - 1: Controlled experiments: evaluate the combined effect of realism and interactivity for a real-world urban planning task - 2-4: Situated tests: observe how non-expert users uses the system in the context of real-world usage	- Study 1: Direct observation by a facilitator using a think-aloud protocol, post-experiment questionnaire (scale questions from 1 to 7) and post-experiment interviews - Study 2, 3 and 4: Thinking-aloud	- Study 1: 3 - Study 2: 10 - Study 3 and 4: No information	- Study 1: Architects, all directly involved in the real Nice Tramway project and in the design of the new Garibaldi square - Study 2: Mainly high-ranking city officials in charge of public spaces and urban planning and the architects in charge of the overall project - Study 3: No information - Study 4: High-ranking officials of the project and the municipality	- Study 1: Barco Baron workbench with tracked game controller. Participant was head-tracked and wore active stereo glasses - Study 2: Laptop, a portable projector with stereo loud-speaker based sound system and the standard gamepad-based controller - Study 3: Full VE-system, tracked stereo-vision workbench - Study 4: No information	- Study 1: Controlled laboratory context - Study 2: City Hall decision meeting - Study 3: Brainstorming session - Study 4: Presentation of different options to officials	No information	- Study 1: Training in simple virtual environment. During real experiment, the participants were asked to carry out a set of predefined tasks. During the experiment, the level of realism changed. - Study 2: Two different scenarios were mapped onto two different buttons on the gamepad. The participants could change and move freely. - Study 3: The users visited different angles of the project and examined three different options. - Study 4: The users could examine four different scenario's by looking at ground level and in a balcony view.	- Both audio and visual realism contribute to a better understanding of the VE. - The VE-specific aspects such as multiple views are important for users to understand a project properly. - The approach of engaging users in the design is time and resource intensive.	- It was only a small testing group, so further research is necessary. - The interface issues need to be resolved in a next research. - Investigation of artistic renderings in VE's. - Can sound have a positive influence on the sense of presence?

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10	**Design phase**	Fuzzy Evaluation Method of Virtual Reality for Urban Landscape Design Wang, H., Ho, Y. & Chen, K. 2007	- Case study of the Chunghua Road pedestrian zone in Taipei City - Evaluation of design proposals and immediate feedback on design decisions	Evaluation and design decision making for a real project	Three design options compared to the present scene	- Fuzzy Evaluation Method - Evaluation based on spatial function, building interface, spatial scenario, street furniture, planting effect and visual simulation - Each aspect needs to be given a rate: very poor, poor, average, good or very good	No information	Experts and non-experts	No information	In virtual environment of Zhonghua Street Ximen Pedestrian Area in Taipei City's Wanhua District	No information	- Three design options needs evaluation. - Answers are set in a relationship matrix .	- Fuzzy decision making question can help in the decision-making for urban pedestrian zones in landscape design. - Computer-aided design technologies promotes the automation of landscape design. - VR improves the quality and results of the presentation of a landscape design.	- Create modules and databases for VR technology. - Add elements as light, water and sound to the study to have a better feeling of reality
