GOLDSMITHS COLLEGE, UNIVERSITY OF LONDON

DOCTORAL THESIS

A Virtual Architecture Framework for Immersive Learning Environments

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Declaration of Authorship

I, Pierre-François GÉRARD, declare that this thesis titled, “A Virtual Architecture Framework for Immersive Learning Environments” and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed:

Date:

"Although for hundreds of years we have been talking about mens sana in corpore sano, we really have not paid any serious attention to the problem of training the mind-body, the instrument which has to do with the learning, which has to do with the living. We give children compulsory games, a little drill, and so on, but this really does not amount in any sense to a training of the mind-body. We pour this verbal stuff into them without in any way preparing the organism for life or for understanding its position in the world — who it is, where it stands, how it is related to the universe. This is one of the oddest things."

A. Huxley

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Abstract

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A Virtual Architecture Framework for Immersive Learning Environments

by Pierre-François GÉRARD

This thesis presents a set of experimental studies to understand the benefits of utilising architectural design to create virtual environments optimised for completing a series of cognitively demanding tasks. Each field of investigation is reviewed separately. The first field of investigation relates to spatial design and analysis from an architectural standpoint. The second is concerned with memory, spatial abilities, and embodied cognition. Two VR-based user-studies are designed to further explore the potential interactions between these fields of knowledge.

An initial experiment called "Archimemory" is based on a *memory palace*, a historical mnemonic technique, to explore how spatial knowledge representation can enhance memory retrieval. It compares the benefits of using different architectural designs in VR to support participants' recall accuracy of a sequence of playing cards. The main user study, called the "Immersive Virtual Architecture Studio" (IVAS), validates a new methodology to study the effect of spatial qualities on embodied cognition related tasks. A spatial analysis using the isovist technique provides an objective approach to measure spatial qualities such as *openness* and *complexity*. Participants have to perform a batch of cognitive tasks in the IVAS. Results from the spatial analysis are compared to participants subjective rating of the same spatial qualities as well as their performance. Findings suggest that a spatial performance metric can be evaluated for each room, for instance, it was the highest in the case of the more closed (fewer windows) and more complex (with columns) condition.

The combination of spatial analysis and performance metrics obtained from these two novel VR applications, Archimemory and IVAS, leads this research to form a Virtual Architecture Framework. Guidelines are proposed for VR architects, UX designers and scientists to adopt this framework to support further exploration and evaluation of spatial design to enhance human cognitive abilities when experiencing immersive learning environments.

Acknowledgements

Since the start of this long journey, I have had the opportunity to work with a few people that deserve my gratitude. It all started in the 1990s, during my Master's in architecture, when I teamed up with Ertu Erbay to start the exploration of real-time 3D graphics user interfaces. His input into the architectural design of the *memory palace* was much appreciated. Then, once I embarked on this PhD journey, the person who first helped me to develop the memory card game was Dr. Karsten Seipp, with his skills in Javascript. Will Gallia also taught me about back-end web development during our attempt to get Archimemory online. Dr. Prashant Aparajeya was my companion during all these years, first as a friend and colleague, but also with his resourceful computer scientist mind for coding some of the game mechanics and position tracking systems for the VR applications.

This thesis would not have been possible without the support of both my supervisors, Prof. William Latham, and Prof. Frederic Fol Leymarie. Also, Prof. Rebecca Chamberlain was of invaluable assistance not only with the statistical analysis but also with her expertise in experimental psychology. Prof. Marco Gillies brought invaluable expertise with his extensive knowledge of virtual reality. I couldn't have run the user-study without the participation of my colleagues and friends, so I thank you all. I am also immensely grateful for the kind support of my proofreader Matt Armstrong, who helped me to improve the quality of the English language used throughout the dissertation.

I would also like to thank my partner in life, Vinciane and our son, Neven, for their support and patience, which I really put to the test. Finally, one key element to the completion of this thesis has been the atmosphere and convenience afforded by the British Library. Thank you for letting me use this wonderful space.

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List of Abbreviations

VR	**V**irtual **R**eality
XR	E**X**tended **R**eality
IVE	**I**mmersive **V**irtual **E**nvironment
HMD	**H**ead **M**ounted **D**isplay
AE	**A**rchitectural **E**lement
SQ	**S**patial **Q**uality
NPG	**N**avigational **P**uzzle **G**ame
VSMT	**V**isuo-**S**patial **M**emory **T**est
PTT	**P**erspective **T**aking **T**ask
SQR	**S**patial **Q**uality **R**ating Task
IVAS	**I**mmersive **V**irtual **A**rchitecture **S**tudio
VAF	**V**irtual **A**rchitecture **F**ramework
VAAG	**V**irtual **A**rchitecture **A**nalysis **G**rid
κ	Card Cycle Time
P	Spatial Performance Efficiency

To my grandfather, who taught me how to craft things, and to my son, who inspires me everyday to do something that matters. . . .

Chapter 1

Introduction

> In Virtual Reality, your centre of experience persists even after the body changes and the rest of the world changes. It peels away phenomena and reveals that consciousness remains and is real. Virtual Reality is the technology that exposes you to yourself.
>
> *Jaron Lanier*, Dawn of the New Everything, 2017

1.1 Context and Motivations

For more than half a century, a small community of scientists, engineers and artists have developed a new technology that has *space* and *embodiment* at its core. The first commercial Virtual Reality (VR) headset, the EyePhone, was released in 1987 by Jaron Lanier, [1]. Despite the huge potential to take advantage of humans' natural spatial abilities and embodied cognition as an innovative way to navigate the ever-growing digital landscape, thirty-year later, progress is still slow.

My vision of the potential of VR as a new medium was born out of my Master's in Architecture final-year project, in 1999. Instead of a projected building made of concrete, metal and glass, I designed a real-time three-dimensional interface as an answer to a famous competition entitled the 'Library of the Information Age' [2]. However, my university could not afford the expensive VR head-mounted displays (HMDs) from the 1990s, and as such, the 3D interface was designed for a desktop computer, as was the case for most virtual environments of that period. A long decade later, once the new wave of VR HMDs kicked off with the introduction of the Oculus DK1, I decide to resume my exploration of the virtual realm.

[1] This was the first company to sell Virtual Reality goggles. The EyePhone 1 cost USD $9400; the EyePhone HRX cost $49,000) and data gloves $9000

[2] 'The Library of the Information Age' was the title of the competition organised by ACADIA, The Association for Computer-Aided Design in Architecture, 1999, `http://acadia.org/`

My first line of research was borne out of an ancient memory technique known as the "Method of Loci" (Yates, 1966). The method consists of placing items to be remembered along a path throughout an imaginary space in the mind's eye. I went on to test the assumption that VR could be used to create these *memory palaces* so that 'learners' could train more easily and use these virtual spaces to store information. Over the years, a couple of similar studies were then published (e.g. Krokos, Plaisant, and Varshney, 2019, Reggente et al., 2020) showing a growing interest in the development of this powerful learning technique.

This led me to focus on how to design these virtual environments to support learning and education. With today's technology, high-speed broadband, high-resolution displays and powerful GPUs, the main constraints to developing a new approach to learning based on human spatial awareness is our imagination. Yet, the virtual spatial canvas does not have to be empty. Architects have assembled a significant library of knowledge on how to design useful spaces and structures to serve human needs and their everyday occupations. Typically, the architectural design process is adapted to this new digital realm. The aim is to explore techniques that are the most suitable for the analysis and design of effective three-dimensional environments to support learning and education in VR. One of these techniques is based on the isovist, which is a method to measure the volume of space visible from any given point (location) in that space (Benedikt, 1979).

Even though VR has been available for a few decades, it is still in its infancy, with affordable equipment only available since 2014. Ideally, more robust methodologies should start to bring more consistency throughout the use of VR, not only in the scientific community, but also in the wider field of UX designers and XR developers. Another goal of the present thesis is to take part in the construction of such methodologies by proposing a framework to assist in the design of meaningful and effective virtual environments.

1.2 Thesis Statement

Architectural design and immersive VR are at the core of this project. On the one hand, architects have developed a series of spatial analysis tools to measure spatial qualities inside buildings and as well as towards those at city-scale.. (Benedikt, 1979; Hillier, 1996). These types of objective evaluations assist in the understanding of how spatial qualities can be beneficial or detrimental to specific human activities. This knowledge in turn, can then be used to improve the design of new buildings or other 'structures'. For instance, a well-designed building such as the British Library provides calm and naturally-lit spaces supporting hundreds of visitors every day in their quest for knowledge; in an office environment, open corridors are more beneficial than open plan for teamwork and increasing the sense of company culture (Peponis et al., 2007).

Simultaneously, VR technologies have been developed by engineers with the dream of creating a system that immerses users in a new form of spatial experience (Lanier, 2017). Immersive VR has already demonstrated a useful range of benefits (Slater and Sanchez-Vives, 2016): particularly in cognitive training, such as enhancing memory for the elderly (Repetto et al., 2016; Lokka et al., 2018); simulating critical events to assist people acquiring new skills, but at the same time limiting risks (Grottke et al., 2009); creating forums for people to share knowledge remotely (*eXp World*).

Nevertheless, despite the commercially available high-end VR systems and the groundbreaking research and development at the intersection of spatial analysis and spatial cognition (Wiener and Franz, 2005; Wiener, Büchner, and Hölscher, 2009; Ostwald, 2011), the effect of architectural design on cognitive performances is still far from well understood. It is also worth noting that each of these VR systems comes with various specifications in terms of to their hardware and software. These influence the quality of implementation (human-computer interaction, computer graphics, sounds,...), which have a considerable effect on the level of presence experienced by participants. These inconsistencies make it difficult to replicate any given experiment from one university laboratory to another, or even from one user study to the next. Moreover, most of the studies compare the effect of different virtual reality systems on a particular cognitive task, trying to understand the affordances of each system. In all these cases, very little care is given to describe the virtual environment encountered in term of visuo-spatial qualities.

In response to these problems, a first experiment is designed to understand the potential of immersive VR systems to explore the effect that different types of spatial design can have on memory performance. Narrowing down from generic spatial design to specific architectural elements and related spatial qualities, a second experiment is designed to evaluate its effects on users' cognitive performances.

1.3 Research Questions

Considering the problem statement, the main research question was formulated:

Main RQ: How to evaluate the effect of spatial design on users' cognitive performance in immersive virtual environments? When aiming to answer the main research question, it is necessary not only to explore the capacity of one approach to address the main challenges of evaluating the effect of spatial qualities on users' cognitive performances, but also to take into account users' feedback of their experience of the same spatial qualities.

Gaining more knowledge in these areas may help to devise an approach which may not only tackle these challenges successfully, but which also corresponds to user expectations and needs. Therefore, the following subordinate research questions emerge by means of which the answer to the main research questions may be formed:

RQ1: How architectural design can enhance users' memory performance when using the Method of Loci in VR? This first question aims to explore the potential of virtual reality in the field of architectural design and memory. Exploring this research question will help to gain a better understanding of users' experience and behaviour when using virtual reality.

RQ2: How to evaluate the correlational relationship between architectural elements and spatial qualities? It is essential to understand what influence a specific set of architectural elements has on the spatial qualities of a place. Because of the variety of architectural elements and spatial qualities, this thesis can only partially address this question.

RQ3: How do perceived spatial qualities correlate to those measured by Isovist techniques? All this is only meaningful as the value it brings to help people optimise their performance. It is essential to compare participants' subjective perception of space to the metric properties obtained by geometric measurements.

RQ4: What tasks can be implemented to evaluate the spatial performance of an immersive virtual environment The spatial performance can be measured by having users complete a series of tasks that once identified will raise the two following questions.

RQ5: What is the effect of specific spatial qualities on participants' spatial abilities performances? A new type of highly demanding spatial cognition task is designed to investigate this question.

RQ6: What is the effect of a specific spatial quality on participants' memory performances? The comparison between isovist measurements and participants' visuo-spatial memory test scores should show a correlation between spatial quality and participants' memory capabilities.

1.4 Approach, Contributions, and Limitations

1.4.1 Mixed-Method Approach

This research follows a mixed method approach, starting with a qualitative methodology to work out the questions from the central statement. Once more precise questions are isolated and formulated, a quantitative approach is used to drive the second part of the investigation and answer these questions. The importance of recognising the duality of the problem can not be underestimated. On the one hand, measuring spatial qualities requires a series of objective measurements using design analysis and other quantitative devices; on the other, the interpretation of one's spatial experiences is a subjective process that can only be partially captured with quantitative data. This layer of relativistic perspective enriches the classic experimental method by taking into account participants' subjective feedback for the development of the study.

1.4.2 Contributions

A multi-disciplinary approach was required to carry out this research in virtual reality, specifically when looking into the effect of the spatial environment on human cognitive performance. A combination of tools and techniques from different fields was required to complete this research: architectural design knowledge and software, spatial analysis methods, programming, video game design, immersive design, cognitive and experimental psychology to name but the most important ones.

The main purpose of this endeavour was to develop a framework to help User-Experience (UX) designers and VR developers in the creation of effective VR experiences (see Chapter 6). To measure this effectiveness, a spatial performance efficiency measurement is proposed. A series of demanding cognitive tasks were designed to evaluate and compare the effectiveness of different spatial designs when using commercially available high-end immersive virtual reality systems. Such a framework can have benefits not only for psychologists and neurologists running experiments in VR but also in the many other applications in which VR is used, such as entertainment, health, training and education.

Coming from an architectural background, the author's main contribution to computer science lies in the integration of spatial analysis tools, such as isovists, in the design of virtual environments. Architects have developed a series of tools to assist in the analysis of human behaviour when occupying buildings and cities; this work suggests a method to integrate such tools in the design of effective immersive virtual environments adapted to the new mode of interactions induced by this new medium.

Furthermore, a series of three-dimensional interactive graphics applications and interactive virtual reality experiences were designed and developed by the author to complete this research, namely two main applications: Archimemory (Chapter 3) and Immersive Virtual Architecture Studio (Chapter 5). Here is a list of the main versions and components:

Archimemory

- ArchiMemory XP 1.0[3]
- Archimemory XP 2.1[4]

[3] Accessible online at `http://archimemory.net/wp/xp/xp010/xp01.htm`
[4] Accessible online at `http://archimemory.net/wp/xp/xp021/xp021.html`

- Archimemory XP 2.3 - A full VR application used as the pilot experiment described in Chapter 3.

Immersive Virtual Architecture Studio (IVAS)

- IVAS Spatial Analysis Software: 2D isovist and isovist field programmed in Grasshopper for Rhino;
- IVAS Sandbox: assembled using Unity, position-tracking system and game mechanics;
- IVAS Navigational Puzzle Game (NPG, details in Section 5.2.2) developed in Unity. [5]

Main Software Used to Develop Content

- Rhino 6 for Windows including Grasshopper, Educational Version. Used to develop the spatial analysis and generative design process with isovist method.[6]
- Autodesk 3Ds Max 2018, Student Licence, used to create all the 3D models, lighting and rendering.[7]
- Unity 2018.3.14f1, Free licence, used to program all the interactions and manage the various assets of the VR applications; most programs were coded in Csharp.[8]

1.4.3 Main Limitations

The primary concern of this research is architectural design. From the various possible scales of the built environment, and for the feasibility of this research, this architectural space was scaled down to the interior space of a building, at room level. The reasons for this were twofold: rooms are integral to buildings; they afford natural locomotion when using a room-scale virtual reality system.

Cognitive psychology brings much of the knowledge to explain human perception and spatial representation. Taking the embodied cognition approach to understand how humans build a representation of the world based on their sensory perceptions, this study voluntarily limited the field of investigation to vision (sense of sight), proprioception (balance) and touch (movements). Vision is the main source of perceived stimuli. Proprioception is coupled with movement as in tactile-kinesthetic. Both these senses are the main focus in VR hardware developments. The other senses: hearing,

[5] A video showing a participant using the IVAS is accessible online `https://vimeo.com/344189167`
[6] `https://www.rhino3d.com/`
[7] `https://www.autodesk.co.uk`
[8] `https://unity3d.com/`

smell and taste are beyond of the scope of this project. Also this thesis is not a behavioural study, a sociological investigation, or psychological research *per se*. However, the tools and methods developed have potential to be used in these fields as well.

Using avatars in VR can have an important effect on the feeling of presence, as demonstrated by Steed et al. (2016). Avatar software was not straightforward to set up when this project started in 2013 and as such, no complete virtual characters were used in this project. However, the latest VR system provided a representation of virtual hands with the controllers used in the main user study (see Section 5).

1.5 Thesis outline

The dissertation is structured as follows:

Chapter 1 - Introduction
The first chapter presents the author's context and motivations, the problem identified, the thesis statement, as well as the research questions. It also describes briefly the new knowledge and insight the study has produced within a multi-disciplinary approach.

Chapter 2 - Background Theory: From Architecture to Virtual Environment
In this chapter, the main concepts and tools used to answer the research questions are defined. Knowledge gaps are identified and references are reviewed to support the discussion.

Chapter 3 - Preliminary Experiment: Archimemory
In this chapter, the first experiment inspired by the Method of Loci is presented. The aim is to explore the potential of using VR as a research tool, as well as to understand the effects of different types of architecture on a participant's ability to recall a random sequence of playing cards.

Chapter 4 - Virtual Studio Prototype and Immersive Design
This chapter explains the prototyping phase to develop the design of the main experiment. It addresses each lesson learned in chapter 3, unveils new challenges and drafts the first virtual architecture principles.

Chapter 5 - Immersive Virtual Architecture Studio: User-Study
The main experiment is detailed. The spatial analysis method used to generate the design is explained. An experimental design, including a batch of cognitive tasks, is proposed to answer the questions with a quantitative methodology.

Chapter 6 - Virtual Architecture Framework
With the practical and theoretical knowledge acquired throughout the research, and building upon established guidelines in the VR community, this chapter proposes a new framework to support the design of effective virtual learning environments.

The thesis concludes with **Chapter 7** by answering the main research question (Main RQ) and discusses the main contributions of the thesis to the field of virtual architecture. It ends with a discussion of future work and closing remarks.

1.6 Public Dissemination of the Work

1.6.1 Conferences

- EVA London 2013: Electronic Visualisation and the Arts. Short paper published in Proceedings of a conference held in London 29-31 July. BCS, The Chartered Institute for IT, 2013.
- International Conference on Spatial Cognition (ICSC 2015) in Roma, from 6th to 11th September, presentation of a poster.
- VRIC ConVRgence 2020: 22nd Virtual Reality International conference - Laval Virtual World. Presentation of a poster and in ConVRgence (VRIC) Proceedings.

1.6.2 Other Events

- A short paper explaining the detail of Archimemory experiment was reviewed by DPPI 2013 Colloquim, International Conference on Designing Pleasurable Products and Interfaces. Paper in annexe.
- First Demo Experiment of "ArchiMemory" at Human Interactive and Creative Machine exhibition, Goldsmiths, London, 6th November 2014.
- Presentation at Building Bridge conference 2015, at Goldsmiths, London.
- Presentation of the workflow used to develop the WebVR GUI for the project Saydnaya at Meetup WebXR, June 2017. [9]
- Second Demo Experiment of the Virtual Studio Prototype during the Future Minds Symposium at Goldsmiths, London, in September 2017.
- TechDay at Yebrury School, London, running IVAS with 24 children from year 1 to year 6.

[9]This project was created by Forensic Architecture for Amnesty International. It can be accessed online here `https://saydnaya.amnesty.org/`

Chapter 2

Background Theory - From Architecture to Virtual Environment

> Our body is not in space like things; it inhabits or haunts space. It applies itself to space like a hand to an instrument. And when we wish to move about, we do not move the body as we move an object. We transport it without instruments as if by magic, since it is ours and because through it we have direct access to space.
>
> *M. Merleau-Ponty*

2.1 Overview

This chapter starts with considerations of different approaches to space. It looks at architectural theories and the characteristics of the interior. Memory and spatial cognition are then explored through the lens of cognitive psychology. An enactive approach is used to bridge human spatial abilities to embodied cognition. Then it offers an exploration of the virtual space and its technical specifications. Finally, a design framework is introduced to facilitate the transfer of lessons learned from the physical world of architecture and embodied cognition to the design of virtual learning environments.

This chapter starts by explaining the concept of space, first from the standpoint of different disciplines, before narrowing down to the scope of this project: the architectural space. An investigation of the literature in the fields of spatial cognition and memory shows the complexity of using virtual reality in a scientific context. There are two main reasons for this complexity of usage. First, the development of virtual reality requires an intricacy of disciplines: computer science, engineering, human-computer interaction, cognitive psychology, and neuroscience. Gathering together all these disciplines is already a challenge; moreover, they usually have different agenda. Secondly, technological obsolescence reduces the repeatability of user studies over time. Many questions need to be considered to understand this technology. What are the minimum requirements to experiment VR from a hardware and a software point of view? How does it compare to real-world experiences, or desktop-monitor settings? How do we interact and move around? How do we define the level of presence and immersion in VR?

Most of these issues have been investigated already at length through different lenses. This literature review will present the most relevant studies concerning human spatial cognition, navigation, memory, and embodiment that underpins the present research project. More specifically, given the general lack of attention to its spatial characteristics, particular attention will be given to the quality of the different virtual environments used throughout the scientific literature.

2.2 The Concept of Space

The concept of space is tied to conventions and codes that allow a group of individuals to inhabit the same shared physical or virtual place. It is therefore a polysemic idea. A multiplicity of space exists at the same time. Each field of research, each art, each culture determines its own space. Moreover, the perception of space is a function of the human body. Space is the result of the representation that an individual or a group of individuals has created.

2.2.1 Different Approaches to Space

The concept of space has been explored over the centuries by many authors from different disciplines as varied as architecture, geography, humanism, psychology, and more recently cognitive psychology and neuroscience. Each approach brings a different light to the concept of space and the way human beings perceive it and interact with it. As an introduction to the idea of space, a few references will be mentioned from each field that supports the current thesis.

The understanding and the representation of our environment has been at the core of the field of geography. Since ancient times, geographers have experimented with many modes of representation of our environments, the efficacy of which is linked to the understanding of how people orient themselves spatially. Geographers are interested in maps, and more recently in mental maps, also called *cognitive maps*, and in a more general sense, in understanding how people navigate in built and natural environments. For instance, Montello (2001), a prolific author at the intersection of geography, sociology and psychology, has published many articles and books on the topic of spatial cognition and navigation in real or in virtual environments (Richardson, Montello, and Hegarty, 1999; Montello et al., 2004; Montello, 2014). These studies establish the foundations of the present work.

Taking into account the built environment, Lynch (1960), a prominent urban design theorist and environmental psychologist looked at how people navigate through the city. In his most important work, *"The Image of the City"*, he describes a method of analysing legibility based on five elements: paths, edges, districts, nodes, and landmarks. He also coined two other significant concepts that have since been assiduously studied by geographers and psychologists: "*mental maps*" and "*wayfinding*".

From a psychological standpoint, Prof. B. Tversky, a leading authority in the field of visual-spatial reasoning, paved the way to understanding the relationship between space and the body, by explaining the existence of the different types of space: the *space of the body*, the *space around the body* and the *space of navigation*. In an influential paper, Tversky and Hard (2009) looked at "*the spaces created by people to augment their cognition*". They also brought into the light another important subject of research in psychology about the reference frame and the question of *allocentric* and *egocentric* spatial representation [1]. This frame of reference has been well determined by Klatzky (1998) and put into practice in many other studies (Dede, Salzman, and Loftin, 1996; Shelton and McNamara, 2001; Burgess, 2006; Ruggiero, Iachini, and Francesco, 2009; Kelly and McNamara, 2010). In experimental psychology, a couple of studies have been particularly influential in this research and brought insights into the practicalities of reference frames orientation in virtual environments. Manning et al. (2014) designed a virtual application entitled "Magellan" in which a taxi driver's skill-set is used to work out a model of navigational efficiency in *unfamiliar environments*.