11	**Design phase; multidiscipli-nary working**	Agent-based augmented reality system for urban design: framework and experimentation Wang, X. 2007	- Pilot study on an agent-based augmented reality system: ARUDesigner - What is the strength/weakness of ARUDesigner in supporting collaborative urban design?	Experimental pilot study	2 - 1: Construct a layout plan at Millers Point in Sydney that focuses on re-establishing new residential area in mixture with commercial district - 2: Design a layout plan that seeks to transform Millers Point into a next commercial area with public services in order to attract foreigners and tourists	- Traditional wooden block method was chosen as the benchmark for validation of ARUDesigner - Additional questionnaire for subjective feedback - Video recording was used as an objective analysis on the de-facto behaviour of the subjects	8	- 4 groups: 2 with architecture background, 2 without - Each group has two members	HMD	No information	10 minute for each part of the study	- All groups had to use two methods on two different design scenarios. - Methods and scenarios were mixed between the groups to minimize the effect of scenario difference.	- The ARUDesigner system could allow designers to assess design solutions. - All the subjects believed that the system holds potentials in urban design.	- Future works are to prototype the simulation and interaction layers and integrate them with the current ARUDesigner.
12	**Design phase**	Evaluating design alternatives using conjoint experiments in virtual reality Dijkstra, J., van Leeuwen, J. & Timmermans, H. 2003	Experiment that explores the possibility of using panoramic views on the internet to evaluate design alternatives	Experiment	3: The subjects received three evaluation sets with four choices	ICARUS: a system for interactive conjoint-based analysis in virtual reality of user satisfaction and decision making	137	- 112 were employed at Eindhoven University of Technology in the architecture department, 25 not - 114 participants had a architectural background, 23 not	Panoramic views on the internet	Panoramic view of office spaces on the internet	No information	- Subjects had access to a site on the internet. - Subjects received a welcome and introductory text relating to the experiment with the purpose and explanation. - Subjects could look around in the panoramic view and need to make choices between the options.	- VR can improve the reliability and validity of conjoint experiments. - The feedback to the system was positive. - VR offers a potential for the evaluation of design performance.	- There was no comparison between the results of the experiment in VR and a conventional form of presentation.
13	**Design phase; multidiscipli-nary working; participation processes**	Virtual reality used in a collaborative architectural design process Frost, P. & Warren, P. 2000	- What are the possibilities of using VR in architectural design processes? - Study on a real project for collaborative design of a laboratory layout	Pilot study of a real case	3 - 1: Traditional design session with paper and pencil - 2: CAVE visit one - 3: CAVE visit two after changes in model	- The participants could give feedback on the visit and the project - The CAVE visits were alternated with more traditional design sessions outside the CAVE with drawing, paper and pencils	No information	- Participants came from two different institutions at the Chemical Department: from a research laboratory at Organic Chemistry and from an educational laboratory at Inorganic Chemistry - Also people from the University's facility management and administrative staff, architects, researchers and others	CAVE	- Chemical Department at Lund Institute of Technology -VR environment of a laboratory - Inside and outside the CAVE	No information	- The participants could make a design together on paper. - Two CAVE visits were planned with two weeks in between. - After the first visit, participants could make changes, which are showed during the second visit.	- The CAVE is working in this project as an advanced visualization tool into the design process. - The users were very positive about using VR. - VR helps founding a common ground between the architect and the users of the laboratory. - The CAVE is seen as a fun way to discover, learn and participate in a free and creative way. - The CAVE immerses the participants, what makes the questions they had more relevant. For example about distance. - Low detailed models already works well in an early design phase, which makes it time efficient.	- It is an ongoing project for the coming two years.