In consideration of the challenges faced in the taxi driver scenario, Maguire, Woollett, and Spiers (2006) have also confirmed these navigational performances using the latest techniques in neuroscience [2]. Neuroscientists have made essential discoveries about how the brain processes spatial information. In 1971, O'Keefe and Nadel (1978) discovered the existence of *Space Cells* in the hippocampus. Subsequently, at University College London, developments by Burgess (2002) discovered more detail about the functioning of such cells (Jeffery and Burgess, 2006; Hartley et al., 2014). The place cells fire in groups in the specific region of the hippocampus known as a *Place Field*. They found a correspondence between the *Place Field* and the environment in which a rat was moving. This fact called again for the concept of *allocentric* and *egocentric* orientation, which has been studied at length in cognitive psychology. More recently, Spiers and Barry (2015) have used computational modelling and neuro-imaging research "to shed new light on how the spatial relationship to a goal may be determined and represented during navigation."

This review's purpose is to extract general concepts that hold throughout the varied fields of investigation. Space is everywhere, physically around us but also

[1] The general consensus is that, in an egocentric reference frame, locations are represented with respect to the observer's point of view, whereas an allocentric reference frame locates objects in relation to each other's position

[2] They used physiological measures, which led to fascinating findings, measuring the difference in the volume of grey matter between taxi driver and bus driver.

virtually inside us. The following section proposes a look at Piaget's theory of cognitive development with a focus on spatial awareness. It shows how, from birth, humans develop a sense of their surroundings by reaching a bit further at each stage of cognitive development, creating a model of the world in their mind.

2.2.2 Five Stages of Spatial Cognition Development

Besides these broad definitions of space, the principal interest of this study is *the architectural space*, its perceptual properties and its meaningful codes. Indeed, to comprehend the effect that architecture has on human performance, we must first understand how the architectural space is perceived and experienced.

Also, there is an apparent analogy between nascent VR technology and the childlike novelty of trying out a new VR experience, as if discovering a new world. Piaget's theory of cognitive development in children, gradually acquiring information about their surroundings, is an excellent match to support and frame this thesis investigation. The following section presents an adaptation of this theory using five fractal stages, each one related to how humans build their own spatial knowledge. Each stage includes the previous ones. These five stages are: from form to object; internal space and perceptions; the organisation of spaces; external space and urban space.

From Form to Object The concept of space is not innate. To tackle the idea of space, we must first incorporate the concept of form. This concept requires the understanding of a various range of characteristics. During this learning process, we undergo different stages, each depending on the level of structure of the perceived form. Indeed, Jean Piaget (1964), who initiated the study of the ontogenesis of logical structures in children, observed that children learn to distinguish between forms according to three types of thresholds that we incorporate sequentially, in the following order: typological, geometric and, finally, metric structures.

The evolution of these thresholds depends primarily on our senses and our proprioceptive system (movement), without which we would not have the experiences that enable us to comprehend the world. It gives the sense of agency (see Section 2.5.5). Furthermore, it is through analogies and comparisons that we enrich our mental library of information, which in return allows us to gradually grasp the relations between the forms that surround us. Objects, as distinct entities, proceed from the relationships between these forms. Consequently, this first stage of learning formed through topology offers us an important key to perceive and comprehend space.

The perception of *internal space* constitutes a second level of understanding when discovering our environment and is of particular interest in this research. This *internal space* corresponds to the pre-operational stage in Piaget's theory. The egocentric point of view is still the main frame of reference at this stage, also called the topologic stage. It is governed by relations of neighbourhood, separation, order, covering and continuity (Denis, 2018). Besides, Pierre Von Meiss (1990), a historian architect, wrote eloquently on the priority of space in architecture:

> Man first perceives the space surrounding him, not the physical objects bearing symbolic meaning.

He insists that one positions oneself primarily in relation to a context, an envelope or topological structure, before shifting one's attention to the abstract meaning of the objects that this space might contain. We must be careful not to confuse the symbolic meaning of objects (paintwork, sculpture) with their formal structure. This remark is especially important nowadays, with the overwhelming amount of information (and its symbolic meanings) surrounding us, outside of any space of orientation. Also, this topological approach acquires new practical applications with the use of three-dimensional modelling software. This type of software proposes, through the use of mathematical algorithms, an intuitive way of manipulating surfaces and volumes, leading us to discover new worlds of shapes, as children do according to the formal level of topological structures. Here is another reason for the excitement around virtual reality technologies with their potential to afford anyone the ability to create and manipulate these structures using natural movement and, at the same time, being immersed in their creations.

Returning to the exploration of space, later on during the 20th century, a prominent architect theoretician, Bruno Zevi (1959) defined architecture as *"the art of space"*. He goes on to explain that:

> Architecture [...] does not consist in the sum of the width, length and height of the structural elements which enclose space, but in the void itself, the enclosed space in which man lives and moves. [...] Internal space, that space which [...] cannot be completely represented in any form, which can be grasped and felt only through direct experience, is the protagonist of architecture.

It is true that one of the first properties of architecture is *to operate on space*, but this does not mean that we should reduce architecture to a *spatial experience*.

The third stage considers the *organisation of spaces* according to their articulation and to their geometry. In Piaget's theory, at this stage children develop the capacity to perceive their environment from different points of view, also known as *allocentric* orientation. This is a decisive step toward the construction of a "total space". It is when we start to move from one room to another, that the internal space begins to get organised, to articulate itself within one's own representations. Different activities take place in different areas. Spatial juxtapositions and inter-penetrations influence the type of spatial relations, and their degree of autonomy. The general geometry of planes, sections, and volumes allows an individual to understand how rooms are connected, how the building functions, and hence how to navigate through it. Architectural design is fundamental to architecture. The design of an environment requires an organisation that must make sense to its users. Every decision concerning the hierarchy of space and the distribution of functions has an effect on the end user's behaviour.

The fourth stage of resolution helps to comprehend the meanings behind the architectural form. ***The external form*** of a building gives rise to, and is generated by a particular symbolism. For instance, if the *vault* represents, almost universally, the sky, one should keep in mind that the idea of a celestial *vault* originated from architecture, and that this holds even for nations that are not familiar with its development. Certain tribes designate the sky as the "cosmic tent", as mentioned by Boudon (1992). He suggests that there are two types of analogy: the formal analogy, employing the example of the *house-face*, where you can perceive a face through the configuration of the house's features, and the structural analogy, with an association of the triangular configuration of a façade with the shape of a human face. The problem is that neither the formal analogy, nor the structural analogy, can sufficiently explain all the potential comparisons between an architectural form and a symbolic image. Therefore, the French architect theoretician Dominique Raynaud (1998) proposes that the association of architecture and symbolism should be based on the concept of *scheme*. He elaborates on the idea that the scheme is a more general explication than the aforementioned analogies.

Additionally, these schemes govern the isomorphism [3] of forms coming from different cultures (historical, modern and traditional societies). Additionally, the results of Raynaud's study show a devaluation of symbols and myths within modern societies, due to the loss of multiple meanings of images. Could VR be used to bring symbolic architectural values back into a new cultural form?

The fifth stage proposes the contextualisation of all the other stages across the urban phenomenon, the ultimate *sharing space*. Following the growth of a child's journey, one moves outside the buildings from one building to the next. The streets, the squares, the canals are the subtracted spaces that make the city. To orientate oneself, one will recall all the spatial knowledge already stored in memory, with the goal of comparing this to the new discoveries. Hence, by way of analogy, new information is managed according to one's representation of the world. The new streets and places are added to the cognitive map in one's mind, so that it can be used to assist with orientation and navigation through the city.

The observation of children's exploration of their environment from birth allowed Piaget to understand how humans process their environment, with a specific focus

[3] Isomorphism is a concept in mathematics where a mapping between two structures of the same type can be reversed. The two isomorphic objects, or structures, share the same properties.

on the architectural space. It is important to keep in mind that Piaget's approach is fractal in the sense that it breaks down a whole system into five intertwined stages of resolution. Although there is a lot more to Piaget's theory, for reasons of succinctness this research mainly focuses on the second stage, *the internal space*.

2.2.3 Sensorimotor Theory and Enactivism

Notwithstanding the depth of Piaget's theory, many authors have criticised his methodology because he undertook most of his experiments himself with a narrow demographic sample. Moreover, it would be short-sighted to reduce the understanding of humans' cognitive development to one theory. Decades, and many more studies later, psychologists understand that not all children are born equal and that their socio-cultural environment has an effect on their development. Looking at the "modularity of mind" (Fodor, 1983), cognitive developmentalists argued that, rather than being domain-general learners, children come equipped with domain-specific methods, sometimes referred to as core knowledge, which allows them to break into learning within a specific domain. Besides these external and innate influences on children, cognitive scientists have started to investigate further stages of development in adulthood. Neo-Piagetian theories of cognitive development aim to better account for intra-individual and inter-individual differences in cognitive development. For instance, an approach such as *Interactivism*[4] proposes shifting the study of the mind from substance to process. Everything can be understood in terms of *process*, as in physics, chemistry and biology. *Interactivism* "rejects Piaget's notion of *figurative* knowledge, which he thought was characteristic of perception, language, and mental imagery"(Bickhard, 2009). Such a theoretical model can be useful when discussing the 'reality' of VR activities.

In more recent years, the most promising scientific trends have considered sensorimotor theory and enactivism (Degenaar and O 'regan, 2014). The primary claim of the enactive approach is that the perceiver's ability to perceive is constituted partly by sensorimotor knowledge. In other words, one is conscious through the perceptions acquired by doing things. In line with Piaget's theory, the field builds on the idea that the brain creates complex models of the world from which it can produce an accurate simulation of both unperceived aspects of the present, and not yet perceived aspects of (multiple) potential futures. Many discussions are ongoing in the cognitive sciences community, from which different models are proposed to explain how the brain works.

There is a growing body of literature that recognises the importance of the built environment on the psychology, cognitive development, and health of humans. However, there has been little agreement on measuring the effect of the built environment on human cognitive performance. But, before diving into these fields of investigation

[4]Interactivism involves a commitment to a strict naturalism, based on the idea that a series of emergence is possible only if the world consists of processes and organisations of process.

more specifically, the following section proposes to focus on the architectural space and its codes.

2.3 The Experience of Interior Architecture

In the last two centuries, many authors and architects have attempted to propose a unified theory of architecture (e.g. Semper, 1989; Mitchell, 1990; Bachelard, 1994; Alexander, 2005). This represents a vast enterprise, from which the two most important concepts are: the essence of architecture, and the relationship between geometrical structures and human perception.

2.3.1 Geometric Structure and Human Perception

In the early 2000s, a seminal opus by Christopher Alexander (2005) greatly influenced the trend towards unifying the two domains of geometric structure and the feeling it creates.[5] The author reaches out far beyond architecture to depict the coherence of our universe. He also identified 15 properties that influenced the 'beauty' of architectural design. Leitner (2015), a software engineer published an introduction to Alexander's work in which he explains how each one of these spatial properties corresponds to a pattern of living things (see Figure 2.1). Alexander proposed this list based on his empirical experience as well as hundreds of other architectural projects. These spatial properties represent a vast resource for future exploration to confirm his findings not only from the architectural standpoint, but also from the psycho-physiological response of the potential inhabitant of such structures.

Interdisciplinary attempts between architects and psychologists are still sporadic. When these collaborations do occur, the lack of hard data makes it difficult to measure the effect between architectural design and cognitive response. Most of the studies are empirically-based, with considerations of existing buildings or cities, and the observation of their inhabitants (Werner and Long, 2002).

2.3.2 The Interior Space Unit

The second focus of this section relates to the second stage from Piaget's theory of cognitive development, the *internal space*. Many authors and architects have proposed theories of architecture exposing the *internal space* as the foundation of architecture (e.g. Semper, 1989; Krier, 1988; Salingaros and Mehaffy, 2006). One of the first attempts was proposed by G. Semper, a 19th century German Professor of Architecture. In his book, "Four Elements of Architecture", Semper (1989) explains that,

[5]The four volumes of The Nature of Order are: Book 1, The Phenomenon of Life (2001); Book 2, The Process of Creating Life (2002); Book 3, A Vision of a Living World (2005); and Book 4, The Luminous Ground (2004). The volumes are published by the Center for Environmental Structure, Berkeley, California.

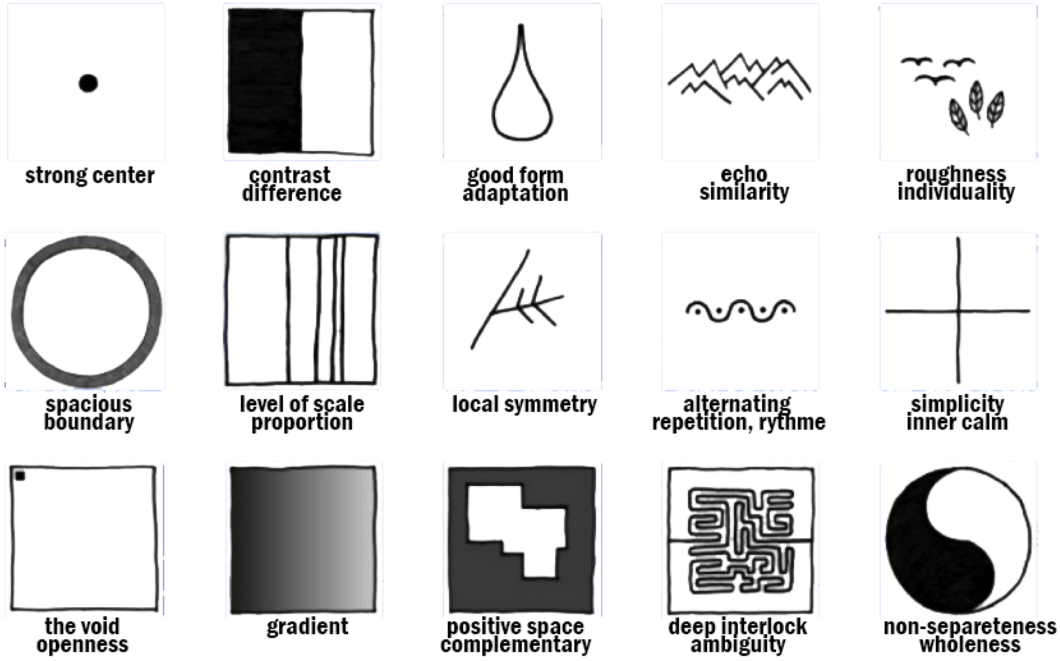


FIGURE 2.1: The Fifteen Properties of Living Structure, image by Helmut Leitner

> Throughout all phases of society, the hearth formed that sacred focus around which took order and shape. It is the first and most important element of architecture. Around it were grouped the other three elements: the roof, the enclosure, and the mound (Semper, 1989).

Historically, the first places 'designed' by humans happened to be around a fire, also known as a 'hearth'. It usually was located near a mound, providing shelter of some sort. These two elements, as important as they are in defining a place, are dependent on the nature of the location. Meanwhile, the other two elements evolved rapidly into something more consciously crafted. Semper goes on to explain that: *enclosures* have their origins in weaving, and are the most basic form of a spatial divider still used in most parts of the world; mats, draped over frames, used in primitive huts interchangeably as floors, walls, and roofs, are the origins of architecture. In other words, the roof (or ceiling) was mostly a fabric draped around a frame, and the enclosure (or walls) was a fence made with woven sticks. Subsequently, such structures had to be supported by bigger poles plunged into the ground, which seems to be the origin of the column.

A century later, another theorist and architect, L. Krier (1988) [6] illustrated in the first section of his book, "Architectural Composition", a wide variety of interior spaces (see Figure 2.2). Krier explains that,

[6]See Architectural Design Magazine No 49, Elements I: Interiors, `http://robkrier.de/elements-of-architecture.php`

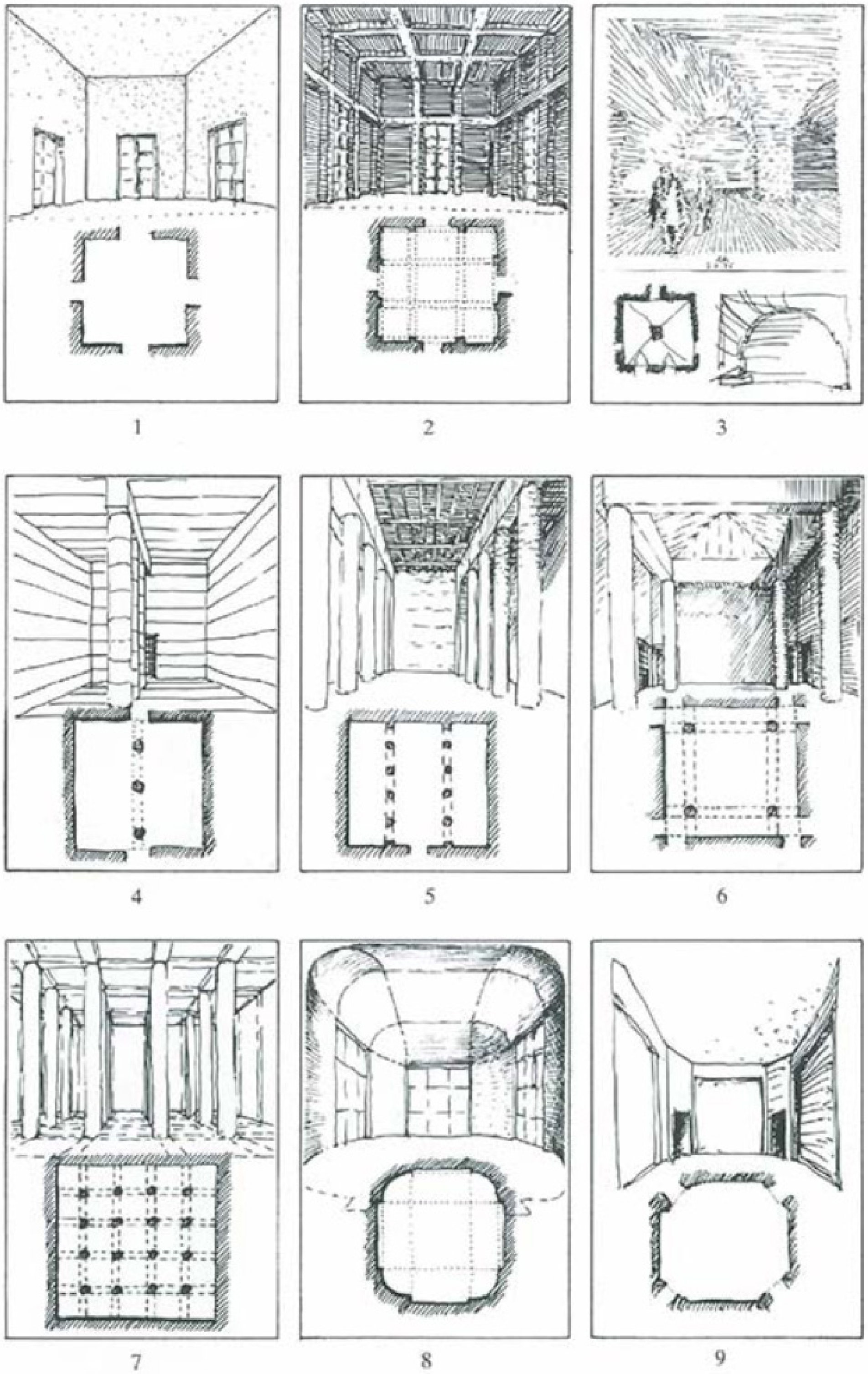


FIGURE 2.2: **Square Interior Space:** each image present a variation of the square plan with different number of opening placed at different position as well as with variations of columns layouts. Image by Krier from Architectural Design Magazine No 49, Elements I: Interiors

> As the starting point of architectural composition, the smallest spatial unity, the interior room, should first be studied. Normally, an interior space has for its bounds, walls, piers, ceiling and floor, being the traditional elements. Windows and doors serve as the connections with the exterior. By these, the technical elements of a space are determined (Krier, 1988, p.72).

More recently, the relocation of Google workplace to the King's Cross area in London is considered. The Google Real Estate team commissioned Allford Hall Monaghan Morris Architects to develop a modular unit, called "Jack". This unit is a fully functional meeting room that can be assembled, dissembled and reassembled elsewhere in a matter of days (K. Sailer)[7]. Stripping away the furniture and other details, what remains is a ceiling and four walls. Each wall is made out of a frame filled with either glass or wood panels. This contraption suggests already the potential of a meeting room that can be attached anywhere within the building structure, like a virtual room with physical boundaries.

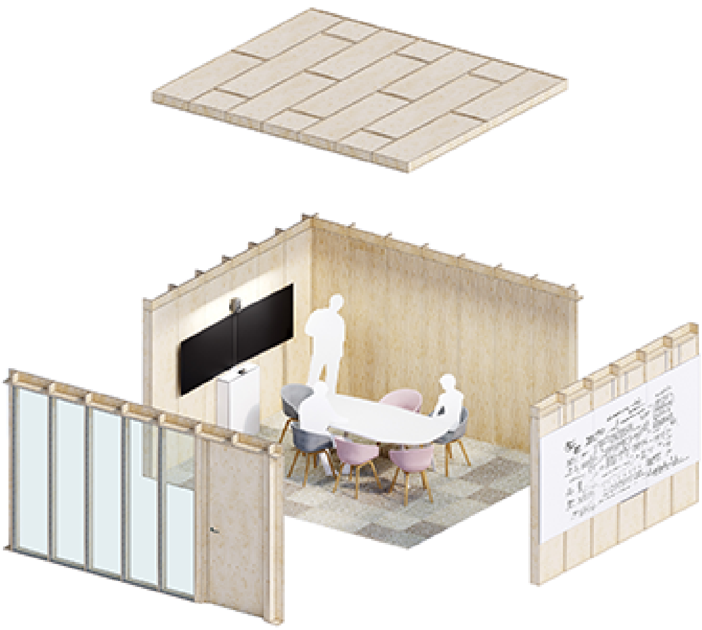


FIGURE 2.3: Modular small room and spatial accessory system 'Jack', image by AHMM, downloaded Jan 20

[7] The article *The Room of Requirements: Is flexible workspace possible?* was accessed online on 12 February 2020

From ancient times to today's most recent research in modular architecture, theorists and architects alike agree upon what makes the smallest unity of space, a room. The design of that *internal space* consistently uses the essential *architectural elements*: walls, ceiling, and floor. Columns or piers can replace a wall. The room, and its basics elements are the main focus of exploration of the present research. For a complete list of architectural elements, see Appendix A.

Each element has a function to fulfil. In parallel, it also developed a meaning as part of an abstract structure built upon language and culture. Architectural elements play an important role in our everyday language, known as metaphor. An obvious one is the window metaphor, as it is used in reference to exploring files and folders on today's computers.

2.3.3 Spatial Metaphors

The concept of metaphor has been thoroughly investigated and discussed by Lakoff and Johnson (2003). In their most influential work, "Metaphors we live by", they argue that, "most of our ordinary conceptual system is metaphorical in nature". They claim metaphors do not just point out similarities that are objectively true, like the one we have learned as an artefact of language use; they *create* the similarities. The most exciting part of their argumentation is that most of these metaphors are inherently *spatial* ones. For instance, it is a metaphor to use spatial prepositions to describe non-spatial relationships, as with "Sophie is in love" or "Peter is in trouble." Furthermore, Lakoff and Johnson have described a small number of highly productive metaphor schemata, also called embodied schema:

- *Spatial*: up-down (more is up), front-back, left-right, near-far, center-periphery, contact, straight, verticality
- *Containment*: container, in-out, surface, full-empty, content
- *Locomotion*: momentum, source-path-goal

Following his line of thought, it is worth reflecting on the meaning of the three basic architectural elements: ceiling (floor), wall and column. To begin with, they induce the two axes, the horizontal and the vertical, which do not possess the same force. *Ascending*, *descending*, *being high* are actions more meaningful than just looking to the left or to the right. The floor has a practical meaning, due to gravity. It supports life and objects. The walls and every vertical structure (columns) support the ceiling, and guide one's movements (cf. affordances, see Section 2.4.4, p. 36), contain activities, objects, and furniture. Their mouldings, their texture, and their capacity to host messages play a primary role in determining a place's character and ambience. The ceiling, in addition to its protective role, acts as an antithesis and an accomplice of the floor, and can take on more metaphysical meanings. Remote as it is, and very often untouchable, it is a favourite place for the expression of dreams, ideals and the sacred.