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14	**Construction phase**	Innovation and users: virtual reality in the construction sector Whyte, J. 2003	- How do project size and extent of design reuse affect the technological requirements of users? - Study about the implementation and us of VR in the lead user firms in the construction sector	Multiple case study method	No information	- Semi-structured interviews - Research of supporting company documentation	- 11 lead-user organizations - 4 suppliers	- Firms were identified through participation in industry for on virtual reality or through VR software suppliers' recommendations - Firms are architects, real estate owners, housing developers, construction contractors or consultant engineers - Firms are based in the USA or UK	Not specified	USA or UK	No information	- Interviews were taped and transcribed or extensive notes were taken. - Interviews were used in conjunction with supporting company documentation. - Extensive background data about the use of VR in the construction sector was collected. - Extensive background data about the use of VR in the construction sector was collected. - Case studies were conducted with four of the main suppliers.	- Results are only a snapshot of the rich and varied early uses of VR within the construction sector. - A single virtual reality application does not have a market in the construction sector. - There are different uses and divergent technological requirements for every user. - For construction contractors VR can help in identifying errors and clashes early in the process. - For consultant engineers and project managers VR can help to co-ordinate design information for a wide range of professionals. It also helps reduces costs an make decisions. - Real estate owners and developers uses VR for scheduling construction and to improve the product and reduce waste in the process. - Architects uses VR for the designing process and visualizations.	- Researchers and policy makers needs to be aware of the different needs for each sector. - Interaction between design, engineering and construction firms and the IT suppliers needs further study. - The role of intermediary organizations, for example universities and model builders, needs to be examined in adapting technological capacity to the rate of change in the production of generic technologies.
15	**Multidiscipli-nary working, participation processes**	Integration of CFD, VR, AR and BIM for Design Feedback in a Design Process Fukuda, T., Mori, K. & Imaizumi, J. 2015	Can VR and AR help answering questions about a housing design project?	Experimental study of a real case	2 VR-simulations and 1 AR experience - VR 1: the study observed if the bath was visible from any of the buildings in the neighbourhood - VR 2: CFD simulations were done in the VR simulation - AR 1: for studying the arrangement of the car park in the house	- VR 1: looking from the perspective of buildings in the neighbourhood - VR 2: arrows showed the wind directions and a colour map showed the temperature - AR 1: comments while wearing HMD	3	Collaboration between architect, engineers and client	- VR application on the internet - HMD for AR	No information	No information	Users can freely navigate in VR and AR environment.	- The CFD simulations in VR helped the client to understand the airflow more intuitively. - The VR application can be used for (a)synchronous distributed meetings via the internet, which can replace face-to-face meetings.	- The house is in construction. When it is complete, temperature sensors will be installed to measure the actual thermal environment and verify the data.
16	**Participation processes**	Tunnelvisie: Totaaloverzicht van studies en bevindignen naar de beleving en waardering van stedelijke barrières voor fietsers in Schiedam Translation - Tunnel vision: Total overview of studies and findings on the perception and appreciation of urban barriers for cyclists in Schiedam Tunnel vision: Total overview of studies and findings on the perception and appreciation of urban barriers for cyclists in Schiedam Dijkzeul, D., Vos, B., de Leeuw, G. & Atlantis Games BV. 2017	Study to measure cycling experience in underpasses and tunnels with the help of VR	Experiment	4 - 1: Introduction scenario - 2-4: 3 different biking routes	- Questions after introduction scenario - Questionnaire with 7 point scale after each route	159	Everyone could join the experiment	HMD combined with CycleSpex (VR simulator with bikes)	Schiedam	- Riding bike on own speed. - 6 minutes between each experiment.	- The participants will join three different experiments. Each experiment shows a different route. - In each experiment there is first an introduction scenario, followed by four other scenarios. - After the introduction scenario, the participants needs to answer questions about the VR-technology. - After each experiment, the users needs to answer question. - Between the experiments there is six minutes free time.	- The reactions on the use of VR were very positive. - The amount of people who experienced dizziness was relatively low for people who first come in contact with VR. - The participants were surprised by the quality of the environment and how real and familiar it looked. - VR helps to attract people to join in the participation process. - There is a barrier between the urban designers and the game engineers. They do not speak 'the same language'. - There is a difference in the use of programs between urban designers and game engineers. - Showing a real environment in VR means that the environment needs to be simplified. It is important to see how to do this, so it still looks real and familiar for the participants.	- In which phases of the design process is VR useful?