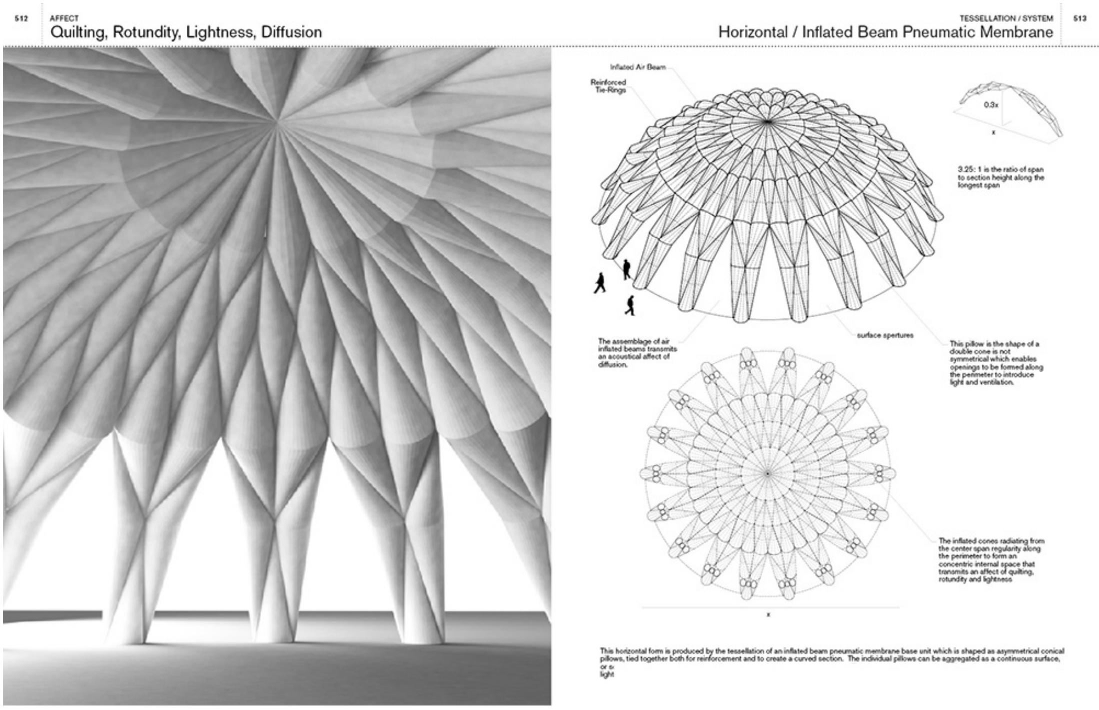
The main motivation for looking into the meaning of architectural elements and architecture in general, is to be able to incorporate it into the planning and design of a virtual environment. Indeed, as part of a virtual world (see Section 2.5), where there are no real physical constraints, the metaphorical meaning of individual architectural elements becomes even more important.

Nonetheless, one does not process, on a conscious level, every architectural element and its metaphor each time one enters a room. One grasps one's surroundings as a whole in a glimpse - the gist of a scene (see Section 2.4.2); then, one moves and interacts within that space; humans act on their environment, and in return, the environment affects them. Humans are the product of their interaction with their environment. This approach to space and time perception has been extensively explored by Merleau-Ponty and Landes (2013) in their seminal book, "Phenomenology of Perception", first published in 1945. From there, the "architectural phenomenology" movement grew to reach its apogee in the 1970s with the work of the acclaimed architect, theorist and historian Christian Norberg-Schulz (1974). For many architecture students of the 1980s and the 1990s, his book, "Genius Loci: Towards a Phenomenology of Architecture", provided accessible explanations to translate a phenomenological approach to architecture into designs. In the same vein, Dovey (1993) suggested a more radical approach to the design process which considers the division into two models, the *lived space* and the *geometric space*. These three theories, Lakoff's metaphors, Norberg-Schulz phenomenology of architecture, and Dovey's two models of space, are essential components in the development of this project.

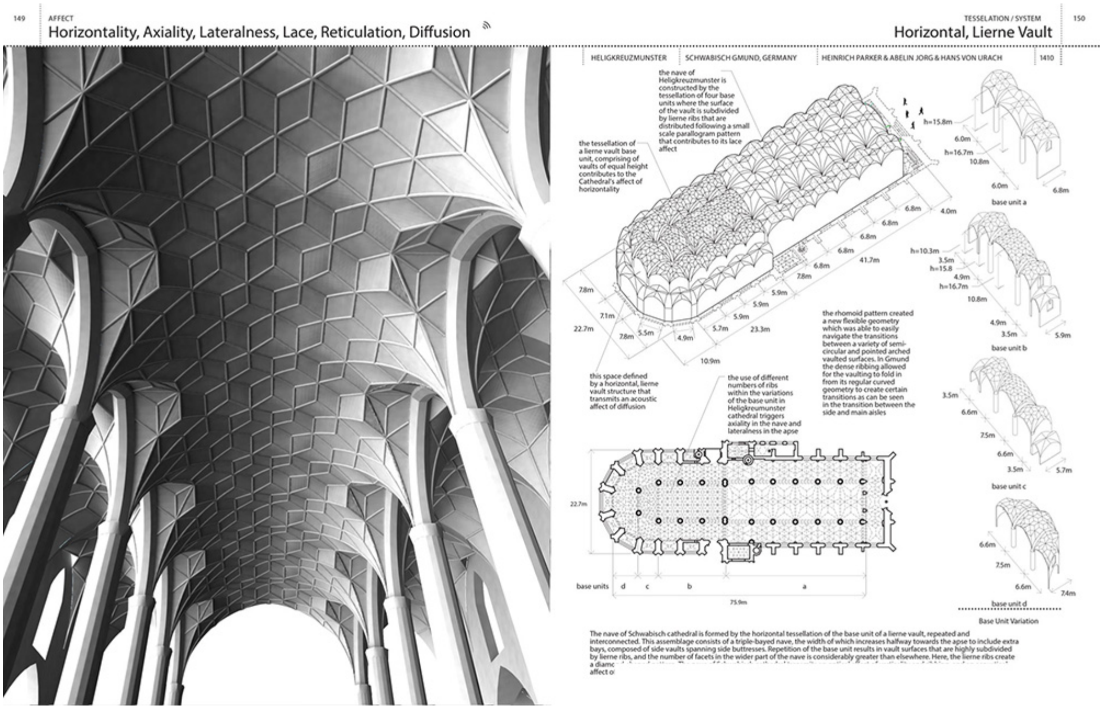
An excellent work of illustrations revealing the wide range of potential *affects* created by the larger spectrum of architectural spaces is proposed by Farshid Moussavi, an active contemporary architect. She has published a series of three books: "The Function of Ornament" (Moussavi, 2006), "The function of Form" (Moussavi, 2009), and "The Function of Style" (Moussavi, 2015). From an architectural standpoint, Moussavi's following quote gives a remarkable summary of what affect describes.

> Affects are autotelic or non-representational - they have a purpose in and not apart from themselves - and therefore are like a language prior to words, or a form of indirect speech that is perceived by different people in different ways.

It would be interesting to explore ways to measure the effect of such features on human perception by using biomarkers for instance. However, it can be argued that the term *affect*, as it is used to qualify hundreds of architectural features, ornaments, forms and elements in these books, is another type of *metaphor*. Figures 2.4 shows two examples of interior architecture. Typical qualities used in Moussavi's work are for example: quilting, rotundity, lightness, diffusion, horizontality, lateralness, reticulation.



(A) Affect: Quilting, Rotundity, Lightness, Diffusion, p.512-513



(B) Affect: Horizontality, Axiality, Lateralness, Lace, Reticulation, Diffusion, p.149-150

FIGURE 2.4: **Illustration of Affect in Architecture** Images by F. Moussavi, from *"The function of Form"*, Moussavi (2009)

Moussavi's work considers very advanced forms of architecture. It does not provide the most accessible angle from which to start answering this particular research question. However, it does show the range of possibilities that architects have deployed over the centuries to express a wide variety of human activities and emotions.

2.3.4 A Spatial Extension for the Mind

Stepping back from the architect's point of view, to humankind as a whole, M. Donald (1991) suggests three stages in the evolution of culture and cognition [8].

1. First transition: mimetic skill and autocueing
2. Second transition: lexical invention
3. Third transition: the externalization of memory

The third transition of development brings humanity from reliance on memory structures like language, to external devices, whether through sketching, drawing, building sculptures, architecture, computers, or more recently, virtual reality.

Throughout the last ten millennia of history, humans have developed an acute sense of their spatial environment. In the beginning, they sought protection from the weather, and from other forms of danger; then they started to build meaning into their surroundings for more complex reasons, such as spiritual and religious purposes, and created the first signs of an architecture; architecture became urbanism with more social, political and cultural purposes, covering everything that the human experience could imagine. In the belief that the human mind co-evolved in close interaction with both brain and culture, as suggested by M. Donald (1991), one of the main pillars of the present research rests on the dynamic created between language and architecture through the use of spatial metaphors. In today's western culture, people spend more than 80 % of their time inside buildings. This has to have an impact on our lives and on our brain. It is an emerging field of investigation, however, and studies struggle for funding because it is difficult to suggest that people are dying because of the lack of spatial metaphor applications (cf. Jackson, 2003). It was not always like that!

In ancient Greece, people realised early on that they were able to inhabit the architectural space, virtually, in their mind's eye. At a time when there were no convenient ways to write things down, they started to train their memory, by using visualisations, to help them remember things, people's names, or lengthy texts. In her book, Frances Yates (1966) covers 2500 years of history of "The Art of Memory". The following extract proposes a short abstract.

> The ancient Greeks, to whom a trained memory was of vital importance - as it was to everyone before the invention of printing - created an elaborate memory system, based on a technique of impressing "places" and "images" on the mind.

[8] The interdisciplinary work, "Origins of the Modern Mind" by M. Donald

In a more recent book, "Moonwalking with Einstein", J. Foer (2011) draws on cutting-edge research, a contemporary description of how top "mental athletes" enhance their memory using architectural-based visualisations. Foer went on a quest to learn ancient techniques once employed by Cicero to memorise his speeches, and by Medieval scholars to remember entire books. Using methods that have been largely forgotten, Foer discovers that anyone has the ability to dramatically improve one's memory.

> The point of memory techniques is to take the kind of memories our brains are not good at holding on to and transform them into the kinds of memories our brains were built for (Foer, 2011 p. 91).

Indeed, with the exception of remembering visual imagery extremely well [9], humans are not well disposed to remembering other kinds of information, like lists of words or numbers. Moreover, humans have developed different types of memory (see Section 2.4.1). Memory champions, like J. Foer, have practised *elaborative encoding*, which is a mnemonic that effectively relates to-be-remembered information to previously existing memories and knowledge. One can make such connections visually, spatially, semantically or acoustically (Groome, 2006).

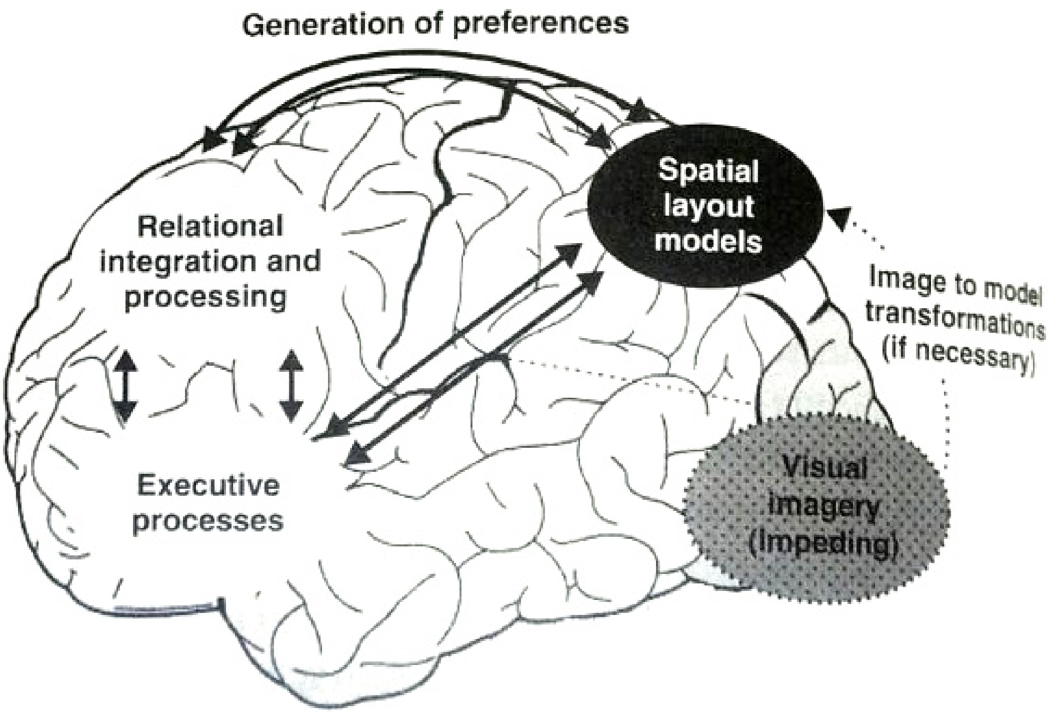


FIGURE 2.5: Illustration of the space to reason theory. Image from M. Knauff, *Space to Reason: A Spatial Theory of Human Thought* (MIT Press, 2103, p.180)

The method of loci, as a spatial extension for the mind, is an interesting device that bridges the gap between architecture and memory. It also raises more questions

[9]This capacity is usually well demonstrated with a two-alternative forced choice test.

than it answers. It is these questions that have brought together cognitive scientists from varied fields such as linguistics, psychology, artificial intelligence, philosophy, neuroscience, and anthropology, with the shared goal of studying the mind and its processes. The cognitive sciences began as an intellectual movement in the 1950s often referred to as the cognitive revolution.

In recent years, there has been an increasing interest in humans' spatial abilities. Knauff (2013) goes as far as rejecting the visual theory of reasoning for "A Spatial Theory of Human Thought" as illustrated in figure 2.5. He explains that our comprehension of the world is personal and embodied in our being; that most of our thinking processes are inscribed in some form of spatial processes; that our spatial model of the world is filled up with new stimuli all the time. The following section explores the different theories explaining how spatial information is processed by the brain and the latest trend toward embodied cognition.

2.4 From Spatial Cognition to Embodied Learning

In the 1980s, cognitive scientists started debating actively the interrelationship between the physical body, the local environment, the complex interplay between neural systems, and the wider world in which they function. Andy Clark (1999) raised critical questions concerning the nature and scope of the approach and proposed a theoretical framework that is still debated to this day. The reason for such debates on the notion of embodied cognition resides in the fact that it proposes an alternative to dualism as a philosophy of the mind. Nevertheless, in a second paper, Clark and Chalmers (1998) presented the idea of *active externalism*, in which objects within the environment function as part of the mind and form an extended cognitive system, also called *situated cognition*. The essence behind the theory is that the way one perceives and moves influences the way one creates and recalls one's internal model of the world (Vega, Glenberg, and Graesser, 2008). The idea that one's internal model of the world stored in one's memory can be activated, and even updated through one's movements and perceptions of the world is a key element to the present research.

Embodied cognition covers a variety of concepts and ideas. The representation of visual and spatial information in the brain is the main focus of this section. This has been subject to considerable discussion throughout the literature,. Three unresolved debates matters particularly: visual versus spatial perception; object position versus spatial orientation, which goes in parallel with the mode of representation; and spatial navigation.

Equipped with a better understanding of human spatial abilities, the last section will look at how architects, educators, and scientists are designing embodied experiences. But before examining the spatial dimension, it is essential to understand how information is acquired by the brain in general, which is accommodated by the theory of information processing and memory.

2.4.1 Memory: Stages of Mental Processing

Memory is the ability to encode, store and recall information. Additionally, a fourth process, memory consolidation, can be considered separately. Some of the physiology and neurology involved in these processes is highly complex, and still not completely understood. As such, it lies largely outside the scope of the present research, although at least the most relevant theories are presented here. Different models of memory have been proposed over the years. The most common one is the multi-store model. Atkinson and Shiffrin (1968) explain that information acquisition passes through three stages of mental processing: sensory memory, working memory (or short-term memory), and long-term memory.

Sensory memory holds sensory information for less than one second after an item is perceived. It is the ability to retain impressions of sensory information [10] after the original stimuli have ended. Information is passed from the sensory memory into short-term memory via the process of attention [11]; it is an automatic response.

The process of attention brings about another critical model of information processing, the *Dual Process Theory*, which began with the empirical and theoretical work described by Schneider and Shiffrin (1977) over twenty five years ago, and which is still debated today (e.g. Schneider and Chein, 2003; Frankish, 2010; Handley and Trippas, 2015). The two processes consist of an implicit (automatic), unconscious process and an explicit (controlled), conscious process. This theory has many ramifications throughout this present research.

Short-term memory allows recall for a period of several seconds to a minute without rehearsal and has a limited capacity. The often-cited experiment by Miller (1956) suggests that the number of objects an average human can hold in working memory (known as memory span) is "seven plus-or-minus two chunks" [12].

Long-term memory is intended for storage of information over a long period of time. It decays very little over time, and can store a seemingly unlimited amount of information. The specific way information is organised in long-term memory is not well understood, but researchers do know that these memories are arranged in groups like clusters. Short-term memories can become long-term memory through the process of consolidation, involving rehearsal and meaningful association.

2.4.2 Object Position vs Spatial Orientation

Visuo-spatial perception comprises two entangled systems: visual and spatial perception. It is essential to distinguish between these two systems, as they are complementary,

[10] Received through the five senses of sight, hearing, smell, taste and touch.

[11] Attention is the cognitive process of selectively concentrating on one aspect of the environment while ignoring the rest.

[12] Miller described the "seven plus-or-minus" as the “magical number”, and sometimes referred to as Miller’s Law. A chunk is a collection of basic familiar units that have been grouped together to be stored in a person’s memory.

but use different parts of the brain, and by doing so, use different ways to process information. It becomes even more relevant when considering the difference between studies where participants are presented with images representing scenes on a flat surface, compared with immersive virtual environments. Again, this is not the place to undertake a complete review of this complex subject, but it is worth noting the dynamics of the two systems.

Visual Processing

Visual perception is the ability to interpret the surrounding environment using light in the visible spectrum, reflected by the objects in the environment. This light creates stimuli on the retina before being processed by the brain. The visual processing is what remains as a never-ending source of bewilderment. For instance, the study of visual illusions (cases when the inference process goes wrong) has yielded much insight into what sort of assumptions the visual system makes (e.g. Leymarie, 2011).

One influential school of thought came about among the Gestalt psychologists in the 1920s. They emphasised that organisms perceive entire configurations, not merely individual components. The Gestalt theory attempts to describe how people tend to organise visual elements into groups or unified wholes following five principles: similarity, continuation, closure, proximity, and figure and background.

Furthermore, Gestalt theory had a considerable influence on modern design and architecture to the point that renowned architects Walter Gropius, Hannes Meyer and Ludwig Mies van der Rohe, led the Bauhaus School with the idea of creating a *total work of art*, which had a huge influence on modern design and architectural education.

Spatial Perception

Spatial perception is defined by the ability to perceive spatial information (such as features, properties, measurement, shapes, position and motion), and spatial relationships, in respect to the orientation of one's own body. In contrast, the three other types of spatial abilities usually explored in the field, spatial visualisation, mental rotation, and mental folding, are dependent upon some form of visual imagery.

The difference between the way visual and spatial stimuli are processed, and represented in the mind, often accounts for a lack of clarity in the literature, when discussing the representation of spatial information about a *scene* compared to an *object*. The following example is taken from the dissertation by Kirsh (1995), entitled: "The Intelligent Use of Space", and it highlights the confusion between the different modes of representation:

> Having a body, we are spatially located creature: we must always be facing some direction, have only certain objects in view, be within reach of certain

> others. How we manage the spatial arrangement of items around us, is not an afterthought; it is an integral part of the way we think, plan and behave.

Yes, "we are spatially located creatures", but then, Kirsh goes on to experiment with three main situations: spatial arrangements that simplify choice, spatial arrangements that simplify perception, and spatial dynamics that simplify internal computation. He explores the way the brain processes spatial information and abstracts different models. One of his main conclusions confirms the efficiency of the brain in reducing memory load, which is an essential factor in information processing. However, that experiment, in which participants were presented with images, does not take into account the position of the body and how it interacts with its spatial environment. This generates the confusion between spatial perception and the arrangement of objects within a space in front of the body. In the light of sensorimotor theory and the definition above, there is barely any spatial perception involved in that study.

Gist of a Scene and Atmospheric Sense

A more recent concept, the *gist of a scene*, has helped to shift the focus away from visual perception, to a fuller appreciation of the spatial dimension of a scene. In an influential publication on this phenomenon, Oliva and Torralba (2006) describe the role of global image features in recognition, and propose a space-centred approach to visual scene perception. They explain how,

> A growing body of evidence from behavioural, imaging and computational investigations has shown that the perception of complex real-world scenes engages distinct cognitive and neural mechanisms from those engaged in object recognition.

Architects have evidently developed a highly spatial perception of their environment. But in fact, everyone has. Instead of looking at pictures, consider the following thought experiment: someone enters a restaurant and looks to pick a table. Providing the person arrives early, there is a complex cognitive task. The mind is looking for cues to answer many questions such as, "Will I choose the table in a corner expecting a quieter moment or in the middle of the room to enjoy the atmosphere?" - "Do I want to face the window for the view outside or do I prefer looking at the entrance to see who is coming in?" - "Do I choose to sit back to the wall to avoid movement behind me, despite facing the door with people frequently entering and leaving?" How many of those choices do we make to get the right seat, at the right time, in the proper context? A study by Sailer and Psathiti (2017) has been carried out on this matter using spatial analysis, which will be introduced in chapter 4.

Besides the three dimensions of a room, there are many other elements comprising the definition of its architectural qualities. Humans conceive a global idea of space, in connection with the subjective filtering of their perceptions, experiences, language and culture, before consciously noting the parts. Robinson and Pallasmaa (2015), renowned architects and authors, go as far as introducing a sixth sense, the *atmospheric sense*.

> Our capacity to grasp qualitative atmospheric entities of complex environmental situations, without a detailed qualitative recording and evaluation of their parts and ingredients, could well be named our *sixth sense*, and it is likely to be our most important sense in terms of our existence and survival.

Returning to the duality between object and scene representation, the following study aimed to assess whether spatial abilities, acquired when training within a virtual environment, could affect achievements in spatial thinking of 10th graders in Israel. Using *Virtual Spaces 1.0*, a virtual learning environment, Hauptman (2010) reports on users' abilities to build a spatial model and to manipulate it in their mind's eye.

The geometric manipulation used in that study was based on a long-running trend of research, originating from the seminal paper on Mental Rotation of Three-Dimensional Objects by Shepard and Metzler (1971) which will be further explored in Chapter 4.4.3. The study is concerned with object recognition and manipulation, and not with the spatial perception of the environment.

The question of how humans process spatial information still lacks a full and complete explanation. *Spatial Cognition* is a broad field of investigation concerned with the acquisition, organisation, use, and revision of spatial knowledge.

Spatial Knowledge Acquisition

Previous findings suggest that the human brain could combine different mechanisms. The dominant framework in the field of spatial knowledge acquisition dates from Siegel and White (1975), who invented the spatial cognitive microgenesis theory, also known as the *Landmarks, Route and Survey knowledge model* (hereafter LRS), which humans would follow to create a cognitive map [13] of their surroundings. Nevertheless, *Spatial Cognition* is a complex field of investigation; large differences exist between the brain and nervous system of individuals, as well as from a social and cultural point of view. Daniel R. Montello (2001), a Professor of Geography, continued the discussion, introducing a different model, the *Continuous Framework*, adding the idea of metrically-scaled survey knowledge. A more recent study comparing both frameworks confirms the validity of the Continuous Framework solution (Aber, 2012).

Yet another critical element to understand is how spatial information is represented in one's mind. How does one remember the position of an object in comparison with one's position relative to a location? One of the main arguments is the distinction between the frames of reference humans and animals use to remember not only where

[13] A cognitive map is a type of mental representation which serves an individual to construct and accumulate spatial knowledge about the relative locations.

objects are in space, but also how they navigate their environment. Many authors have devoted time discussing the idea of frames of reference (e.g. McNamara, 1986; Wang and Spelke, 2002; Ruggiero, Iachini, and Francesco, 2009); the general consensus is that, in an egocentric reference frame, locations are represented with respect to the observer's point of view, whereas an allocentric reference frame locates objects in relation to each other's position. Klatzky (1998) wrote a review highlighting the various complications of such a framework, pointing to the lack of explanation about what exactly is represented in each frame.

In an attempt to explain the dissociation between the two types of frame, Ruggiero, Iachini, and Francesco (2009) proposed an experimental setup which involved an object-to-object representational system versus an egocentric perspective transformations which involved a self-to-object representational system. Their findings confirm that egocentric processing is more accurate and faster than the allocentric one. However, the "Ego-Allo Task" introduced for the experiment was based on spatial judgements of distance between memorised three-dimensional objects previously presented on a desk. Participants were not required to move around the room.

It can be argued than most of the spatial knowledge acquired in the aforementioned experiments were essentially visual imagery taken from a single point of view, as while participants were able to look around 360 degrees, they remained in a fixed position. So far, very little information has been provided about spatial navigation. This argument supports the idea of designing experiment that afford navigating a space to better understand how it is represented in the brain.

Spatial Cells Identified

In contrast with these somewhat confusing studies, a review of the findings made over the last four decades of neuroscience, indicates a growing understanding of the mechanisms of spatial cognition in mammals. Recent developments have seen a proliferation of studies that demonstrate the existence of dedicated categories of spatial cells. Hartley et al. (2014) describe the different categories as, "place cells, head direction cells, grid cells and boundary cells, each of which has a characteristic firing pattern that encodes spatial parameters relating to the animal's current position and orientation."

For instance, Spiers and Barry (2015) designed an experiment where brain-imagery techniques were coupled with VR technology to study how humans process visual and spatial information. Findings show how the brain encodes the spatial relationships to the set goal during navigation.

A team of neuroscientists and behavioural psychologists from University College London have come up with convincing explanations. Burgess (2006) proposed a two-system model combining egocentric and allocentric mode of representations. Three important factors are taken into consideration to understand what system of representation is used: (a) the amount of *self-motion* between presentation and retrieval; (b) the size and intrinsic *spatial structure* of the environment; and (c) the extent of *prior experience* within it.

These three factors offer an exciting new path of exploration: prior experience relates directly to acquired spatial knowledge and memory (see Section 2.4.1), but what happens when exploring an unknown environment? How does self-motion participate in our spatial understanding of the world? What are the different scales of spatial abilities?

2.4.3 Spatial Abilities in Motion

Once an environment is too big to be perceived form a single point of view, one has to move to perceive further; moving from one place to another is also called (loco)motion. Locomotion involves planning that can vary in complexity depending on the surrounding and the task at hand; for example to avoid bumping into obstacles, or to find the shortest route. This planning is referred to as wayfinding, the cognitive element of navigation, well defined by Darken et al. (2001), "navigation is the aggregate task of wayfinding and motion."

This section outlines key elements studied in the field that will be used in the present research. It starts by explaining the fundamentals about human's accurate estimation of their own motion relative to the surrounding objects.

Self-Motion Perception

Self-motion is an important and well understood phenomenon explained at length by experts in the field (e.g. DeAngelis and Angelaki, 2011). A quick introduction is nevertheless necessary as it is one of the key elements to help understand how spatial knowledge is acquired and how this phenomenon transfers into VR (see Section 2.5.4).

Self-motion perception is a demanding problem requiring the brain to create an "image" of our location and orientation based on a combination of sensory inputs coming from the eyes (vision), the ears (balance), and other proprioceptive cues less well understood.

It has long been recognised that visual cues provide a rich source of information about self-motion (Gibson, 1979, see also Section 2.4.4). Our eyes gather information about shapes, colour, depth, distance, binocular disparity and movement parallax. [14] As we move through the environment, the resulting pattern of "optic flow" [15] can be used to estimate heading.

[14]Binocular disparity and movement parallax are especially relevant to VR as parallax works fine in near space because of greater angle differences; and a far object moves less than a closer object when moving the head.

[15]Optic flow is the pattern of apparent motion of objects, surfaces, and edges in a visual scene caused by the relative motion between an observer and a scene

Our ears contain the vestibular system, which is a group of components within the inner ear [16] that contribute to the sense of balance. It provides a powerful independent source of information about head motion in space. Specifically, vestibular sensors can provide information about the angular rotation and linear acceleration of the head in space, and thus provide important inputs to self-motion estimation (DeAngelis and Angelaki, 2011).

Moreover, a cognitive process called proprioception assists the brain's awareness of the position of each body part without the person making visual contact. So by combining visual inputs, vestibular inputs, and proprioception, we know where we are in the world, and the direction we are heading.

The physio-neurological understanding of locomotion is critical in the development of efficient human-computer interfaces, such as the one used to navigate an immersive virtual environment. There is a caveat: when sensory misalignment occurs (the vestibular feedback does not correspond to the visual cues), the brain gets confused and that phenomenon can create motion sickness. Different strategies for locomotion in VR are considered in section 2.5.5.

Navigational Abilities

The ability to find one's way in a complex environment represents one of the most fundamental cognitive functions. Although involving basic perceptual and memory-related processes, spatial navigation is a vast and complex field of research that involves multiple sensory cues, interacting processes, and modes of representation. In an influential paper, Wolbers and Hegarty (2010) look at the most recent research in neuroscience, and propose a model of how different factors interact to produce individual patterns of navigational performance. Besides the different theories, a recurrent problem is found in the literature. Experiment design varies widely in regards to their scale (a room or a city), as well as to how spatial information is acquired (locomotion, from map, or video, etc.) and retrieved (distance estimation, map drawing, navigation to a goal, etc.).

With a focus on how humans remember different locations, McNamara, Sluzenski, and Rump (2008) have proposed a thorough review of empirical and theoretical advancements in the scientific understanding of human spatial memory and navigation. Their primary goal was to examine the ways in which memories of *familiar environments* are used to guide locomotion, reorientation, and wayfinding. Of particular interest are the different strategies used by humans to navigate their surroundings.

- Hierarchical structures
- Contextual cueing

[16] The inner ear contains a chamber full of fluid with small hairs called cilia affixed to the inside wall. When the head or/and the body moves, the liquid sloshes around and stimulates the cilia, and their motion tells the brain what is happening to the body.

- Cognitive map
- Axial lines, boundaries, layout, clusters
- Landmarks vs layout

Familiar Environment vs Unknown Environment

Different systems of representation are at play when navigating familiar environments or unknown environments. The main difference between the two is the recall of information from memory which occurs only in the case of familiar environments. In an unknown environment, the consensus is that humans use the LRS continuous framework. Thus far, a number of studies have attempted to explain the effect of environmental familiarity on wayfinding performance (for example, O'Neill, 1992; Baskaya, Wilson, and Özcan, 2004; Slone et al., 2015).

One study by O'Neill (1992) investigated layout complexity and level of familiarity. Participants were required to navigate a low resolution virtual environment on a computer display. The level of familiarity was assessed through a post experiment sketching task. It demonstrated a significant linear trend for wayfinding errors, which decreased with the level of familiarity.

Using a similar evaluation method, Baskaya, Wilson, and Özcan (2004) reported on the importance of landmarks and spatial differentiation in the acquisition of environment knowledge between two real hospitals. Results showed that most of the participants of the asymmetrical setting, containing repetitive units along one side of a linear corridor, could complete a sketch map with a minimum of errors. In the symmetrical setting, however, some participants drew incomplete sketch maps but could find their way through the building with a minimum of errors.

In a more recent study, Slone et al. (2015) performed an experiment where findings provided strong evidence that people's ability to navigate in unfamiliar surroundings is affected by the layout complexity of the environment. The virtual environment was of much higher quality than the much older study by O'Neill (1992). However, the evaluation method was still based on sketch maps. They used an objective measure of plan complexity, that is, the average number of connections at each decision point along the corridors.

The evidence reviewed here seems to suggest a pertinent role for using sketch maps to evaluate participants' wayfinding performances. Yet, the method to measure the difference between the compared environments differs widely.

The following two studies, from Manning et al. (2014), and Hamburger and Knauff (2011), describe how navigation performances can be evaluated using predictive models. In an insightful study to understand what mechanisms people use to find their way in *unfamiliar environments*, Manning et al. (2014) developed a model that predicts the ease (or difficulty) with which different environments are learned and, within a given environment, which landmarks will be easy (or difficult) to localise from memory. The Magellan model, described in the study, uses an allocentric computational model to explore human wayfinding, including the role of landmarks, saliency, routes length and complexity. Using two spatial parameters, they were able to generate different levels of complexity of environment, to study the way in which participants acquired experience over time and stored spatial information in their cognitive map to improve their navigation.

Conversely, the Squareland system from Hamburger and Knauff (2011), which was also used to investigate the neural basis of human wayfinding, proposes a simplistic grid to represent modern cities' urban space. It does not allow realistic or organic variations.

Both of these studies propose a standardised and controllable research tool that could improve comparability and repeatability of different effects in navigation performances. However, both studies have been using the desktop monitor setup, projecting the virtual world again on a two-dimensional screen with low quality graphics. The present review discusses the validity of such setups with regards to the evaluation of spatial cognition.

Figural, Vista, and Environmental Spatial Abilities

It is important to note that the scale of the studied environments differs widely: some studies require participants to complete a task inside one room, where the relevant spatial information can be perceived from a single vantage point; other studies ask participants to complete navigational tasks in complex environments where they have to infer spatial relationships between distant locations. No theory covers such a wide range of abilities. Comparisons need to be taken with caution. With that in mind, Wiener, Büchner, and Hölscher (2009) did a review of numerous studies and proposed an extended taxonomy of wayfinding that distinguishes tasks by external constraints as well as by the level of spatial knowledge available to the navigator. However, considering the present research focusses on interior spatial design, notions of wayfinding, more often used in large buildings or even cities, do not need to be covered in more detail.

A simpler framework would be beneficial. In that regard, following an insightful workshop, Montello, Golledge, and Org (1998) reported on the distinction between three levels of spatial abilities. The *figural spatial ability* corresponds with small scale objects in relation to the body, which can be perceived from a single viewpoint. *vista* refers to the ability to perform spatial transformations internally, in order to make inferences from the acquired information. Indeed, Hegarty et al. (2006) explains how humans have developed the faculty of representing spatial information internally, at any scale, object or scene, that can consequently be examined mentally from different viewpoints. This ability also supports the idea that one can imagine what someone else sees or what a scene looks like from another point of view. This is known as *perspective-taking* and is well-documented in the field of theory of mind (cf. Tversky and Hard, 2009; Surtees, Apperly, and Samson, 2013). Finally, the *environmental spatial ability*, refers to larger scale (relative to the body) scenes (see Section 2.4.2), like a building or even a city, which require locomotion to navigate.

2.4.4 An Enactive Approach to Embodied Learning

Without going too deeply into the fascinating discoveries made in neuroscience and embodied cognition - authoritative accounts have been provided elsewhere (Gallagher, 2005; Pezzulo et al., 2013; Riva, 2018) - this section proposes following the enactive approach to learning. Research into learning and education is increasingly influenced by theories of embodied cognition. As explained by Skulmowski and Rey (2018), in a theoretical paper, the current literature shows a wide variety of ways to transfer embodied cognition into learning from the use of gesture to full body movement, such as locomotion (e.g. Johnson-Glenberg et al., 2014).

Embodied Learning

Embodied learning focusses on bodily action and perception in the context of education. In the early years of the 20th century, Dr. Montessori postulated that learning relied on how children interacted with their environment. This led to the Montessori Method of education used around the world.

> Movement, or physical activity, is thus an essential factor in intellectual growth, which depends upon the impressions received from outside. Through movement we come in contact with external reality, and it is through these contacts that we eventually acquire even abstract ideas. (M. Montessori, 1966)

From the practical observations of children interacting with their environment to the development of embodied cognition and the advance of human-computer interaction technologies, a few constructs remain constant. Willing to compare and discuss the wide range of embodied learning studies, Skulmowski and Rey (2018) and Johnson-Glenberg (2018) suggest a similar taxonomy. The former propose a more general model based on the dimensions of bodily engagement and task integration. The latter propose three constructs with sensorimotor engagement, congruency of gesture, and feeling of immersion as experienced by the user.

The sensorimotor theory was explained previously (see Section 2.2.3). The following section describes the concept of immersion and VR (see Section 2.5.3). *Affordance* has already been mentioned earlier (see Section A and 2.4.3). What exactly is an affordance, and how does it lead to the concept of congruency of gesture?

Visual and Spatial Affordances

American psychologist James J. Gibson originally explained the concept of affordances in, "The Ecological Approach to Visual Perception",

> An affordance is a resource or support that the environment offers an animal; the animal, in turn, must possess the capabilities to perceive it and to use it (Gibson, 1979).

One of the highlights of Gibson's approach is the *pattern of potential movement*, also referred to as *embodied interaction*. An obvious example of affordances is the hammer; give a hammer to someone that has never used or seen one before, and the recipient will likely soon discover its purpose, and start *hammering* on the closest thing. The same idea applies to a door handle (see Figure 2.6a), a chair, and any other object design with a minimal sense of agency in mind. Another example comes from user experience (UX) designers that created the perfect button, to encourage users to click on it (see Figure 2.6b). Indeed, affordances are critical in graphic design, as a user can only perceive potential actions based on the look and feel of a "button". In that context, giving incorrect visual cues will have the effect of ruining the UX, and will lead to user frustrations. Performance metrics, or even A/B testing, are well established methods for gathering valuable feedback for UX designers in order to improve their design. However, how does that translate into spatial design?

Despite a huge number of affordances in everyday life, their identification in our spatial environment (in architecture) is less obvious. The main reason for this is that one does not pay direct attention to one's surroundings in the same way one does to objects in direct sight (see Section 2.4.2). As mentioned above, human response to a scene, or a larger scale environment, is different from their response to an object. It requires different spatial abilities, and uses different modes of representation. It can be argued as well, that one's spatial surrounding is perceived as secondary (in reference to the dual processing theory explained earlier, see Section 2.4.1) and thus, not brought to one's attention if not specifically required by the situation at hand. An arch is a good example as an architectural element: it has a clear functional purpose to offer a passage between two different spaces (as well as supporting higher structures); the consequence is that one has to walk underneath it to reach the other space (see Figure 2.7). One could thus say that the affordance of an arch is to link two spaces.

In "Mind in Architecture", an inspirational multi-disciplinary book (Robinson and Pallasmaa, 2015), Prof. Michael Arbib, a prominent scientist concerned with architecture, wrote about affordances as a way:

> [...]to identify the opportunities for action that our brains register without necessarily being consciously aware of the object which affords those actions.

(A) One door with two different ways to handle it

(B) Which button invites you to click the most?

FIGURE 2.6: Affordances in Interior Design and Graphic Design

He introduces another instance of this concept applied in the architectural space as follows:

> So, returning to the idea of wayfinding, as architects might assess, on the one hand, how people will experience their passage through the spaces of a building based on cues afforded by the spatial structure of that building and, on the other hand how to use signage, appealing to the symbolic aspect of their cognition to help assist their navigation when other cues fail.

Furthermore, from the same book, philosopher Mark L. Johnson explains how architecture provides material and cultural affordances that bring meaning to humans' lives. Borrowing from Dewey's ideas, he points out that one's account of any affordance must include the crucial role of the qualitative dimensions of any previous experiences.

One of the purposes of this literature review is to understand how architects, designers and scientists think about using these types of spatial affordances in the realm of virtual learning environments. Potential for action is embedded in any form of affordances. Conversely, interaction with the digital world is usually restricted to specific gestures due to the human-computer interface available. These restrictions limit the transfer of existing affordances to the digital realm.

Congruency of Gesture

For several decades, the primary technological interface in education used to interact with digital content has been the mouse and keyboard. However, these are not highly

(A) End of Sitting (Courtesy RAAAF)

(B) Four arches make an arcade separating two places. Images downloaded from the web.

FIGURE 2.7: **Architectural Affordances** Illustrations of a couple of architectural affordances in the work environment (top) and the arcade from the classical architecture style.

embodied interfaces, as explained by Johnson-Glenberg et al. (2014). An embodied interface refers to the *congruency of the gesture*, that is, the movement should be well-mapped to the concept to be learned. As an example, imagine an experience where someone has to use the arrows on the keyboard to walk through a building showing the real-time feedback on the screen. This would be considered less embodied than someone actually walking through the same building wearing a virtual reality headset automatically capturing one's movements.

The concept of *congruence* originated from geometry, where two shapes are congruent if they have the same shape and size. In the context of embodied learning, it means a large overlap between the action performed and the content to be learned or interacted with. The way one interacts with the digital landscape is poised to change with the advent of immersive technologies and natural user interfaces. Immersive virtual environments that can be manipulated with hand controllers or even bare hands will have a tangible effect on how content is encoded and retained (Johnson-Glenberg, 2018).

Moreover, in a meta-review of VR simulations, Riva, Wiederhold, and Mantovani (2019) show how successfully simulations have been used in the field of behavioural health. The review accumulates evidences of the benefit of using VR to help patients with mental disorders. In an attempt to explain the reason for the success, they explain that VR and the brain share the same basic mechanism: *embodied simulation* (see Section 2.5.3). This mechanism is based on the increasingly popular theory of predictive coding [17], suggesting that,

> [...] The brain actively maintains an internal model (simulation) of the body and the space around it, which provides predictions about the expected sensory input and tries to minimise the amount of prediction errors (or "surprise") (Riva, Wiederhold, and Mantovani, 2019).

Notwithstanding the significance of *embodied cognition*, and the intuition about the potential of VR in learning and training, the technology is far from being able to fully simulate the real world. The following section explores the key components to VR technology in its current state.

2.5 The Virtual Space and its Specifications

What does *virtual* mean? The meaning, "being something in essence or effect, though not actually or in fact" is from the mid-15c., probably via the sense of "capable of producing a certain effect" (early 15c.)[18]. Keeping a focus on a technical history of this virtual space, the first device that was capable of producing this kind of effect dates from the 19th Century.

2.5.1 A Brief History of Virtual Reality

The first stereoscopic photos were shown in 1838 by Charles Wheatstone. In the 1930s a story by science fiction writer Stanley G. Weinbaum (Pygmalion's Spectacles) describes a pair of goggles which let the wearer experience a fictional world through holographics, smell, taste and touch. In 1965, Ivan Sutherland published a paper that would become a core blueprint for the concepts that encompass virtual reality today. Three years later, Sutherland and his student, Bob Sproull, created the first head-mounted display (HMD), with motion tracking, connected to a computer, and not a camera [19].

The Virtual Reality Society website proposes the following definition,

> Virtual reality is the term used to describe a three-dimensional, computer-generated environment which can be explored and interacted with by a

[17]Predictive coding is part of the same theoretical framework mentioned in the introduction of this section, enactivism Clark (1999)

[18]In the computer sense of "not physically existing but made to appear by software" is attested from 1959. Definitions are provided by the Online Etymology Dictionary, accessed on 31 March 2020, `https://www.etymonline.com/`

[19]It was a large and scary looking contraption that was too heavy for any user to comfortably wear and was suspended from the ceiling (hence its name, the Sword of Damocles. "History Of Virtual Reality." Virtual Reality Society, accessed on 31 March 2020, `www.vrs.org.uk/`)

> person. That person becomes part of this virtual world or is immersed within this environment and while there, can manipulate objects or perform a series of actions [20].

Besides their specificity to Virtual Reality (VR), the three central concepts mentioned in the definition rely upon embodied and visuo-spatial cognition (see Section 2.4):

1. Immersion is used to evaluate the quality of a VR experience based on the theory of sensorimotor contingencies.

2. Exploration, interaction and manipulation of objects are dependent on spatial cognition and navigation, as well as on the concept of affordances and congruency of gesture, with the aim of replicating humans' natural movement.

3. Three-dimensional, computer-generated environment. Using the same software used by architects and designers, virtual environments are rendered in real-time. Renders include the concept of visual realism.

Jaron Lanier, who coined the term *virtual reality* in the 1970s and who set up the first company to sell VR systems, expanded the definition by saying that, "[VR] gives us this sense of being able to be who we are without limitation; for our imagination to become objective and shared with other people.[21]

This gives a better idea of the ultimate potential of VR, which is to develop our imagination and to share it with other people. In a well-received review about how VR can enhance humans' lives, Slater and Sanchez-Vives (2016) revisit the main ideas behind VR in a wide variety of fields. In particular, they focus on cognitive training such as enhancing memory for the elderly (Repetto et al., 2016; Lokka et al., 2018), simulating critical events to assist people acquiring new skills, but at the same time limiting risks, (Grottke et al., 2009), as well as creating forums for people to share their knowledge, organise meetings, even though physically remote (e.g. Second Life, AltSpaceVR).

Still, one critical element is not explicitly stated in most VR definitions. Neither the VR Society's definition, nor Jaron Lanier's comment mentions the spatial design of the virtual environments, or their architecture. In their paper, Slater and Sanchez-Vives (2016) focus more on this omission when comparing different studies looking at "spatiality and realism" - the word *spatial* appears 45 times - however, nothing is said specifically about *spatial qualities* or *architecture* and their effect on people's behaviour.

Two further points need to be mentioned before analysing the technicalities of VR systems: (a) the duality of VR used as a research tool, and as an object of research.

[20] "What is Virtual Reality." Virtual Reality Society, accessed on 31 March 2020, `https://www.vrs.org.uk/`

[21] Jaron Lanier at SIGGRAPH Panel 1989, Virtual Environments and Interactivity: Windows to the Future.

This problem is of epistemological concerns and contributes to the confusion in the literature; (b) the somewhat broad use of the term "VR", which leads researchers to use terms like *virtual environment*, to describe any computer-generated content, even if displayed on a two-dimensional screen. In a review of VR in education, Freina and Ott (2015) suggest a useful distinction between *immersive virtual reality*, where the virtual environment surrounds you, that is when using an HMD, and *non-immersive virtual reality*, where one looks at the virtual environment on a traditional desktop computer monitor. The rest of this literature review attempts to bring clarity to this nomenclature. The following section gives a brief introduction to the ecological validity of virtual environments, before exploring VR specifications, mostly from a spatial perspective.

2.5.2 Ecological Validity of Immersive Virtual Environments

Using VR as a research tool to study spatial cognition and navigation related topics has unique advantages. Virtual environments can be modelled and controlled precisely following an experiment's requirements. This allows studies to be conducted in laboratory settings, which affords the opportunity to maintain the same conditions for each participant. VR systems offer many ways to collect valuable data on user behaviours including location, movement and gazing.

Besides this powerful behavioural measuring tool, the question remains whether the results of VR studies are valid in comparison with traditional navigation research methods. Many authors have explored these questions by using comparative studies to evaluate to what extent results of a VR study are comparable with results acquired using real-life navigation (e.g. Richardson, Montello, and Hegarty, 1999; Ziemer et al., 2009; Ham, Faber, and Venselaar, 2015; Cipresso et al., 2018; Murcia-Lopez and Steed, 2018).

However, being concerned with the use of VR as a new type of training environment (not to replace real-world situations), this research provides insight into the different modes of interaction within the virtual realm. The main caveat when using VR in research is the lack of consistency between studies. Comparison between studies is difficult and the lack of replicability does not suit the scientific method well. Furthermore, most studies are media-comparative (HMD-based compared to real-life settings or non-immersive VR) and carry too many confounding variables. Furthermore, with the novelty and the complexity of the different technologies involved in VR, there is neither consensus on the hardware to use, nor any standard framework to develop the software. In a comprehensive review on the use of VR HMDs in education and training, Jensen and Konradsen (2018) show the disparity in quality between 21 studies using a variety of VR systems.

As a starting point, the creation of a framework for using VR as a research tool requires a method to be defined in order to evaluate the two main factors driving any

VR experience: the level of immersion and the feeling of presence (Slater and Wilbur, 1997).

2.5.3 Immersion, Presence, and Illusion

How can the extent to which someone feels as though they are "really" there when taking part in a VR experience be evaluated? This phenomenon was debated at large in the 1990s resulting in two different concepts: *immersion* is based on objective and quantitative measures of the VR system, and *presence* is the subjective point of view of the participant's feeling. In an early tentative to propose a "Framework for Immersive Virtual Environments", Slater and Wilbur (1997) speculated on the role of each concept,

> [...] immersion ideally requires inclusive, extensive, surrounding, and vivid display systems, where there is real-time matching between proprioception and sensory data. [...] presence is the potential psychological and behavioural response to immersion. [...] a highly present individual would be observed to behave in a Virtual Environment in a manner similar to how they would behave in a similar environment in everyday reality.