	Empirical study			Method			Participants		Virtual reality	Study			Evaluation/results	
	Keywords	Title and source	Information about study	Method	How many parts in the study	How evaluated	Amount	Selection criteria	Form of VR	Location	Timing	Task and procedure	Results	Further research
17	**Participation processes**	Using virtual environment technology to improve public participation in urban planning process Howard, T. L. J. & Gaborit, N 2007	- Case of public engagement with the process of government - Focus on interaction inside the virtual environment	Case study	4 - 1: Test to see if the technological aspects worked on a standard home computer - 2: Test the usability of the environment - 3: Experiment of an urban planning simulation - 4: General public survey	- People can give feedback on the model - People can make changes in the m - Communication during the consultation is also possible - General public survey: "on street" survey	- Study 1: no information - Study 2: 25 - Study 3: 25 - Study 4: 26	- Study 1: The researchers did this - Study 2: No information - Study 3: No information - Study 4: Age from 24 to 80 years, with a mean of 44 years. 12 male and 12 female. Different level of experience with computer science.	Standard computer	- Study 1: No information - Study 2: Public consultation - Study 3: Public consultation - Study 4: Event	- Study 1-3: No information - Study 4: 15 min presentatio n and demo	- First a tutorial of the application was tested to see if it worked. - Next the real experiment was done. The participants could make changes and give feedback on the model. - Also a public survey is done with other people. They received a presentation and demo. Next they need to fill in a questionnaire.	- Model was suitable for general public use, in terms of technological availability and usability. - The survey showed good support from the public community, showing a potential increase of their participation in the process if there is VE-based consultation software.	- A full-scale ground experiment with the collaboration of a city council on a selected urban planning project.
18	**Urban behavioural study**	Visibility of urban activities and pedestrian routes: An experiment in a virtual environment Natapov, A. & Fisher-Gewirtzman, D. 2016	Behavioural experiment where individuals needs to make route decisions in an immersive virtual reality	Experiment	1	- Statistical analysis - Routes have a visibility score - The selected routes are associated with the visibility scores - The selected routes are associated with the visibility scores	40	- 19 male, 21 female - Age from 20 to 54 - Students, researchers, academic and administrative staff from the Technion's Architecture and Town Planning Department	- Visualization Laboratory (CAVE) - Joystick movement controller	Virtual reality laboratory	- 5 min preparing time - Real experiment without time limits	- Pilot study on five participants. - Preparing real experiment with getting familiar and walk-through test for participants. - Real experiment with walk-through task. - Data analysis: comparison of chosen routes to simulated routes.	- Behavioural data from a virtual environment can be linked to the theoretical graph-based spatial measurement. - The experimental procedure an the results highlight the potential of VR laboratory as a research tool for complex urban situations.	- No further recommendations.
19	**Urban behavioural study**	Experimental Research in Urban Spatial Cognition by Using Virtual Reality Technology Yuan, S., Song, S. & Zhang, Y. 2014	- Experiment investigating how people construct the cognitive map in mind, generate spatial memory and respond when exploring the urban environment - Case study on the virtual town of Xidi	Experiment	1	- Space syntax: with axial map and visibility graph analysis - Questionnaire - Participants are asked to redraw the street structure afterwards to examine the spatial memory and cognitive map	76	No information	- Wide screens with 3 projectors - Mouse, keyboard, gamepad or joystick can be used as control equipment	Virtual town of Xidi	15 minutes	- Participants can navigate freely. - They are told to try to remember the street network. - After experience: fill out the questionnaires and redraw the street structure.	- The movement pattern presents the behaviour logic during the spatial exploration. - The movement pattern reveals the intrinsic cognitive mechanisms. - Movement pattern reveals a main spatial structure of the town. - VR can help in investigating people's spatial cognition, memory and behaviour in different environments.	- No further recommendations.
20	**Urban behavioural study**	The Use of Virtual and Mixed Reality Environments for Urban Behavioural Studies Park, A. J., Calvert, T. W., Brantingham, P. L. & Brantingham, P. J. 2008	Study about the use of a 3D virtual model to investigate the role of fear of crime in pedestrian navigation?	Experiment	5 decision points in the study between a longer and shorter route - 1: Narrow passageways with no escape - 2: Passageways with hidden spaces off to the side - 3: Passageways with dumpsters and other hiding places - 4: Passageways with a threatening individual - 5: Passageways with multiple threatening individuals	- Study the pedestrian navigation of human subjects - How many percent of the participants chose which route?	59 participants	- 37% male, 63% female - 49% age 19-29 ; 25% age 30-39 ; 14% age 40-49 ; 8% age 50-59 ; 3% age 60 or older	- Large screen that reached to the floor - Nintendo Wii remote was used as a controller	Virtual urban environment	No information	- Participants can navigate freely in the environment. - Black curtains around the screen and participants needs to help with the feeling of being more presence. - Background sound of traffic was played during the experiment.	- Simple and inexpensive virtual environment can be used for behavioural and other studies. - Game engines are a good system for this study: support of navigation, rendering, collision detection and other features to navigate the environment. - Creating realistic detail can take a lot of time. - Mixed reality can help in reducing the time of making the virtual environment. - A virtual environment has advantages in terms of cost, time, flexibility and safety for a human behaviour study.	- No further recommendations.

4.2 DISCUSSION RESEARCH

The mentioned aspects out of the literature review are confirmed here. Virtual reality can provide great added value both at the level of city models and at project level. First there is the scale of an entire city, also called the VR city models. Melbourne is the subject of study 5, which investigates in which ways a VR city model can contribute in the field of studies. Study 6 is about the city model of Glasgow and examines how users experience the use of a city model and walk around in the virtual city.

Another option is to use virtual reality in the design phase of an urban project. Most of the empirical studies deal with this topic, namely studies 7, 8, 9, 10, 11, 12, 13, 14 and 15. The studies and their purpose are explained further below. Also on a project scale, there is the option to use VR in the construction phase, as did in study 14.

VR can be used for various reasons in these different domains. A first option to use it is within the design process for assessing a design, as is done in studies 5, 8, 9, 11 and 13. It can also be used to compare different designs and help in the decision-making process. Studies 10 and 12 were experiments based on evaluating different design options. The feedback from the participants is overall positive over all these studies.

Another commonly used function is discussed in study 14. The empirical study proves that errors and clashes can be found and removed from a project at an early stage before it goes into the construction phase.

Next, VR offers a big advantage in the design phase for multidisciplinary working and co-design. Studies 5, 11, 13 and 15 are investigating this and the results are positive about the fact that the use of VR is suitable for this purpose.

Much empirical research has also been done into the use of VR within participation processes. For example, study 5 states that VR can help in the dialogue between different parties. Studies 7, 13, 15, 16 and 17 agree with this and it appears that all parties can communicate with each other in the same, understandable way. The results of research 13 even shows that the relevance of the questions asked by the participants increases according to the level of immersion. It shows that a good form of VR leads to better participation. Studies 16 and 17 show that VR helps to attract people to join in the participation processes.

The last important function is the use of VR to conduct studies. A first option is technical studies as is the case in study 5. Here research is conducted into thermal comfort, transportation and data management. Another option is to do studies on the human behavior. This can be very general to see how people interact with an urban environment and how they decide their routes through a city, as in studies 1, 6, 8, 16, 18, 19 and 20. This can be interesting to make changes in the design depending on the choices people make in the virtual environment. For example, study 20 focusses on the role of fear of crime in a pedestrian navigation. This information can help in making better urban designs.

The reactions of participants are mainly positive when it comes to the use of VR in an urban context. In studies 1 and 18, VR is praised for its strong potential as an empirical research tool. In studies 8, 11, 12, 13, 14, 15, 16 and 17 the positive reactions are about the role virtual reality can play in the design process. Studies 9 and 14 compliments the use of VR for the good quality and results to propose an urban design. Study 13 says that virtual reality is a fun way to discover, learn and participate in de urban process. Study 20 talks about the advantages VR can give in terms of cost, time, flexibility and safety for a human behavior study. Many of the positive remarks are not only focusing on the current use of VR in urban design, but on the potential it has for the future. This is for example the case in studies 11, 12 and 18.

The main reason why some of the studies are focusing on the future is most of the time because of technological problems that occurs. In studies 9 and 20, there were interface issues and the design time in VR is long. Study 14 deals with the fact that the technological requirements and the way VR is used, is different for every user. This makes multidisciplinary working in VR sometimes difficult. Another reason is the accessibility of VR. In study 5 the key challenge for implementing virtual reality is the cost for the hardware and software. The last reason that comes forward is in study 16. Virtual reality models are often created in a game engine. The problem is that the urban designers and the game engineers do not speak 'the same language' and that there is a different use of the program between the parties.

The negative reactions are very limited. Apart from the fact that the programs are not always known by the urban designers and the sometimes high costs, there is always the need to search for the correct way to visualize a project. The correctness and the amount of detail of the VR-file, largely determine the reactions of the participants. Study 8 decides that insufficiency of information in VR causes different sensation than in a real environment. Mainly the estimation of dimensions and distances is strongly determined by this factor. Study 10 also talks about the value of adding extra elements, such as light, water and sound to have a better feeling of reality. Last, study 16 gives remarks on this topic by saying that the real environment needs a simplification to make it work properly in VR, but that it is important to see how to do this. The environment still needs to look real and familiar for the participants.

When looking at the empirical studies, several concerns can be made. First, the discussed forms of virtual reality which are examined in the studies. In most studies the choice was made to discuss one or a few VR devices, but they are never all covered. Studies 5, 10 and 14 do give information about the used form of VR. The impact and the results can be very different between the different VR devices. Studies 1, 2, 3, 4 and 7 looked at a selection of different forms of VR and made a comparison on different topics and functions. However, it is still a selection of all the different devices.

The next main remark about the empirical studies, are the participants that took part in each study. Sometimes there is no information about the amount of people involved in the studies or about some parts of the study, as in studies 4, 5, 6, 8, 9, 10 and 13. When the number of test persons is given, it is striking that these numbers are sometimes very low. Some examples are studies 7, 8, 9, 11, 14 and 15 with less than twenty participants.

Subsequently, almost never there is information reported about the experience level of participants. However, it plays a major role whether the participants have already used VR before and whether they are familiar with the displayed city or project. This prior knowledge will have a major influence on the results and experiences of the test subjects. Studies 2, 3 and 16 mentioned that the test persons do not have knowledge about VR or the project. In studies 9, 10, 11,12, 13, 14 and 18 it is said that the persons already know the shown project. This means that there is no information available for studies 1, 4, 5, 6, 7, 15, 17, 19 and 20. This is a big gap in the empirical studies.