In this sense, the level of immersion is described as the level of sensory fidelity offered by a specific VR system. The main factors to consider when evaluating the level of immersion include, but are not limited to, the field of view, the display size, the stereoscopic effect, and the parallax. For instance, Ragan et al. (2010) obtained better performances on a memory task when using a wider field of view.

The level of immersion influences the level of presence but is not the only influence. There was no real consensus on what being present in VR involved (e.g. Witmer and Singer, 1998). In response to the criticism of their proposition, Slater (1999) refines both concepts of *presence* and *immersion* in a follow-up paper. Dozens of different studies have trialled many questionnaire types in the quest to evaluate the two concepts. Different types of measurements, such as subjective, psycho-physical, continuous, corroborative and many more variations were tested (cf. Baren and Isselsteijn, 2004 and Chertoff, Goldiez, and LaViola, 2010).

In another major paper, Slater (2009) explains that VR activates sensorimotor contingencies in a way that fools the brain into believing that it has been transported to another world. He argues that the level of presence in VR can be described with two main illusions: (a) *place illusion*, "I am here even though I know I am not", (b) *plausibility illusion*, "the events I am perceiving are happening, it conforms to my expectations". Any encounter that breaks these illusions will break the sense of presence. Breaks of *place illusion* - like seeing pixels too closely - are only temporarily disturbing because they are only perceptual. Sensorimotor contingencies bring the sense of presence back. However, breaks in *plausibility illusion* are cognitive, and are much harder to overcome. They usually result in a break of presence, and the end of the VR experience.

A third illusion is also described by Slater (2011), the virtual body ownership illusion, in which one identifies a virtual body (avatar) as one's own body. The consequences of this in terms of the attitudes and behaviour of the participant who experiences the transformed body are remarkable, if out of the scope of the present research.

2.5.4 Modes of Interaction - Hardware and Studies

Historically, VR has often been used interchangeably to refer to one of the three following human-computer interaction categories, defined mostly by the type of displays used to render the visual feedback, as well as the type of controllers used to acquired the inputs. For each system, the virtual environment is presented either on a large display (or on more than one), or on the walls of a room-based system such as a CAVE, or a head-mounted display. Recently, a fourth option has become readily available by using a smartphone inside a cardboard-style headset. A description of the four different VR systems follows with the level of immersion they afford in term of degrees of freedom (DOF) borrowed to the field of statistics. This represents the number of independent ways by which a dynamic system can move (independent coordinates). Basically, 3 DOF devices support rotational motion, and 6 DOF devices support rotational motion (3 DOF) and positional motion (3DOF), which is the equivalent of a full range of motion.

Hardware and Degrees of Freedom

Desktop Computer (2 DOF): The computer desktop system consists of a computer tethered to one or two monitors, a keyboard, and a mouse or a joystick. Readily available for the last five decades, it is a cost effective solution in research labs. It affords only 2 DOF following the XY coordinates of the joystick. However, little adaptation from the participant is needed as their widespread availability has made them part of our daily lives.

Mobile VR and 360 video (3 DOF): For the last few years, VR is used to describe any 360-degree video which is available on a smartphone in conjunction with a "Google Cardboard" style HMD [22]. This type of VR offers only a basic level of immersion within the virtual environment, restricted to head rotation (3 DOF). Basic user interaction is possible either by gazing at a target or using a simple controller with buttons. It includes 360 degree panoramic views or videos that are not stereoscopic. It counts only as a gimmick in comparison with the potential that VR has to offer and is not part of this review. Finally, the video game industry does not label VR any classic video game played using a controller. Although computer-generated environments, they do not qualify as VR.

[22] A Google cardboard is a piece of cardboard including lenses in which the smartphone fits

Cave Automatic Virtual Environment (CAVE - 6 DOF): A CAVE consists of a room where the virtual environment is projected onto as many as six surfaces (four walls, one floor and one ceiling). The user stands in the middle of the room. A key advantage of this setting is that the observer need only wear a light-weight pair of glasses, which provides a stereoscopic signal and the freedom to move around (6 DOF). A disadvantage is a constraint of space required to project images onto the walls which, consequently, affects the resolution of each image in function of the distance between the freely-moving observer and the walls. Regardless, the fact that participants are able to stand up in the CAVE and walk around freely is a real advantage as it allows for more than one person to be involved in the experience.

As Heim (1995) explains, after having tested an early prototype, the CAVE system offers an *aperceptive immersion*, as the participant is still physically present without the need to adapt to a series of devices such as with a HMD or data gloves. There is no loss of self-awareness as is usually the case with the HMD. However, this type of system does not provide a high level of immersion, which brings some limiting factors in the case of this research project.

Head-Mounted Display (6 DOF): Palmer Luckey activated the last wave of VR HMDs in 2012 with the Oculus Kickstarter campaign. Until then, HMDs were an expensive piece of hardware only a few universities could afford. Those HMDs had a non-negligible weight, which was a problem for prolonged use. Another consequence of their weight was the limitation of movement because of rendering errors introduced during high-acceleration head movement (Gilson and Glennerster, 2012).

Today, HMDs are still tethered to a computer to run high-quality real-time renderings through a powerful GPU. Cables can get in the way and reduce the freedom of movement (also relating to the feeling of presence). Different solutions exist already to counter this. One is to hang the computer, which is a small laptop, on the participant's back. Another option is a wireless HMD, which brings some other issues of latency in addition to the burden of wearing them. These solutions are still not ideal, although very promising in the near future.

VR HMD systems include hands controllers affording 6 DOF each. Virtual hands are usually attached to the controllers, giving a real sense of virtual hand ownership (cf. Slater, 2011). It can be said that these type of system offer a range of 18 DOF (headset + two controllers). Additionally, various tracking devices can be added into the system to track the legs. Even full body suits can be considered.

Multimodal Studies - Main Issues

Much of the previous multimodal research has tried to evaluate the key benefits and disadvantages of a wide variety of VR systems. Most of the experimental design required participants to complete a particular cognitive task, e.g. a navigation task, using different modalities. A series of issues were identified with mixed results.

Level of Immersion: Richardson, Montello, and Hegarty (1999) assessed the nature of spatial representation of an environment acquired from maps, direct experience, and virtual environments. Virtual learners showed the poorest learning, and were the most disoriented. In a comprehensive study, comparing a variety of modes of interaction, Mania et al. (2003) showed that the highest level of immersion is not always the most adapted when assessing the simulation fidelity of a virtual environment (see Section 2.5.6). In yet another study, examining perceived spatial orientation in a small environment under three different conditions (real-world, desktop monitor, and HMD), Lathrop and Kaiser (2002) obtained significant results, suggesting the weakness of desktop monitors to support spatial orientation.

Distance Underestimation: A frequent issue extensively studied is the underestimation of distances. It is noteworthy that this issue is a legacy in the field of VR. Most of the studies looking into this issue usually used a low level of immersion compared with what is offered by more recent technologies (e.g. Knapp and Loomis, 2004; Willemsen et al., 2004; Plumert et al., 2005; Ziemer et al., 2009). In contrast, in the field of 3D visualisation in architecture, it is well known that the details (objects, humans, plants and flowers) of a model, and even more so in a still image, are critical in bringing a sense of scale. The problem of distance underestimation is at the core of the experiment proposed by Grechkin et al. (2010) where distance perception in real and virtual environments are compared using either timed imagined walking or direct blindfolded walking. They found that, while wearing the HMD can cause some degree of distance underestimation, this effect depends on the measurement protocol used. Besides the usual lack of validity between studies, a more recent paper by Ghinea et al. (2018), compares the accuracy of perceived distances in a virtual space ranging from 0 to 15 m in a CAVE system compared to an HMD. Results show that the HMD provides the best results for distances above 8m while the CAVE provides the best results for close distances. Thus, the CAVE system shows some advantages in specific circumstances. Furthermore, Siegel and Kelly (2017) presented significant results indicating that object size judgements do benefit from interaction with the VE.

Illusions of Self-Motion: The concept of self-motion was explained earlier (see Section 2.4.3). In a VR system, as there is not always enough room to walk around, the illusion of self-motion, also called *vection*, needs to be designed. In recent years, since more accurate and affordable self-tracking systems have been integrated with HMD, many studies explore vection [23].

[23] Vection can be visual, auditory, or biomechanical

In a review of the literature on *presence* and *self-motion perception*, Riecke and Schulte-Pelkum (2015) showed their interrelations. A variety of solutions, hardware or software-based, are discussed,

> Compared to increasing the visual field of view, using a motion platform, or building an omnidirectional treadmill; cognitive factors can often be manipulated rather easily and without much cost, such that they could be an important step towards a lean and elegant approach to effective self-motion simulation.

Indeed, whatever the level of immersion involved, each system has inherent constraints in the way it affords natural movement within the IVE. To be able to walk around in VR using body-based information means, on the one hand, to have enough physical space to correspond to the virtual environment, and on the other hand, to have the capacity to track body position along that space. That is, there is a dichotomy between the physical constraints and the limitless potential of the IVE; the physical space will often be smaller that the virtual one.

However, studies have shown promising results in achieving effective self-motion within IVEs using room-scale VR. For instance, a study by Ruddle and Lessels (2009) shows comparable results on a navigation task with HMD and in real-world settings, in contrast with much lower results when using a tethered HMD for head rotation, but pressing a button to move around, or even more so, with a desktop monitor and no body-based information at all.

To sum up, many studies have investigated the quality and variety of the modes of interactions in VR since the 1990s. The recent development of room-scale VR systems has already shown promising results regarding their ecological validity. Their main advantage is to procure a higher level of immersion, from a visual and auditory perception outlook. As Heim (1995) puts it, "HMD produces a perception-oriented immersion. The participant identifies with the image, the real world vanished". One perceives the IVE as a new realm. In other words and in line with Slater's framework, room-scale VR affords the highest level of place illusion and sensorimotor contingencies (Slater, 2009). Still, many challenges lie ahead in this new field of investigation. Once a robust VR system is in place, the whole user experience need to be designed and programmed.

2.5.5 Agency and Embodiment

The room-scale VR brings the highest level of immersion that VR hardware can afford today. But how does the virtual environment come about from a software design point of view? Two profound affordances are at play: *presence* and *embodiment* (Johnson-Glenberg, 2019). The possibility to design Natural User Interaction (NUI) intertwined with agency is the key factor that makes these affordances possible.

Agency refers to the capacity to act in a given environment. It implies the *sense of agency*, which plays a pivotal role in cognitive development, and the theory of mind mentioned earlier (see Sections 2.2.2 and 2.4). Cognitive scientists have recently elucidated the required mechanisms to recognise oneself as the owner of a body and the agent of actions. Jeannerod (2003) explains how one experiences being an independent self, partly as a consequence of the brain monitoring the signals arising from bodily movements, a fascinating area of study that is out of the scope of the present study. However, it emphasises the importance of the sense of agency in the development of the feeling of presence and embodiment in a virtual environment.

Agency heightens one's engagement in cognitively demanding tasks by focusing one's attention on the possibility for action. Evidence continues to accumulate of the increased performance of participants having the opportunity to physically engage with the learning task. For example, in a laboratory experiment, involving college students, Kontra et al. (2015) explored the importance of physical experience in science learning. Participants who were active and physically held a spinning bicycle wheel learned more about angular momentum compared to those who, more passively, observed the spinning wheel. Using virtual settings, Jang et al. (2017) compared medical students who either directly manipulated a virtual model of an inner ear or passively viewed a recorded animation. Results indicate that participants in the manipulation group show greater post-test knowledge compared with the viewer group.

Actions (movements) can be of two main types, object interaction and locomotion. Before examining these two types of movements, and to stay aligned with the designer/architect mindset of the present research, what is the general approach required to design a VR experience in regards to agency? Three levels of agency are possible: (a) no agency, leads to a directed path and a passive experience, more like being part of a film or a guided tour; (b) local agency, the user can move around and interact with objects in the local scene [24]; (c) global agency, the user creates a unique journey throughout the whole experience, like in an open world.

Object Manipulation and Natural User Interaction

As suggested earlier, the integration of two controllers, one for each hand, with the HMD and the motion tracking system, increases the level of freedom of movement: 6 DOF for the HMD (head/body) and 6 DOF for each controller (hands). These controllers increase the feeling of immersion by increasing one's sense of agency. One is now able to manipulate objects using one's own hands. This type of interaction is trending towards a more NUI, compared with a keyboard. Even though it still requires a device as a human-computer interface, it increases the ability to use gestures to interact with

[24] In video game design production, it is called a level

the virtual content in three dimensions (see Section 2.4.4). Hand tracking provides the ultimate way for NUI. However, this comes with a whole new set of challenges [25].

Co-location means that when users are performing any object manipulation with their hands, they can see the action happening at the exact physical position of their hands, represented by either a virtual model of the controllers, or the hand, or both. The game "Beat Saber" is an excellent example of such a mechanism at play. "Beat Saber" is a rhythm action game in VR and was one of the first big hit VR games. The simple use of the controllers that simulate the lightsaber style of swords is very successful. Lightsaber affordances are as straightforward as for a hammer.

It gets more complicated when trying to increase the level of complexity of the affordance. How can a user stack objects without haptic feedback? All these types of actions are technically challenging in VR and represent a vast area for potential research. For instance, Wilson et al. (2018) are looking at amplifying movement in VR. Fox and Schubert (2018) explore ways to arrange and assemble virtual objects. Indeed, objects' weightlessness and the lack of haptic feedback makes this kind of task highly hazardous.

Self-Directed Movement and VR Locomotion

Locomotion in VR has one main challenge, the limitations of the physical location. Numerous studies have proposed a wide range of solutions (e.g. Razzaque, 2001; Bruder, Steinicke, and Hinrichs, 2009; Cliburn et al., 2009; Bozgeyikli et al., 2016). First and foremost, it is fundamental to understand the importance of self-directed movement.

> Self-directed movement is correlated with the sensory changes that it brings about allowing successive places and vistas to be connected within a single coherent cognitive map (Gibson, 1979).

In an early review of the potential of VR, Foreman (2010) explains the importance of self-directed movement in maximising the benefit of VR because, "movements in virtual space, and accompanying perceptual changes, are treated by the brain in much the same way as those in equivalent real space."

Changing Scale: One way to solve self-directed movement in VR is to play with different scales. Architects have always made physical models at different scales that gave them the flexibility to observe the project from a different angle, but still have a realistic impression of the light distribution. In the study, "Arch-Explore: A natural user interface for immersive architectural walkthroughs", Bruder, Steinicke, and Hinrichs (2009) implement two types of interaction. The first consists of a zoom in and out. The

[25] In January 2020, Oculus Quest released an update which equipped the headset with hand-tracking functionalities

user looks at the project from above, then enters one room at a 1:1 scale, then returns back from the model to *god view* before entering another room. The second interface implemented is redirected walking when in the room.

Redirected Walking: has been studied extensively since the 1990s, and shows promising results with different ways of redirecting participants so that they remain within the boundaries of the limited physical space available, but making them believe they are walking without limits (Razzaque, 2001). Figure 2.8 shows the principle of a redirected walking scenario. The downside of this technique is it requires a physical space of a minimum floor surface of 30sq m.

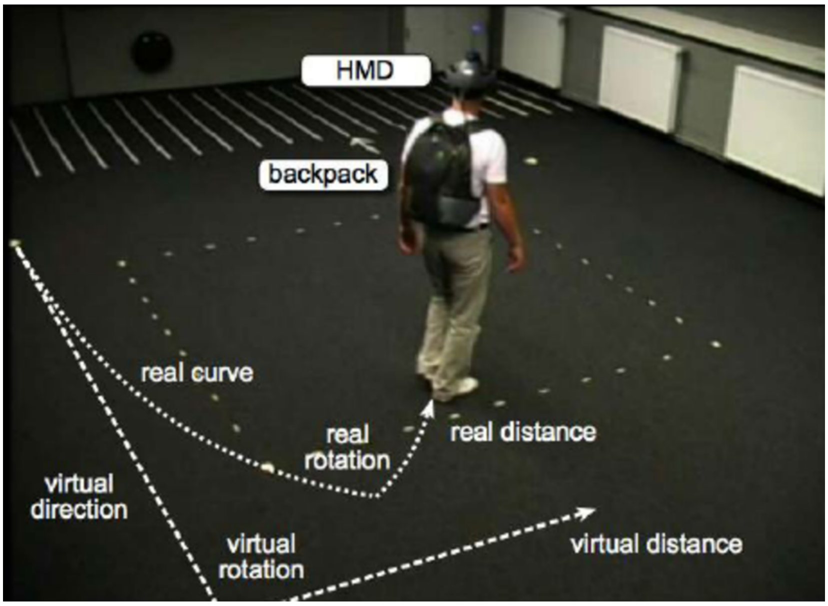


FIGURE 2.8: Redirected walking scenario, images extracted from a study by Bruder, Steinicke, and Hinrichs (2009)

Teleportation: Still another way, and which is most commonly used with the commercially available HMD such as HTC Vive or Oculus Rift, is the point and teleport locomotion technique (Bozgeyikli et al., 2016). One moves from one location to the next by pointing one of the controllers to the ground further away from the current location and pressing a button. This works well when having to navigate large-scale IVEs. Unfortunately, teleportation is known to cause disorientation in many users; it disrupts the feeling of presence and is far from being the best solution to take advantage of one's spatial abilities (Cliburn et al., 2009).

Large Area Tracking System: Yet another solution is using a backpack computer coupled with an infra-red device placed on the HMD that send rays to the ceiling reflected by little stickers [26]. This system can give an accurate location along a theoretically infinite space if provided with enough stickers.

Several systematic reviews on the subject of walking in VR have been undertaken. Steinicke et al. (2013) have published a survey of past and recent developments on human walking in virtual environments up to the arrival of the most recent commercial wave of HMDs. More recently, following a systematic literature review, Boletsis (2017) proposed a typology with four VR locomotion methods: motion-based, roomscale-based, controller-based and teleportation-based locomotion.

In addition to these advances in HMDs, motion tracking engineering, as well as self-directed movement and natural user interaction, another factor that supports the feeling of presence in a virtual world is the realism of its visuals.

2.5.6 Visual Realism

The trend in computer graphics, video games, and architecture visualisation, since the first three-dimensional wired model produced five decades ago, is towards high realism, so much so, that a viewer can not differentiate the computer-generated visual from a photo, coining the term photo-realism. Advances in computer graphics, such as real-time ray tracing, radiosity and light field rendering, bring VR and Augmented Reality (AR) closer to photo-realism [27]. The question of visual realism takes part in a wider field of investigation touching on questions of ethics being discussed elsewhere (cf. Slater et al., 2020).

However, the history of video games shows that realism is not a necessary component for a game to be highly interactive and effective. The original Tetris or more recently, Minecraft, are good examples of successful, immersive games, (see Figure 2.9), but which display unrealistic graphics. Nonetheless, other games like the most recent version of the racing game *Forza Horizon 3*, is a fine example of the level of realism achievable in recent years.

People found VR compelling even with a visually low quality environment. Zimmons and Panter (2003) investigated the physiological reactions of participants along with their accuracy, as they attempted to drop an object onto a target within different virtual environments. Each environment was drawn with varying degrees of texture and lighting quality (ranging from wire frame through radiosity). The quality of the rendering did not seem to have an effect on participants' stress level, measured with heart rate.

In a similar experiment, Mania et al. (2010) compared the effect on memory performance of a room using either flat-shaded rendering or radiosity rendering. Results

[26] When I tried the system in June 2017, the company was called Startracker, although it no longer trades under this name.

[27] Gilson and Glennerster (2012) refer to the phenomenon as a sort of Turing test for VR

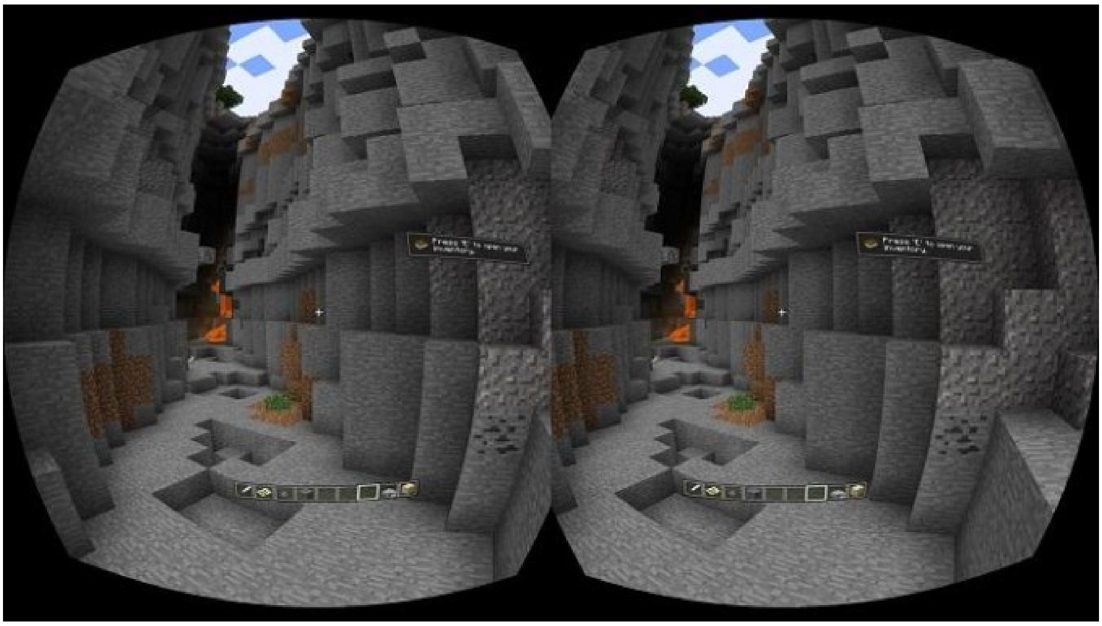


FIGURE 2.9: VR Mod for Minecraft PE on Android, image retrieved from https://apkpure.com/vr-mod-for-minecraft-pe/

revealed a higher proportion of correct object recognition associated with mental imagery when participants were exposed to low-fidelity, flat-shaded training scenes rather than the radiosity rendered ones.

A small-scale study by Slater et al. (2009) exposed people to two virtual environments depicting a precipice, using a HMD. One environment was rendered using ray-tracing including shadows and reflections of their virtual body, while the other was rendered using a ray-casting method (shadows and reflections not included). Results showed that the quality of the environment did not influence the responses of participants. However, a post experiment questionnaire revealed that real-time shadows and reflections that followed participants' movements (only rendered with the ray-traced solution), did enhance anxiety in response to an event within the virtual environment.

Overall, several different factors contribute to the impression of visual realism, mainly geometrical detail, accuracy of light and shadows, fidelity of texture, and mapping of materials. Taken together, these studies support the notion that higher visual realism is not always the best solution. It depends on the task under consideration. The essential differences in rendering quality seem to be more related to dynamic features, such as real-time shadows of moving objects, and moving bodies.

2.6 Summary

If one of the challenges of VR is to simulate reality, as posited by Slater (2014), then, architectural design and visualisation undoubtedly play a significant role in creating realistic virtual environments. However, these do not necessarily need to be realistic in the sense of copying the physical world. VR evolves and develops its own affordances, which dictate a unique new reality with its own style of interactions and architecture.

So many concepts, theories and models have been taken into account to understand the characteristics of immersive virtual environments. VR is a technology that builds upon a wide variety of components and fields of research. With the particular focus on spatial design, a *Virtual Architecture Analysis Grid* is proposed. It gathers the main elements mentioned in the chapter, in a condensed format. The table will be revisited at the end of each chapter to help summarise the findings and to add the new elements towards the development of a functional framework (see Chapter 6) that can be used to answer the main research question (Chapter 7).

Background Theory	**VAga**	**Geometric Space**	**Experienced Space**
	Design	**Architectural Design**	**Immersive User Interaction**
		Architectural Elements	Level of Immersion, Agency and Embodiment
		Architectual Features	Feeling of Presence: plausibility and place illusion, body ownership
		Architectural Style	Fixed Position 3DOF (Desktop, 360VR, Oculus DK1): low level of immersion, agency and embodiment
		Architectural Properties	Room Scale VR - 6DOF (HTC Vive, Oculus Rift): higher level of immersion, sense of agency with hand controllers and embodied Cognition with NUI
	Measures	**Spatial Qualities**	**Objective**
		Layout Complexity	Spatial Abilities
			Wayfinding Task
			Memory Task
			Method of Loci
			Subjective
			Open questions
			Sketches

FIGURE 2.10: Virtual Architecture Analysis Grid - Background Theory

Chapter 3

Virtual Memory Palace - Preliminary Study

> One must employ a large number of places which must be well-lighted, clearly set out in order, at moderate intervals apart, and images which are active, which are sharply defined, unusual, and which have the power of speedily encountering and penetrating the mind.(Cicero)
>
> *F. Yates*, The Art of Memory, 1996

3.1 Overview

Based on the Method of Loci, the following experiment compares the effect of two different virtual environments on participants' memory performance. The primary task consists of remembering a sequence of random playing cards. Each virtual environment is based on a different architectural style with a different layout. One is inspired by Palladian-style architecture, and the other by an organic plan with curved walls.

As previously discussed, human spatial memory is one of the key factors for our survival. Humans have developed their spatial cognition to a high level of complexity, and to the point where they started to modify their environment and built architectural structures to host their activities. At the same time, they also developed different techniques to enhance their internal memory. The "Art of Memory", written by Yates (1966), tells us the long history of the development of such techniques used to structure and extend the human mind.

Nowadays, people use their memory differently. With the exponential growth of technologies, discs, hard drives, memory cards, social networks and smartphones, people externalise more of their memories into the digital realm everyday. Many philosophers, psychologists and technologists are pondering the effects of such a cultural shift (e.g. Sundet, Barlaug, and Torjussen, 2004, and Lynn and Harvey, 2008). Technology is not the only reason, however, and it is not going away. Another way to approach this cultural shift is to better understand the tools at our disposal that actually can suit humans' natural spatial abilities better to manage the new age of digital information.

In the context of contemporary technological and visual culture, spatial cognition and visuospatial memory merit a much deeper understanding. Studies in psychology have already demonstrated that human long-term memory capacity is essentially infinite (Eysenck, 2001). It would make sense to use such an internal capacity more actively instead of storing our visuospatial memories in external devices in the form of images. That being said, the number of people playing video games, and now using virtual worlds is increasing significantly. A majority of people are familiar with computer-generated three-dimensional worlds. An increasing number of people are predicted to use augmented and virtual reality devices to interact with their digital landscape. Although the majority of the virtual environments today are created for entertainment, the potential for education and training is endless.

The Art of Memory, with a particular interest in the Method of Loci, has shaped the origins of this research project. By practising the Method of Loci, one can quickly visualise in the mind's eye the latest public building they have visited, and organise a journey along which it is possible to attach information to be remembered. From an architect's standpoint however, many questions started to arise. How would a building with its specific spatial design support the memorisation of a set of given information? How could the benefit of using one internal space over another be evaluated? Are there particular architectural elements necessary to facilitate such a process? It seems that VR presents an opportunity to set up an experiment that would lead to potential avenues for finding answers to these questions.

So with regards to the above, the first research question was formulated.

RQ1: What architectural properties can enhance humans' memory performance when using the Method of Loci in VR? To help answer this question, the goals are to:

- **G1:** Identify the rules of the Method of Loci and implement them in VR.
- **G2:** Identify the scientific theories behind the Method of Loci and apply them in VR
- **G3:** Test that the Method of Loci in VR can improve memory performance.
- **G4:** Evaluate the effect of different types of virtual architecture on memory performance.

3.1.1 A Brief History of The Method of Loci

The Art of Memory (AoM) is a collection of mnemonic techniques, one of which is the called the *memory palace*. It was the main method utilised for remembering information from the classical period of Simonides of Ceos in Ancient Greece to the renaissance era of hermeticism with Giordano Bruno. These techniques were almost universally practised by the thinkers of the ancient world, who believed that mnemonic training was essential to the cultivation of creativity. Creativity was an act of synthesis that could only occur within the mind of a trained mnemonist. Appropriately, in Greek mythology, Mnemosyne, the goddess of memory, was the mother of the Muses. It was common for orators to memorise their speeches, or any other items, by imagining a journey (perhaps from their doorstep to the fora) with a sequence of places (loci) and mentally tracing their steps to recall each article or paragraph associated in each location. These techniques can be synthesised with the three pillars of memory: Imagination, Association and Location (Buzan, 2006). Imagination and Association give memory. Location gives the flow.

Memory techniques were then adopted by early Christian monks. They became the principal method by which monks would meditate upon the bible after committing it to memory. Safe within the curriculum and cloistered walls of Christian monasteries, the art of memory made it through to the later Middle Ages. By the Renaissance, mnemonic training was taught to almost all students, alongside grammar, rhetoric and logic. Even the invention of the Gutenberg printing press and the relative availability of books had little effect on the status of a trained memory; books were considered aids to recall rather than a replacement for a well-stocked mind. The Renaissance did however give rise to a technological trend that would eventually contribute to the decline of the AoM. As far back as 1550, Italian thinker Giulio Camillo published a book outlining plans for construction of what he called a memory theatre. Only a few years after Camillo published his plans, the AoM became the target of religious persecution that signalled its decline and eventual removal from education systems. In 1584 in England, the Puritans launched a fervent campaign against the AoM because of its frequent use of sexual, violent and absurd thoughts. Memory in education eventually turned a full 180 degrees. Mnemonic practice, which depended on the creative and mindful painting of mental pictures, was replaced with rote learning and repetition. Memorisation went from being an intrinsically rewarding activity to being a task that elicited boredom at best, and reluctance at worst.

An anonymous teacher wrote the following description in the "Ad Herennium", one of the famous text relating the technique.

> The five rules for choosing places are now quoted, namely (1) in quite spots to avoid disturbance of the concentration is needed for memorizing; (2) not too much alike, for example not too many identical intercolumniations; (3) neither too large nor too small; (4) neither too brightly lighted nor too

> obscure; (5) with intervals between them of moderate extend, about thirty feet (Yates, 1966, p. 75).

3.1.2 Spatial Memory Theories

Information processing, memory capacity, spatial abilities, and navigation have all been studied at length by cognitive psychologists (see Chapter 2.4). This section looks more specifically at the essential mechanisms at play when humans are using the MoL, which triggers memory in relation to locations.

Dual Coding Theory

An influential memory principle was proposed by Paivio (1971). The "Dual Coding Theory" explained how the human mind operates with two functionally independent (although interacting) systems or stores, *verbal memory* and *image memory*. The chances that a memory will be retained and retrieved are much greater if it is stored in two distinct functional locations rather than in just one. Paivio updated the theory in 2014 with "evidence-based suggestions about nourishing mental growth through applications of Dual Coding Theory in education, psychotherapy, and health" (Paivio, 2014).

Context-Dependent Theory

In a review of visual memory capacity, Brady, Konkle, and Alvarez (2011) proposed a model based on a hierarchy of visual knowledge from object-generic parts to objects-specific parts to the whole object, linking stored knowledge and context-dependent stimuli. This approach explains how visual memory works as an entire associative process connecting new stimuli to stored knowledge and also how visual memory is context/scene dependent. The *context dependent theory* originates with the experiment carried out by Baddeley and Hitch (1974), in which they compared participants' performance to recall a list of words within two different natural environments. Results showed that lists of words learnt in a specific place were best recalled when participants were situated in the environment of the original learning.

In their study, Brady, Konkle, and Alvarez (2011) also suggest that architecture can be used to anchor that information in a structure linked to previously stored spatial knowledge. As one moves around from birth, one accumulates vast data about one's surroundings (see Section 2.2.2). Most of this information is processed and abstracted into cognitive maps, which can be accessed at any time to find one's way or to find an object left behind.

In light of these explanations on how human memory works, and with the awareness of the method of Loci described earlier, it is one of the assumptions of this research that spatial arrangement can be used to extend the human mind by offering scaffolding to support memory formation and recall. Indeed, as highlighted in the Art of Memory, the three pillars of memory are imagination, association and location. Imagination and association create new memories. Location helps with the sequencing and anchoring.

3.1.3 Related Work

For many years, mnemonics such as the MoL was surprisingly neglected by the scientific community. Apart from the historical facts outlined above, demonstrating the efficacy of the MoL mnemonic was challenging, given that participants rely on their mental imagery to implement the memory palace. One of the main difficulties explained by Kosslyn et al. (1984), is the individual difference in mental imagery ability. Other differences are the size and uniqueness of each environment, the amount of time spent in the environment, and the emotional associations one has with the space; many variables that are difficult to quantify.

Also, people's use of effective mnemonic strategies is generally low (McCabe et al., 2013). Despite the endorsement of mnemonic techniques by universities, undergraduates who are exposed to mnemonic strategies as part of their academic curriculum often do not implement them in their daily practice (Susser and McCabe, 2013). One of the main contributing factors to this apparent mental barrier is the need for long training periods before the technique becomes effective (Foer, 2011).

As such, an investigation can benefit from an experimental approach that provides participants with standardised environments such as familiar nearby locations or virtual environments, which participants can be exposed to in a more controlled manner (McCabe, 2015). In a pivotal study by Legge et al. (2012), the research subjects received instructions to use either a virtual environment for the MoL (on a desktop monitor), or a traditional MoL (using their imagination), to remember 10 lists of unrelated words. Firstly, it is noteworthy that the subjects using the traditional MoL had trouble completing the task, which relates to the mental barrier mention above; secondly, the virtual environment was as effective in supporting memory as the traditional MoL. This was a first step in demonstrating the potential of using VR as a new methodology to study the MoL.

3.2 Experimental Design

The broader idea behind this experiment was to build a VR training system that could be used to enhance one's memory. Immersed in a multi-sensory virtual environment, one would be able to construct an infinity of places to organise information in the user's own memory palace. The application was called Archimemory. The main objective was to explore ways to design environments that could enhance memory performances. This experiment was also designed to understand what kind of data could be collected from the participants in an immersive virtual environment. A mixed method approach was used to gather both quantitative and qualitative data. The rest of this section describes the experimental design.

3.2.1 Applied Theories

Based on working memory average digit span for a normal adult of seven plus or minus two as demonstrated in Miller (1957)'s experiment, participants were asked to remember nine random cards in an attempt to avoid reliance on short-term memory. The main idea was to activate long-term memory through the association between space, images (existing memories) and playing cards.

At the core of the game mechanics developed for ArchiMemory was the Dual Coding Theory from Paivio (2014). The formation of associative memories between a card and an image would support the participant in storing the specific card in memory. The method was to use any associative trigger – like shapes, numbers, colours, metaphorical or allegorical – which the participant would think of between an image and the playing card. The participant then had to attach the chosen card to the image.

Another critical component of this experiment related to the seminal work of Baddeley and Hitch (1974) on *context cueing*. Each image was framed on the walls at specific locations in the building. Each participant was able to navigate their own route, following a path along the rooms and the frames, and therefore creating their own story to support the memorisation of the sequence of playing cards.

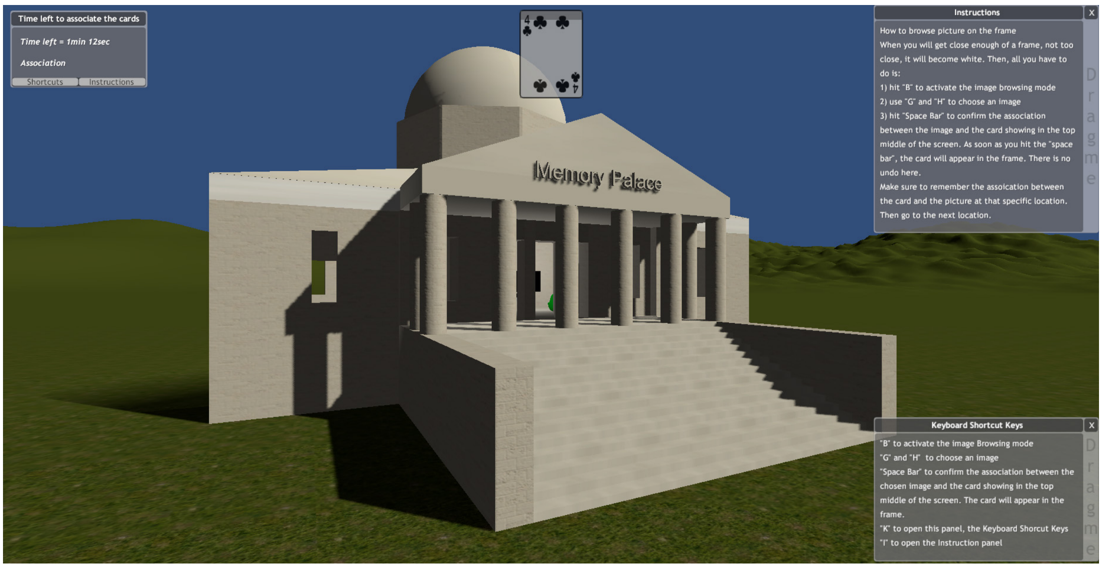


FIGURE 3.1: **ArchiMemory - The Palladian Palace view from outside.** The next playing card is shown at the top middle of the screen. Pop up text boxes, part of the Graphic User Interface are shown in each corner

3.2.2 Memory Card Game - Control Group

The first task consisted of a basic memory task game displayed on a desktop monitor, which functioned as a control task to evaluate participants' raw memory capacity before using the mnemonic device.

3.2.3 Virtual Memory Palaces - Two Conditions

To compare the effect of different styles of architecture on memory performance, two different environments were designed [1]. Participants would start their exploration from outside the main entrance with a view like in Figure 3.1.

Palladian Palace: The layout was generated using the Palladian Graphs by Thomas Grasl and Economou (2011). It is a typical Palladian plan with multiple interconnected rooms (see Figure 3.2). Participants had the opportunity to choose their path through the building using a variety of doors. There was no specific direction to follow. Specific features and pieces of furniture (red or green sofa, blue carpet, brick walls, table, chairs and plants) were placed in each room.

The Curved Palace: This model was an exploration of a design with opposite features to the Palladian house (see Figure 3.3). It was based on the idea of a cave, in which participants could choose between two spaces that take them deeper inside the building, ending up in a room with similar furniture to the Palladian option, either green or red. From the main entrance, there were only two directions to choose from. The space on the right-hand side contained the green pieces of furniture; the space on the left-hand side contained the red pieces of furniture.

3.3 Materials and Method

3.3.1 Participants

A total of 18 participants (6 female, 12 male; average age 22.45 years, *SD*=4.23) were recruited from the student and staff population at Goldsmiths University of London. The first set of experiments were conducted during the *Creative Machine Exhibition* on 6th November 2014 (see exhibition abstract in Appendix C). 7 participants were able to take part in the experiment during the exhibition. However, it was constrained by time. Participants did not have the time to answer the qualitative questions. In the following month, 11 more participants took part in the experiment in the laboratory, and qualitative interviews were conducted.

[1]More environments were tested as can be seen in appendix A

FIGURE 3.2: **ArchiMemory - The Palladian Palace.** The next playing card appears at the top middle of the screen. On the left corner is the count of cards already associated.

FIGURE 3.3: **ArchiMemory - The Curved Palace.** The next playing card appears at the top middle of the screen. On the left corner is the count of cards already associated

3.3.2 Materials and Implementation

Memory Card Game and Recall Board

The Memory Card Game was developed with HTML, Javascript, and MySQL. Participants were presented with a computer running Windows on a 20" display, a mouse and a keyboard. They used the mouse to interact with the web page on which the memory card game was displayed. It consisted of a deck of cards on which participants could only click to see the next random playing card. After the 9th card, the *Recall Board* showed a first row with the 9 cards in order and a second row with 9 empty slots (as shown in Figure 3.4). Participants had to place each card in the corresponding slot in the correct sequence. The sequence of cards was then sent to the MySQL database to compare with the given sequence. Participants would receive the results directly at the bottom of the screen [2].

Most of the Javascript that coded the memory card game and recall board is presented in Appendix A. The script for the card 'shuffler' was borrowed from Jonas Raoni Soares Sila [3]. The nine playing cards were picked from a digital shuffled deck of 52 playing cards. Some of them are shown in Figure 3.4). the same images were used inside the virtual environments.

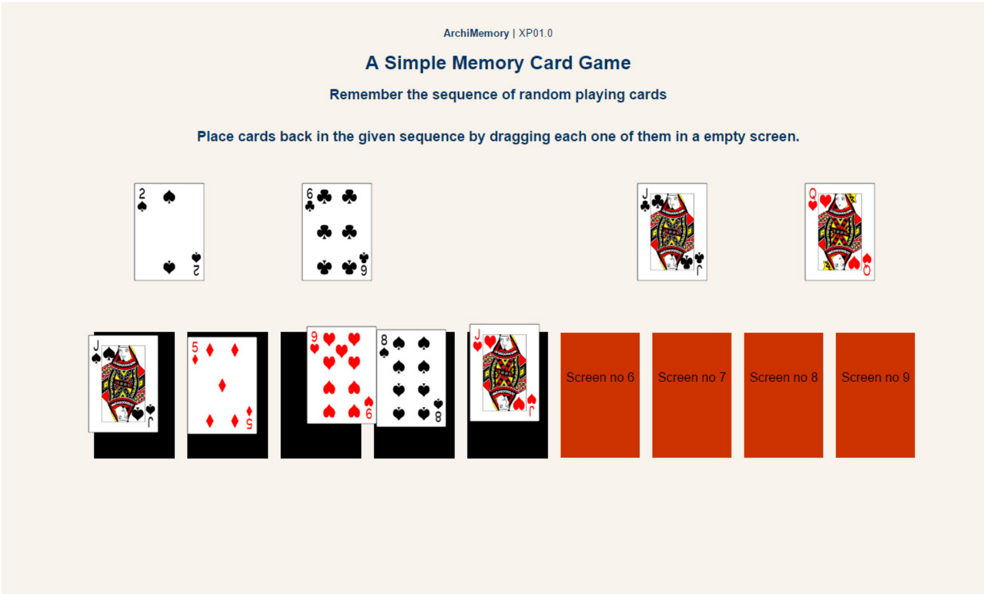


FIGURE 3.4: **Archimemory - Memory Card Game.** The control experiment was a simple memory card game played on a desktop monitor. The same interface was also used as a Recall Board for the player to retrieve the sequence of cards post virtual memory palace experience. The Recall Board shows two rows, the first row with the 9 given cards in order, and the second row with 9 empty slots. In this instance, 5 cards have already been assigned to a slot.

Virtual Memory Palaces

Participants were equipped with the Oculus Rift DK2, which had a resolution of 640 x 800 pixels per eye, a refresh rate of 60 Hz and persistence of 3 ms. The position tracking volume covered only a square metre to cover the head movements. An XBox controller was used to move around in the virtual environment, which was run on an Intel computer with a dual-core processor, 4 GB of main memory and a Nvidia GeForce 8800GTX graphics card. The frame rate was stable between 45 and 60 frames per second. The real-time rendering was processed on the computer, which was directly connected via cables to the HMD.

[2]This task called ArchiMemory XP 1.0 is still accessible online. Created in July 2012, you can play it here `http://archimemory.net/wp/xp/xp010/xp01.htm`

[3]Jonas' website was accessed in November 2012 at `http://jsfromhell.com/array/shuffle`

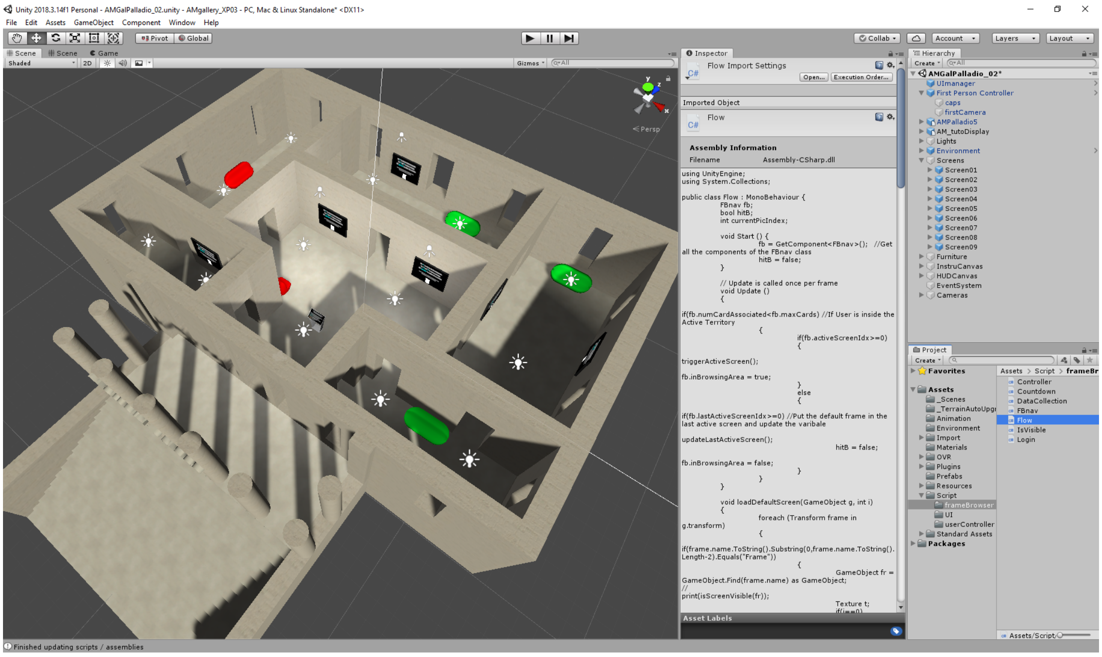


FIGURE 3.5: **Palladian Memory Palace in Unity.** This image is a screen capture taken from Unity to show the different elements involved in the programming of the Palladian Memory Palace. The screens where the users can create the associations between playing cards and images are visible on the walls.

The virtual memory palaces were designed using the following workflow. The first step was to sketch by hand a potential plan for the building. As this was a preliminary experiment, the idea was to use a different style of architecture. Another motivation was to be able to find a way to generate these plans using an algorithm. This method would enable the auto-generation of an architectural layout adapted to user's needs and characteristics. From the 2D drawing, a 3D model was created using 3ds Max. The model was then textured and imported into Unity 3D. All of the behaviours and interactions were designed with Unity 3D and CSharp (see Figure 3.5). The final result was then exported as a Unity Web Player file inserted into a PHP/Html webpage.

Another important element of the memory palace was the series of images selected to make the associations on the frames. Figure 3.6 shows how these images were organised into five categories: animal, action, landscape, people and theme. Participants were able to browse through the categories in that order to select the one they felt was a good match by which to remember the given playing card.

Heads-up Display: The Heads-up Display (HUD) is frequently used in video games to simultaneously display several pieces of information (e.g. character health, items, and indication for game progression). In Archimemory, it consisted of an opaque top panel showing the current *Playing Card* and a small left panel showing how many

FIGURE 3.6: Pictures used for the association organised by category

cards were already associated and the time remaining to complete the task. Figure 3.2 and 3.3 show the general presentation of the HUD.

Navigation Mode: Inside the Virtual Environment, the main feature was the frames hanging on the walls. These frames were black until the participant was in range. Then an image, reminding the user of the different buttons to manipulate, was shown before turning into one of the pictures chosen by the user. Two modes of interaction were possible, either the Navigation Mode, used to navigate around the environment; or the Frame-Browsing Mode (FBM), used to browse through the pictures and choose one to associate with the card. The standard Oculus plugins were adapted to manage movements of a first-person interaction. Participants' movements were assigned to the Xbox controller. Their head movements were assigned to the HMD.