Finally, there is a problem with the number of control groups. There is no problem in studies 4, 8 and 11. For studies 1, 2, 3, 7 and 9, different VR devices were tested as control for the other devices. The other studies did not work with control groups.

Of the discussed articles, a number also focuses on the architectural field rather than on the urban planning field. Several experiments have already been carried out within this working area, but these are nevertheless very interesting to include in this review paper. This is the case for studies 9, 13, 14 and 15. VR is often used in the same way for architectural projects than for urban designs: to assess designs, make decisions and weigh proposals against each other, to conduct participation processes or to work in a multidisciplinary way. With all these aspects, it can be stated that the use and the results will be very similar for both areas of application.

A lot of research has been done for many years into visualization methods within urban planning. However, the technological world has evolved very much and rapidly during the last years, which results in only very limited research into the current options and possibilities of VR within this field.

Many of the empirical studies that can be found date form the period from 1990 onwards. The technology of virtual reality is still developing, but where we are today cannot be compared with virtual reality back then. Many older studies focus on researching virtual environments, abbreviated VE. These

VE’s would be shown today in a CAVE or with a HMD, but in the examined studies, usually a standard desktop or a screen with a projector was used. As a result, the studies are often about 3D images instead of a real immersive virtual 3D environment.

These studies, more specifically studies 6, 9, 12, 14 and 17, are very interesting as they already provide a good idea of what is important for users and how the constantly improving technology can offer options and possibilities for the future. However, it is very important to keep in mind that the results from these studies have not always been tested or confirmed for the use of current technological applications.

5.
CONCLUSION AND RECOMMENDATIONS

From both the academic literature review and the empirical studies, it can be concluded that the use of VR in urban design entails many positive aspects. First, it can be applied to different scales and domains: from a city model to a specific project. Within these different domains, there are many benefits to be found with this innovative way of working.

There is a big advantage for multidisciplinary working. Different parties can easily collaborate and communicate in a clear way thanks to virtual reality. This makes it easier to evaluate designs and facilitates the decision-making process. VR also offers great benefit for participation processes because it is a clear and understandable way of communicating for all parties, including non-experts. It has a positive effect on the risk perception of stakeholders and increases social acceptance. In addition, virtual reality can also be used to replace traditional studies or to carry out experiments in which human behavior is observed in an urban space.

Nevertheless, a number of negative aspects and areas for improvement also emerge for the future. Especially the technology itself remains the biggest disadvantage for the use of virtual reality. Despite the rapid changes and improvements, the total cost of the hardware and software together remains high, depending on the chosen devices. In addition, problems often arise, which means that the most optimal VR experience cannot occur. Languages of urban planners and computer programmers or game developers, whom have developed these type of software, differ strongly. Last, there are also still some social and psychological side effects, as well as VRISE. These are all aspects that inhibit the optimal use of VR.

Despite the generally positive comments and prospects for the future, it must be clearly stated that caution must be exercised here. The results from the empirical studies cannot simply be generalized because there are far too many gaps, ambiguities or problems within the studies. The studies have not been conducted systematically. Often too few test subjects are used or there is no information about the number available, nor about their background and knowledge. There is also a large lack of control groups within the empirical studies. In addition, not all forms of virtual reality or augmented reality were discussed during the investigations, while the different devices can lead to very different outcomes. Due to the large differences in the studies, it is difficult to compare or generalize results with each other.

Finally, many of the studies are already outdated and only a few recent empirical studies can be found due to the very rapidly evolving technology. The existing studies should therefore be conducted again with current technology and devices.

Further research is needed to fill the gaps. First of all, it would be useful if empirical research could show which form of virtual reality is most suitable for which purpose. For example, which VR device is most suitable for participation processes?

In addition, further research should be carried out into which software and hardware is most suitable for the various functions. There must also be a study about the knowledge that is needed to create good VR models and how there can be an improvement between the needs of an urban planner and the available software.

All these investigations should be done in a very systematic way, making it easier to examine them next to each other and to make conclusions.

Because of all the problems and weaknesses, it can be said that the predominantly positive responses from participants must be handled with caution. Because it currently gives a positive picture, it is certainly worthwhile to conduct further research into the use of VR for urban planning and design.

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