Frame-Browsing Mode: The FBM activation was dependent on the participant field of view. The combination of three variables was necessary to activate this mode: angular (θ), horizontal distance (δ), and vertical distance (γ) (see Figure 3.7). These variables were obtained using the following lines of code with the value of (γ) set as $1.3m < \gamma < 3.0m$.

```
isScreenVisible (GameObject)
val = false;
cameraRelative = Camera.main.transform.InverseTransformPoint
screenPos = Camera.main.WorldToScreenPoint
```

```
if (screenPos.x > 0 && screenPos.x < Screen.width &&
screenPos.y > 0 && screenPos.y < Screen.height &&
cameraRelative.z>0)
# Checking the delta value
val = true;
return val;
```

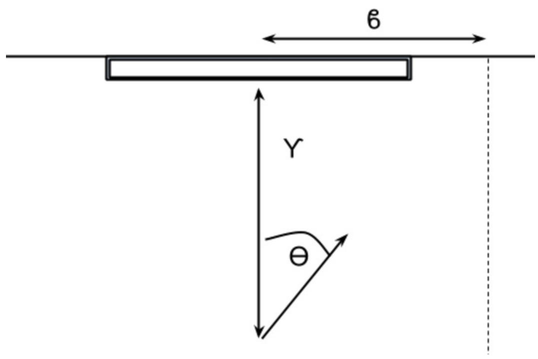


FIGURE 3.7: **Frame-Browsing Mode.** The participant had to be within a certain range of each of the three variables to activate the browsing mode.

The sequence of commands to use the Xbox controller, once in FBM, was set using the following pseudo-code:

```
Assign Key ‘‘A’’ -- to activate the image on the frame
Assign Key ‘‘B’’ -- as Browsing the image
Assign Key ‘‘X’’ -- to get the last image
Assign Key ‘‘BR’’ (right-trigger button) -- to confirm
the association of image with the card
```

3.3.3 Procedure

All the participants started with the control experiment, using the desktop version of the memory card game. They were then split between the two virtual memory palaces to complete the main task, which was to navigate the virtual environment and associate each playing card with one image inside each one of the located frames hanging on the walls. As soon as they got close enough to one frame, the FBM was activated, a reminder of the controls was displayed on the frame, and from there, they were able to browse through the set of images. Once all the playing cards were associated, they could take a couple of minutes to consolidate the association by navigating the palace. Then they would remove the HMD, access the Recall Board and recall the sequence of playing cards.

1. Control Experiment (2 min): Participants had 2 minutes to remember the sequence of random playing cards showing on the frames with no visualisation help.
2. Recall Board (1min): Participants had 1 minute to recall the sequence by placing the cards in the empty slots of the *Recall Board*.
3. IVE - Warm up (2min): Participants had the opportunity to familiarise themselves with the setup, and discover the IVE with its specific archetype.
4. Encoding (10min): Participants had 10 minutes to remember a random sequence of 9 playing cards given one-by-one at the top of the screen (HUD). They had to associate the current card with an image on a frame at a given location. Once they reached one of these frames, the FBM was activated. Then they had to choose a picture to associate with the current card, and remember the association. Next, a new playing card would appear at the top of the screen. Participants then had then to walk to the next frame, and repeat the same actions.
5. Consolidation (2min): When done associating all the cards, participants took a couple of minutes to revisit the space and consolidate their memories. The HMD was then removed.
6. Retrieving - Short Term Memory (1 min): Participants were then presented with the *Recall Board* (same as Control Experiment), which would show the ten playing cards in order. By walking through the visited space in their mind's eye, they would be able to move each one of the playing cards visible on the screen into the correct empty slot, following the original sequence. The experiment ended with their score displayed at the bottom of the screen.
7. Sketching and Questionnaire (5 min): A five-minute dialogue was usually sufficient to complete the three questions once the participants had completed a sketch of the experienced layouts.
   (a) "What characteristics of the space do you remember?"
   (b) "Draw a map and locate as many features and characteristics (frames, furniture, materials, colour) as possible on the map?"
   (c) "Pick three associations and explain why you associated that card with that image at that location."

3.4 Results

The two hypotheses were (a) that virtual memory palaces support a better memory performance than the desktop solution when attempting to remember a sequence of random playing cards ; (b) different types of architecture have a different impact on memory performance. Quantitative data and analysis are presented first, followed by the qualitative approach.

The data collection was implemented utilising PHP and Javascript functionalities to extract the different types of data from the web application and the Unity Web Player. All of these data were then sent to a MySQL database. Three types of data were collected for each participant: the sequence of cards given and recalled, their positional data, and the images associations. During the control experiment, the sequence of random cards was recorded in a separate table on the database, to be compared later with the sequence recalled by each participant.

Among the 18 participants, one showed unusual behaviour as he/she did not recall any cards after being exposed to the virtual memory palace for the full allotted time of 9 minutes [4]. For that reason, the data was removed. The rest of the analysis is based on the performance data of the remaining 17 participants (8 in the Curved Palace, and 9 in the Palladian Palace).

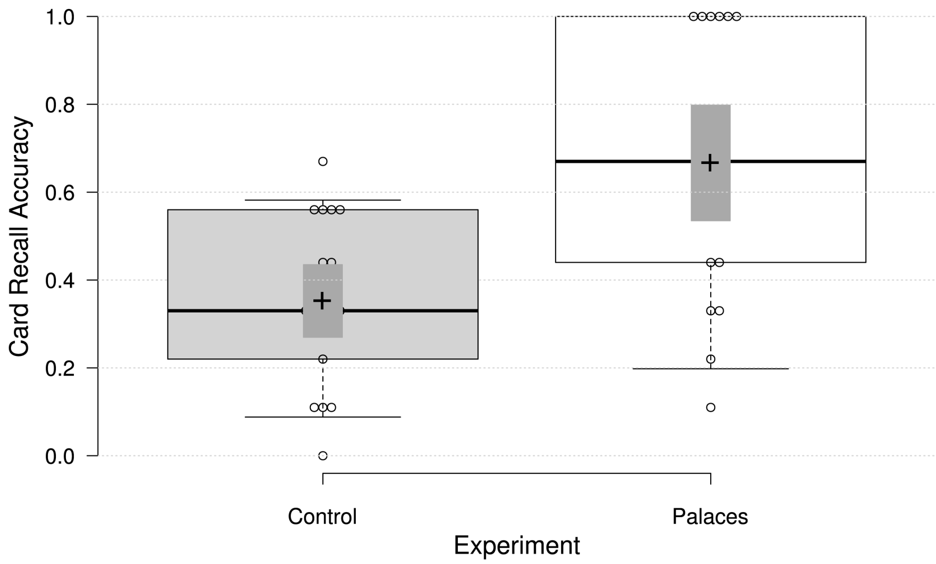


FIGURE 3.8: **Archimemory: Recall Accuracy - Control.** The overall recall performance of participants using a virtual memory palace is about 10% higher compared with the control experiment. Crosses represent sample means recall accuracy percentage: 0.35 for the control experiment and 0.67 for the virtual memory palaces. Centre lines show the medians; box limits indicate the 25th and 75th percentiles as determined by R software; whiskers extend to 5th and 95th percentiles; bars indicate 90% confidence intervals of the means; data points are plotted as open circles. n = 17 sample points.

[4] I reviewed my notes and found out that the participant did not try to remember the cards when using the recall board

3.4.1 Recall Accuracy

The first goal of the study was to examine the recall accuracy differences between a control experiment using a desktop monitor and the virtual memory palaces. Recall accuracy (A) is the ratio of the number of recalled cards to the total number of cards (9).

$$A = RecalledCards/TotalCards$$

Figure 3.8 presents a comparison of the overall performance of the users for the control experiment and the overall use of the memory palaces. A one-way ANOVA was calculated on participants' recall accuracy, which showed a significant difference between the control experiment and the virtual memory palace ($F(1; 32) = 12.47$, p<0,05)

This shows that participants using the virtual memory palaces were better able to recall the sequence of cards than those using a traditional desktop. The percentage of recall accuracy (the number of cards recalled in the correct sequence) during the Control experiment was 35% (M = 0.35, SD = 0.20) compared with 67% (M = 0.67, SD = 0.31) for the virtual memory palaces. This represents an increase of 32% in recall accuracy.

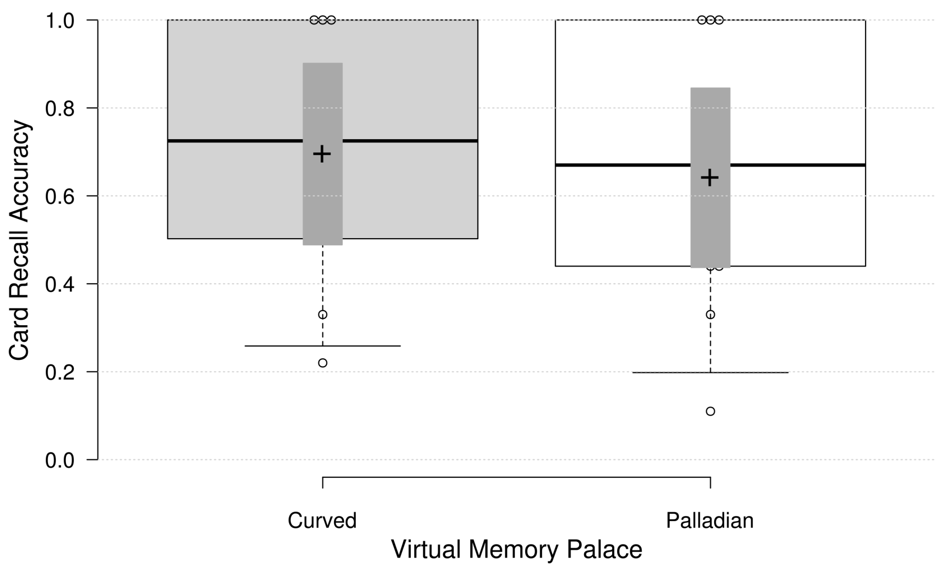


FIGURE 3.9: **ArchiMemory: Recall Accuracy Between Palaces.** The overall recall accuracy of participants using the the Curved Palace with a mean of 0.70 and Palladian Palace with a mean of 0.64 is represented by the crosses. Horizontal lines show the medians; box limits indicate the 25th and 75th percentiles as determined by R software; whiskers extend to 5th and 95th percentiles; bars indicate 90% confidence intervals of the means; data points are plotted as open circles. n = 17.

The second hypothesis is that different types of architecture have a different impact on memory performance. Figure 3.9 presents a comparison of the overall recall accuracy of the users between two different virtual memory palaces. A one-way ANOVA was

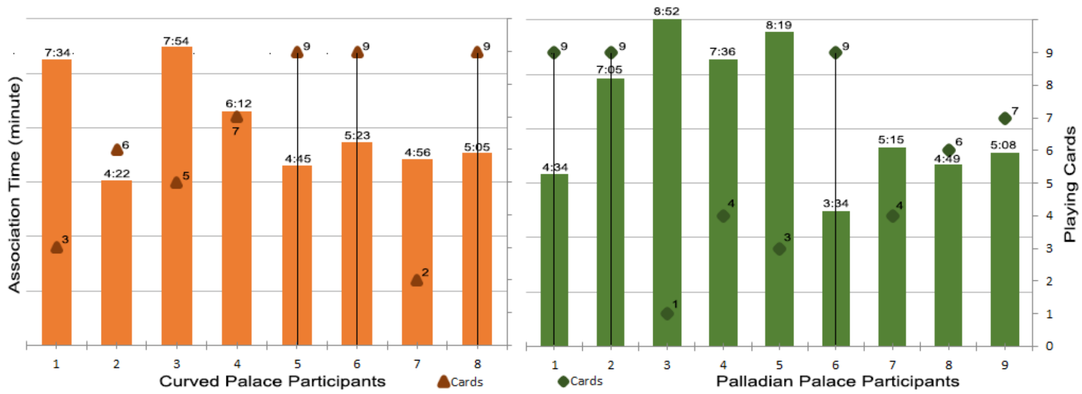


FIGURE 3.10: **Participants Comparison.** The comparison of the 17 participants between the two virtual memory palaces, 8 in the Curved Palace (left) and 9 in the Palladian Palace (right). Dots represent the number of cards remembered, bars represent the amount of time taken (in minutes).

calculated on participants' recall accuracy showing no significant difference between the two virtual memory palaces ($F(1; 15) = 0.12$, p=.73).

3.4.2 Palace Performance

Figure 3.10 presents every participant's data points, time taken and number of recalled cards.

The time taken for participants to memorise the playing cards was necessary to compare their performances. Each user was allotted ten minutes to complete all the associations. The Figure 3.11 shows the distribution of the average time taken inside the two virtual memory palaces. A timer was implemented (visible on the left top corner of the HUD) to give participants some sense of pressure to perform. Even so, variations in the participant behaviours were noted. 10 participants (5 in each condition) were very confident and finished in less than 5 minutes, while the remaining participants preferred to take more time and walk around for as long as the full 9 minutes (the maximum time).

A one-way ANOVA showed that difference in the association times between the two palaces was not statistically significant ($F(1; 15) = 0.20$, p=.66). Figure 3.11 shows the distribution of the mean time spent in each virtual memory palace to make the nine associations. A noticeable difference is a longer duration of time spent by participants inside the Palladian Palace (M=6.1; SD=1.95) compared with that spent in the Curved palace (M= 5.8; SD=1.32).

Different industries (e.g. user experience, product design, software, supply chain) recognise that cycle time (the duration of a process) is a valuable performance metric to measure process efficiency. In the context of using the MoL as a mnemonic device to enhance memory, the main process comprises forming the associations of the card

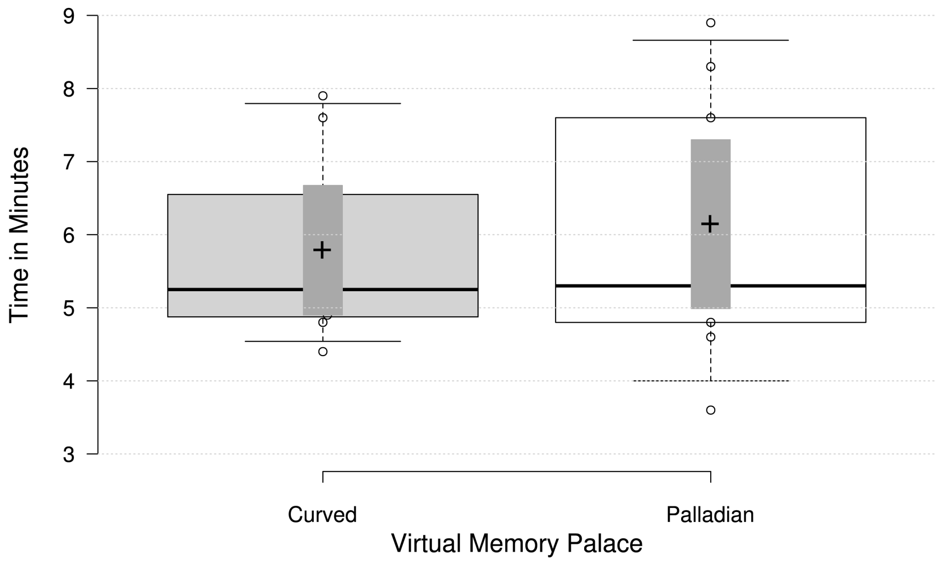


FIGURE 3.11: **Mean Time Comparison between Memory Palaces.** The average amount of time (in min) participants took in each memory palace. Crosses represent sample means of time in minutes: Curved Palace (M=6.1; SD=1.95) and Palladian Palace (M=6.1; SD=1.95). Horizontal lines show the medians; box limits indicate the 25th and 75th percentiles as determined by R software; whiskers extend to 5th and 95th percentiles; bars indicate 90% confidence intervals of the means; data points are plotted as open circles. n = 17.

to be remembered with the trigger image in the situated frame. A good learning method should lead to a more efficient way to remember any given unit of information, so that consequently the system should afford a shorter cycle time. Card cycle time (κ) is defined by the amount of time (in minutes) to successfully record one unit of information (one recalled card).

$$\kappa = time/card$$

A one-way ANOVA showed that the difference in the mean of cycle time between the two palaces was not statistically significant ($F(1; 15) = 0.61$, p=.45). Figure 3.12 shows the distribution of the mean cycle time for each virtual memory palace. It is worth noting that in both conditions, 3 participants recalled the 9 playing cards correctly, taking an average of five minutes to memorise them all (κ = 0.5min/card).

To summarise, difference in recall accuracy between the control experiment and the virtual memory palace (both together) was statistically significant. However, there were no significant differences in recall accuracy between the two virtual memory palaces. From a task performance standpoint, there was no statistical significance in the mean time taken to complete the association process in both palaces. Card Cycle time was proposed as a way to evaluate which of the two palaces was more efficient. That said, no statistical significance was demonstrated between the mean of card cycle

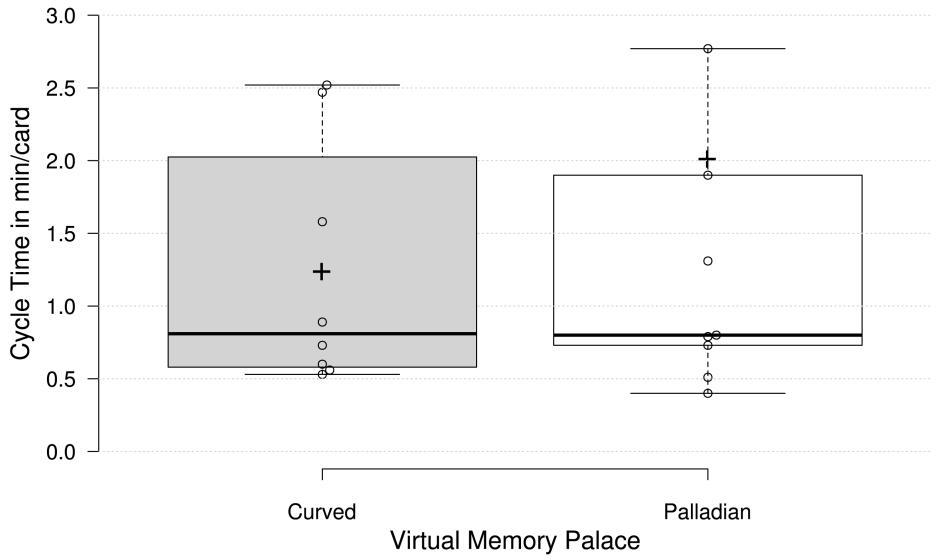


FIGURE 3.12: **Cycle Time Comparison Between Memory Palaces.** The overall cycle time of participants in both virtual memory palaces was approximately equal. Crosses represent sample means cycle time per card: 1.24 in the Curved Palace, and 2.01 in the Palladian Palace. Horizontal lines show the medians almost identical in both case (0.81 in the Curved Palace and 0.8 in the Palladian Palace); box limits indicate the 25th and 75th percentiles as determined by R software; whiskers extend to 5th and 95th percentiles. n = 17.

times.

3.4.3 Heatmap Visualisation

A script collected participants' position and movement inside the virtual environments, that is, the time taken by each participant to either explore their surroundings, browse the pictures, and make the associations with the playing cards. One way to visualise these positional data is by representing them on a heatmap. Figures 3.13 and 3.14 show a sample visualisation of two participants in each condition. Overlapping one participant's heatmap on the layout of the building shows the path taken; the darker the dots, the longer the participant spent at that location. The comparison of these heatmaps brings some insight into the impact of each plan on participant's behaviour. For instance, there are fewer darker dots in the curved heatmap than in the two Palladian layouts. The Curved path seems to be more fluid, with sharper dark circles than its counterpart, where the dark circles tend to spread over a larger surface.

The superimposition of all the heatmaps formed by every participant from one condition can also help to understand the common traits, the mean path, or the most visited locations (see Figure 3.15).

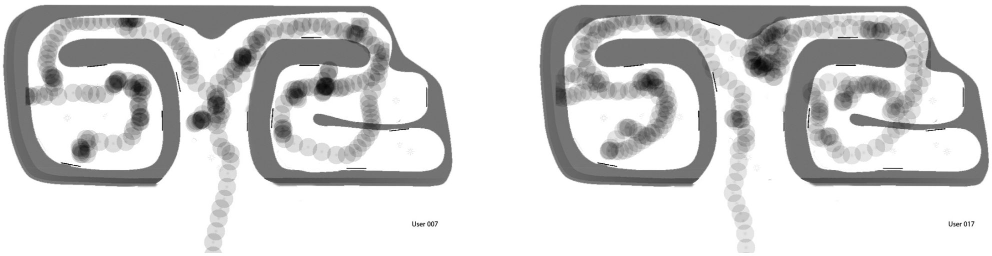


FIGURE 3.13: Two participants' heatmaps in the Curved Palace.

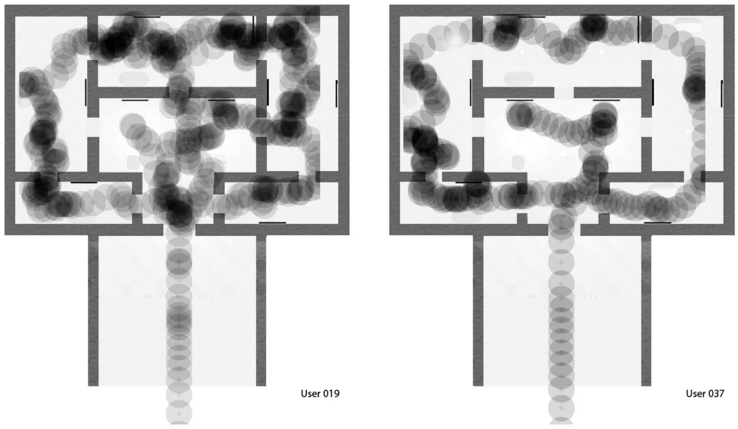


FIGURE 3.14: **Two participants' heatmaps in Palladian Palace.** The dots represent the path taken by each participants; the darker the dot, the longer the participant was stationary, usually in front of a frame.

3.4.4 Qualitative Approach: Questions and Sketches

The most unexpected results were revealed by participants' comments and drawings. Of the three questions, the sketched layouts shed the most light on how well participants remembered their surroundings, even though they had not been asked to do so. Before exploring these drawings, the answers to the two other questions are briefly presented. All participants' answers can be found in the table located in appendix A.1.

The first question was about specific features participants did remember. The different features were: red or green sofa, blue carpet, brick walls, table, chairs and plants. The idea was to understand if one feature exhibited more memory potential than another. Extracting any meaningful patterns from participants' responses was difficult. No particular feature was more cited than any other. These sketches are shown in Appendix A.1.

For the third question, participants were being asked to explain three associations they formed to help them remember the cards. Due to the content of the pictures used to make these associations, a whole new set of questions was raised and behaviour highlighted, which would have required a different set of investigatory skills related more to sociology or anthropology. Despite the potential interest, this was out of the scope of the present research project.

On the architectural comments, however, a consensus of the participants showed

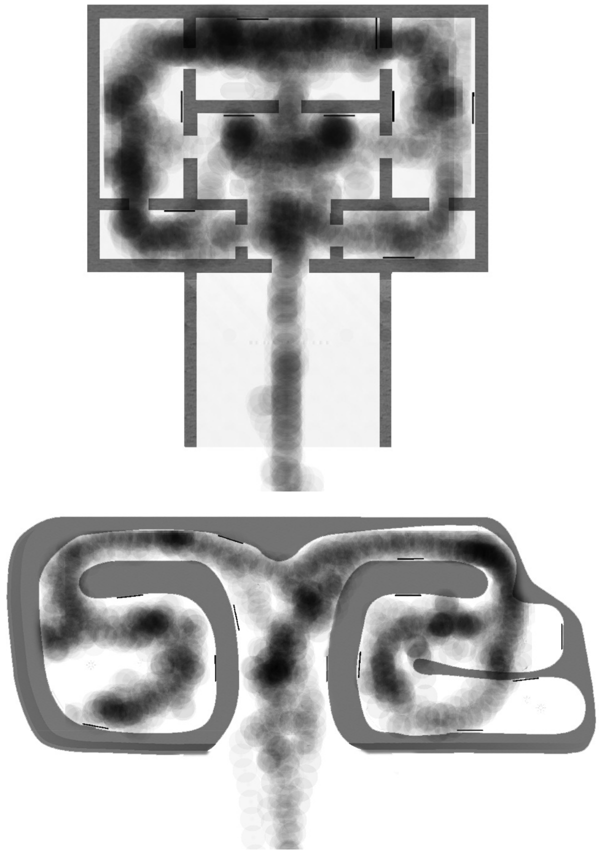


FIGURE 3.15: **Average Heatmap for All Participants.** Palladian (top) and Curved (bottom) layouts showing the average heatmap for all participants

a preference for the Palladian palace. They reported navigating their way with ease, sensing more connections between the rooms, and therefore, creating their own journey. Arguably this is because in our western culture, people have grown up in houses and buildings with mainly orthogonal layouts. This could predispose individuals to be more comfortable processing the similar kind of space.

The results showed, however, that the rational plan of the Palladian palace was less beneficial, even though not statistically significant, to better task performance than in the case of the curved layout. One explanation is that the curved palace offers fewer possible routes (only two) and therefore, supports a linear path more adapted to remembering a sequence of cards. A potential extrapolation would be that a greater choice of paths does not support a more accurate memory performance when using the MoL.

Participants' sketches were quite compelling as they matched the original layout closely enough, but were very different from one another. Two sketches from two participants are shown in Figure 3.16 (all participants' sketches are in Appendix A.1). These drawings show how much participants were able to remember their environment despite not having been asked to do so. They were only told to focus on the memory task of remembering a sequence of cards. Even so, every participant was able to sketch the layout of the palace visited. It confirms the 'dual process theory' set out by Schneider and Chein (2003), where spatial knowledge is processed on an implicit level, compared to the memorisation of the cards which happens through a controlled process (see Section 2.4.1).

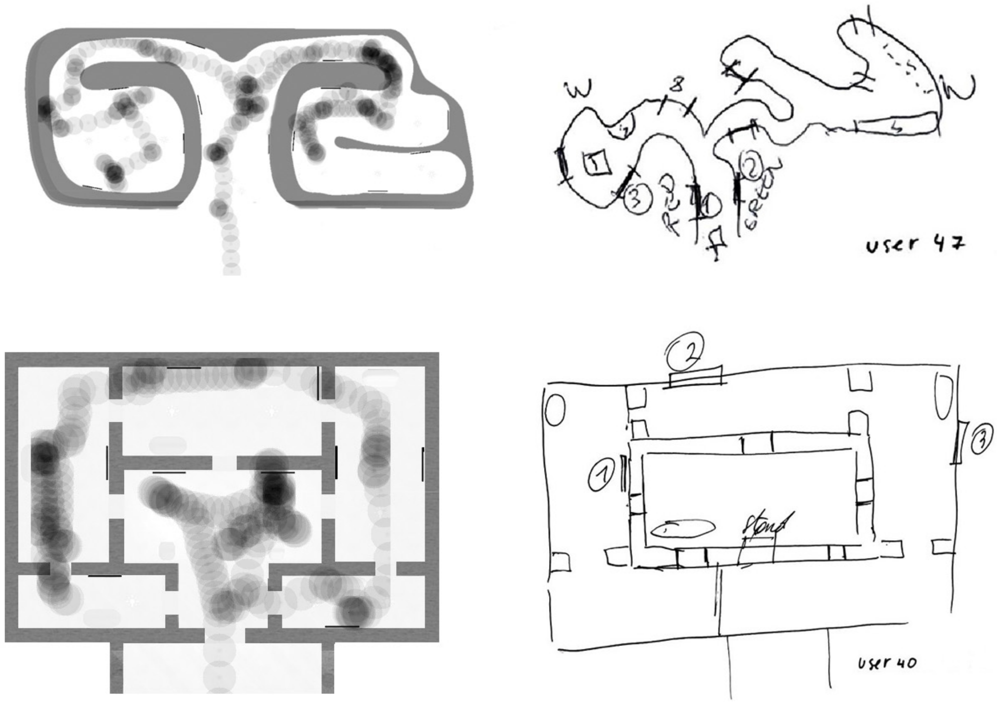


FIGURE 3.16: **Heatmap vs Sketch.** Comparison between tracked position and layout sketches for 2 participants.

Another way of looking at these data is by following each participant's journey and performances. Figures 3.16 shows a comparison between their heatmap and their sketched layout. User 47 recalled 4 playing cards in the control experiment, then all of the 9 cards after having used the Curved Memory Palace for 5 minutes (top); User 40 recalled 2 cards in the control experiment, then 6 cards after having used the Palladian Memory Palace for 5 minutes (bottom).

3.5 Discussion

This section presents the findings of the research goals defined earlier in this chapter. These will be used to answer the first research question.

3.5.1 Findings of the Research Goals

G1: Identify the rules of the Method of Loci and implement them in VR. Two books by Yates (1966) and Buzan (2006) were the main inspiration to understand the rules and techniques used to imagine the memory palaces. The rules are not precise but they give some sense to what is important to keep in mind when designing the environments. These suggestions were applied in the proposed virtual environments.

- there are two kinds of images: one for things, and one for words.
- the environments should not be too similar to each other; for example, too many columns would be confusing as they a create similar type of space.
- the space should be of moderate size, at human scale. If too large, it will render the images placed on them vague, and if too small, then an arrangement of images will be overcrowded.
- the light must be right because if lit too brightly, the image placed in them will glitter and dazzle; if too dark, the shadows will obscure the images.
- the intervals between the loci should be of moderate extent.

G2: Identify the scientific theories behind the Method of Loci and apply them in VR. The Art of Memory and particularly the Method of Loci are based on mnemonic devices studied in various sub-fields of psychology research. The main theory behind the mechanisms at play when using the MoL are:

- Long-term memory vs short-term memory and the seven plus or minus 2 unit of information. The aim of the MoL is to store the information in long-term memory. As such, there are a minimum of 9 items to remember, to ensure participants reach the maximum capacity of their working memory. Moreover, there are a couple of minutes between the time they exit the virtual environment and when they use the Recall Board to retrieve the sequence of cards.
- Dual Process theory, which favours two processes of information acquisition: automatic and effortful (see Section 2.4.1). This is in play between the automatic processing of the spatial environment and the effortful process of remembering the cards.
- Context-Dependent theory, which shows that information is retrieved better when one is situated in the same place as the recording. The frames on the wall are spatially situated and the user is able to travel back to each one in his mind's eye to visualise the associated card.
- Association Principle: the association between the playing card (a number and a colour) to a trigger image that has already some meaning in one's mind and that they can use as part of their own story.

G3: Test whether the Method of Loci in VR can improve memory performance. Findings confirm the assumption that using virtual environment-based memory palaces enhances a participant's memory. Overall, participants remembered more cards when using a virtual memory palace than in the desktop-based control experiment.

G4: Evaluate the effect of different types of virtual architecture on memory performance. Two different styles of architecture were tested: a Palladian layout and a Curved walls layout. The Palladian layout offers only straight walls and more than one potential connection between rooms. The Curved wall option offered only two paths, one to the left and one to the right. Participants had to follow the curved corridor to access a larger room at each end. Despite the fact that most of the results were not statistically significant, there was a trend toward a shorter cycle time to remember each card from participants who experienced the Curved Palace rather than the Palladian Palace. This could be explained by the benefit of using the *continuity* of the walls to aid recall of the sequence of card in order, compared with the Palladian palace offering too many *connections* between rooms, and thus, confusing efforts when attempting to recall the sequence. However, participants' comments expressed a preference for the Palladian option. Another cognitive theory might be concerned. Indeed, it could be argued that, providing users access with a global frame of reference, such as an atrium that connects each room, supports their spatial representation model, in comparison with the curved corridor, which offered participants only local landmarks such as sofas and frames (cf. Werner and Long, 2002).

This is only an early conclusion based on a trend. Six participants demonstrated a good performance, recalling the 9 cards with a card cycle time of 33sec/card. They confirmed in the post-experiment interviews how this type of method benefits their "learning style". It shows that virtual memory palaces work for some people and less for others. 6 participants of the 17 in total, remembered the 9 cards. These were encouraging results.

3.5.2 Answering Research Question 1

How can architectural design enhance users' memory performance when using the Method of Loci in VR? Since, 2012, only a handful of studies have begun to examine the potential of VR to study and develop the MoL mnemonic. Archimemory was developed over the three following years, during which time I published posts and updates on the website archimemory.net [5]. This also means there was no other study to discuss at the time.

[5] The memory game control experiment was published online in September 2012, and the first version of the virtual environment experiment in November 2013. `http://archimemory.net`

Since 2018, similar studies have now been published, using a version of the MoL either on desktop, or in a 3DOF HMD (Vindenes, Gortari, and Wasson, 2018; Huttner, 2019; Reggente et al., 2020). In a small study, Vindenes, Gortari, and Wasson (2018) showed that participants with higher spatial reasoning abilities benefited more from using a MoL. In education, where budgets are generally small, Huttner (2019) experimented with Google Cardboard based MoL and demonstrated that even without conscious awareness of the existence of the MoL, the memory performance is not attenuated. This means that the barrier of a long training period prior to using MoL could be removed by developing an appropriate virtual solution. The most advanced study that has converted the MoL into VR by Reggente et al. (2020) shows encouraging results, where the experimental group remembered 28% more objects than the control group. But this utilised a desktop version because the VR version deployed using the Oculus DK1 (3DOF) was causing motion sickness. Nevertheless, they demonstrated that a virtual environment allows participants to "implement a MoL-based encoding strategy without the reliance on mental imagery." [6]

As outlined in Chapter 1 and Chapter 2, the main challenges of virtual environment design are the level of immersion, the user interaction, and the quality of the spatial design. Although based on the early development kit, the research reviewed on the use of VR as a research tool to study spatial cognition, suggests that well designed virtual environments could also be used as a medium for new learning methodologies. Here, the Archimemory preliminary study, showed the relative potential of using such a method.

In terms of the level of immersion of the VR system used in this experiment, which was manufactured in 2014, and taking into account the literature review conducted on the subject (see Section 2.5), the hardware played an important role in the limitations of the experimental design. The Oculus DK2 consisted of a HMD affording a limited positional tracking; participants sat on a chair. The use of an Xbox controller requesting a level of abstraction by mapping translation movement onto buttons also played a role in reducing the level of immersion. Moreover, these factors had the potential to increase the level of motion sickness. A similar study by Krokos, Plaisant, and Varshney (2019) showed promising insights into the use of virtual memory palaces. The study showed significant amelioration on memory recall when inside the virtual environment using the HMD compared with a desktop monitor condition using a traditional mouse. In that comparison, in both modalities, participants' position was locked, affording only head rotation. Nevertheless, most of the participants enjoyed the experiment and felt present in the different virtual memory palaces. Their reactions when experimenting with VR was excitement and enthusiasm. The new generation of HMDs such as the HTC vive (6DOF) with hand controllers will help to remove most of these limitations.

[6] MunxVR is a VR application using the MoL, see `https://linguisticator.com/p/munxvr`. However, most of the virtual environments are outdoors, and no attention is given to the architecture and the spatial qualities of the environment.

Furthermore, in VR, any programmed interactions can be measured accurately with the data acquired from the different input devices, such as the HMD and the controllers. The FBM has proved to be effective not only in the way participants interacted with the frames and images, but also to track the different level of data, such as card association, time association, and position. More data could be captured, such as head direction. Such a vast amount of available information can rapidly weaken the ecological validity of the system. It is critical to design a controlled environment by narrowing down the scope of the experiment. The independent variables must be clearly defined in the experimental design.

With regards to the RQ1, this chapter presented and applied theories that explained how architectural design can enhance memory performance when using the MoL in VR. The number of connections between rooms, which relates to the potential frame of reference, can have an impact on participants' performance navigating the different palaces. Is it the number of connections in the layout or the lack of global frame of reference that has the biggest effect on the time taken to memorise the sequence of playing cards? The Palladian layout offered an atrium with 5 different passages, compared with the Curved layout, with only 2. This also presents a clearer global frame of reference in the former with more potential paths to choose from, compared with a local frame of reference and only 2 paths to choose from in the latter. It is difficult to know which feature, number of connections, frame of reference, curved or straight walls has what effect. They would need to be measured separately: one experience comparing the difference in the number of connections in the layout; another experience could retain the same layout but compare the *perpendicularity* or *curviness* of the walls. Moreover, further research is needed to identify tools that can quantify the effect of different architectural features.

3.5.3 Limitations

A mixed method approach was used to gather both quantitative and qualitative data. From a quantitative point of view, one of the limitations in the design was that participants had only one attempt in one memory palace, giving rise to insufficient data points with which to establish a benchmark for each system. Future studies should include more participants to increase the quantity of data. A benchmark could then be used to calculate the maximum potential of the system and thus its efficiency. A second limitation was the difficult interpretation of participants' positional data. The heatmaps offered a good visualisation tool but were lacking in terms of measurable outcomes. Yet another limitations of this study was the number of confounding variables. for instance playing cards could be associated with the screens instead of the image.

From a qualitative approach, this pilot experiment showed people's aptitude for drawing maps of their experienced environment from memory. However, the analysis of such feedback is time-consuming and did not bring significant results with which to generalise either to a broader population or to identify a more specific way of designing these environments.

3.6 Summary and Future Work

3.6.1 Summary

This preliminary experiment revealed much insightful information into the potential of using VR not only as a scientific tool but also as a potential mnemonic device to enhance learners' memory performances. VR showed promise as an experimental tool to explore how different types of architecture can possibly affect participants' memory performance. It also offered valuable insights into how users can navigate in VR and how they are able to remember these layouts and sketch them from memory. The programming of the interaction within the IVE was challenging at times, and linked to the controller and the 6DOF headset with their somewhat limited range of movement. The arrival of the new generation of VR headsets will remove some of these limitations.

Another valuable lesson learned from this preliminary study concerned the adaptability of the medium to different contexts. It is essential to be able to extract principles from the results of the experiment that can be applied to a broader array of VR use-cases. One approach to extract potential principles is to work within a *virtual architecture analysis grid* (presented in Chapter 6, p. 171). Figure 3.17 shows an analysis grid applied to this chapter and experiment.

Archimemory	VAga	Geometric Space	Experienced Space
	Design	**Architectural Design**	**Immersive User Interaction**
		2 architectural style tested: Palladian Palace Cruved Palace (Organic Palace)	Sitting Position (Oculus DK2) Xbox Controller for locomotion and interactions Feedback with HUD
	Measures	**Spatial Qualities**	**Objective**
		Layout Connections Straight vs curved walls	Head postion and direction Memory Card Game using the Method of Loci
			Subjective
			Open questions Sketches

FIGURE 3.17: Virtual Architecture Analysis Grid - Archimemory

3.6.2 Future Work

Layout Connections To address the aforementioned issues about the different number of connections in the layout, another environment was designed, the "Organic Palace" (see Figure 3.18), which had no flat surfaces, but consisted of five alveolar-like spaces of different size, shape and colour, all attached to a main open atrium. The layout corresponded to the Palladian layout (5 rooms and an atrium). Comparison between the two layouts used as memory palaces could potentially reveal more about the difference in the effect of *perpendicularity* and *curviness*.

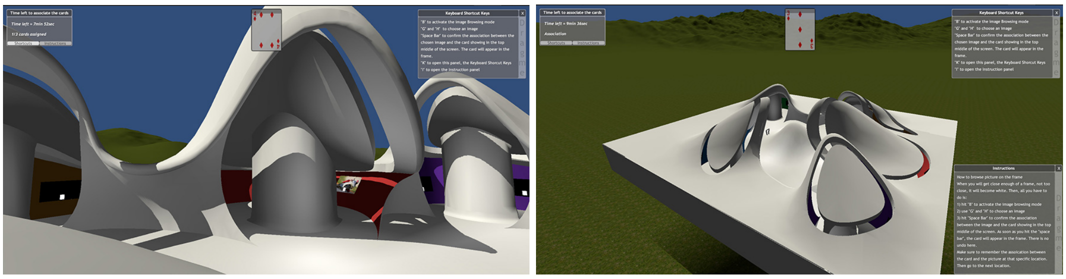


FIGURE 3.18: ArchiMemory XP2.2 - The Organic Palace

Virtual Studio: With *space* being the primary material of this investigation, a next potential step is to design a virtual studio which would work as a spatial framework to manipulate a set of variables directly related to the spatial design of the virtual environment, such as architectural elements. The virtual studio can then serve as a laboratory to evaluate the effect of these variables on participants' ability to perform a batch of cognitively demanding tasks.

Online Development: After this preliminary experiment and these encouraging findings, the next stage was to develop an online version to be able to reach out to a larger number of participants. However, web design and particularly Web XR implementation was in its very early stages and required not only specific programming skills but also a dedicated web developer.

After six months of development, and the concomitant trials and errors, the online version never reached fruition. The main problem was due to incompatibility issues between Unity Web exporter and the web client. So for a lack of resources and the unreadiness of the existing framework, the project had to be placed on hold.

Performance Efficiency: The evaluation of the performance of such mnemonic devices would benefit from the implementation of appropriate metrics, such as performance efficiency (e.g. productivity).

Further Suggestions: Here are some other thoughts and suggestions that arose from the post-experiment discussions. Most of them are beyond the scope of this research, although they offer ideas and opportunities for future research projects.

- Specific events could be added at specific locations to trigger the participant's memory (like a blinking light, or other object appearing). What effect these events would have on participants' memory performance.
- The sociological aspect of this study is under-evaluated. There is much to understand in why participants are making specific associations between playing card and images.

Chapter 4

Virtual Studio Prototype - Immersive Design

> It is high time that I should pass from those brief and discursive notes about things in Flatland to the central event of this book, my initiation into the mysteries of Space. THAT is my subject; all that has gone before is merely preface.
>
> *Edwin Abbot*, Flatland, 1884

4.1 Overview

This chapter explores the different topics raised by the Archimemory experiment described in the previous chapter. It starts by identifying design constraints. Then, a generative design workflow, using spatial analysis, is used to evaluate four spatial qualities in different architectural layouts. User testing helps to identify ways for participants to give real-time feedback on their experience of these spatial qualities, as well as the benefits of different cognitive demanding spatial ability correlated tasks. Overall, this phase serves to prototype the spatial conditions and the immersive user experience that will be implemented in the main experiment.

The following sections cover the design process and prototyping of a virtual studio to evaluate the effect of spatial design on human experience. A wide range of architectural elements and spatial qualities could be used in the design of the experiment (see Section A, p.187). Yet, to reduce the number of confounding variables, only a few elements can be explored at a time. Therefore, it is important to establish the principles and constraints that will support the design of the following experiments.

The architect's design process usually starts with a sketching on paper to support a mental testing phase of potential designs and discussions. Once a conceptual idea takes shape on paper, a second, more tedious phase starts by constructing either physical or digital three-dimensional models. Both types of models can be manipulated and edited to a certain extent. Digital three-dimensional models are more flexible as textures, and lighting can easily be added and rendered as realistic visualisations, stills or animations. The architect reiterates this process until a satisfactory solution is found.

Until recently, the only way for architects to test their solution was to build a full-scale model, which was either cost-prohibitive, impractical or both. Only once it has been built, and people occupy the space, will they be able to evaluate the real adequacy of the solution to the problem by either, getting feedback from the people, or measuring people movement with expensive electronic sensors and cameras. In contrast, the past thirty years have seen advances in the field of spatial analysis to evaluate and predict human behaviour in the built environment based on drawings and geometries. Bill Hillier, one of the main figures in the field [1], wrote eloquently about the dichotomy between architecture and its inhabitants.

> The architect and user both produce architecture, the former by design, the latter by inhabitation. As architecture is designed and experienced, the user has creative a role as the architect (Hillier, 1996).

Such approaches, however, have failed to take into account the perceived space as experienced by the user. A combination of spatial analysis technique with today's real-time graphics computers and VR technology brings new opportunities for architects to test their spatial design virtually, with human feedback. They are able to enter a full scale representation of their building, explore every corner, organise meetings with different parties, and rethink the project from any viewpoint. They can modify the design, test it in real-time, and reiterate as many times as needed to find the best solution more effectively.

Notwithstanding the differences inherent to virtual worlds - notably, no laws of physics - there are limitations to what can be applied from VR to the physical world. Indeed, it requires a lot of effort to simulate things like sound reverberating against the wall of a specific room, the sense of touch from different surfaces, or even the weight of objects. Everything has to be encoded.

This research takes the design process onto a different path. With its own rules, the virtual world is worth exploring for its own ends. Instead of testing architectural design in VR for the purpose of building the physical world, why not try to understand how to use spatial design to affect the human experience for the purpose of building meaningful learning virtual environments?

Moreover, software development (such as Rhino) and rapid prototyping technology (such as 3D printing), have evolved rapidly in the last decade. Product designers and engineers are now able to produce more effective solutions by using *generative design*.

[1] The Space Syntax Laboratory at The Bartlett, University College London and Space Syntax Limited have worked together on the academic development and commercial application of space syntax for over 25 years.

A program generates a number of outputs meeting certain constraints, which can then be tested to gather more data points and are then injected back in the process, to refine the solution.

The Archimemory experiment described in the previous chapter revealed insights into the potential of using architectural space to guide the user's actions within IVEs, with the aim of enhancing his/her performance at remembering a sequence of playing cards. However, too many confounding variables have limited the potential of understanding further how to design better IVEs from an architectural point of view. For instance, no objective variables quantifying the different architectural spaces were extracted. Spatial qualities were not defined. The correlation between spatial design modifications and spatial qualities was not explained. Further questions were raised that will be fully addressed, like immersive interaction design with the implementation of natural movement to navigate the virtual studio, as well as to manipulate objects, and complete spatial cognition related tasks.

Moreover, the quality of the experimental design between studies involving the use of VR head-mounted display in education and training, varies widely, as exposed in Section 2.5.4 and discussed in a recent review by Jensen and Konradsen (2018). The lack of details reported in scientific studies using VR makes it difficult to compare results. This problem underpins the decision to include the Virtual Architecture Analysis Grid at the end of each chapter, with the aim of concisely tabulating the design elements taken into consideration. With regards to the above, the following research questions emerged:

RQ2: How to evaluate the correlations between architectural elements and spatial qualities? To help answering this question, the goals are to:

- **G1**: Define the spatial qualities of a room.
- **G2**: Take objective measures of these spatial qualities.
- **G3**: Test the effect of different architectural elements on these spatial qualities.

RQ3: How do perceived spatial qualities correlate to those measured by Isovist techniques? The goal of this chapter is to:

- **G4**: Find a method to obtain subjective feedback about the selected spatial qualities.

RQ4: What tasks can be implemented to evaluate the spatial performance of an immersive virtual environment? The spatial performance of an environment can be measured by evaluating users' performance completing a series of tasks which still need to be identified. The goals to assist in answering this question are to:

- **G5**: Implement immersive interaction like (a) room-scale locomotion, (b) changing layouts, and (c) physical interaction with task related objects.
- **G6**: Test different tasks and tools to assess users' spatial abilities.

4.2 Two Models of Space

This section positions itself in the larger context of unifying theory of architecture discussed in Section 2.3.1. The division into two models, *lived space* and *geometric space*, is borrowed from Dovey's phenomenological approach to the design process (Dovey, 1993). The two models can be evaluated separately before comparing the results. The first model is subjective, emotional, and qualitative due to one's own interpretations; the second model is objective, tangible, and quantitative, it can be measured using spatial analysis (Dosen and Ostwald, 2017). However, to make sense, a complete spatial analysis requires both approaches: the qualitative experience of the architectural space complements the mathematical analysis (e.g. Franz, Von Der Heyde, and Bülthoff, 2005; Wiener and Franz, 2005; Franz and Wiener, 2008).

4.2.1 Geometric Space and Experienced Space

Notwithstanding Dovey's insightful approach to the conception and perception of space, the notion of *lived space* is not the most appropriate term to describe the way a virtual world is experienced. The concept of *experienced space* is better adapted to the current context. This dual approach represents one of the main factors in the development of a methodology considering the problem statement. Indeed, spatial analysis and users' subjective experiences are fundamental to the evaluation of the effect of architectural qualities on humans' cognitive performance within IVEs.

4.2.2 Definitions: Quality, Property, Characteristic or Attribute

The four following terms are often used to describe the architectural space: *quality, property, character and attribute*. As one of the aims of this research is to evaluate the qualities of the architectural space, it is fundamental to clarify their denotations.

Dictionary definitions of these terms show high synonymity. Further research in the literature shows differences of use when describing abstract *objects* like a chemical element or when describing *space* like in architecture.

The first definition of *quality* ("quality", n.d.)[2], is a peculiar and essential character, a distinguishing attribute, an inherent feature or property. It is a general term applicable to any trait or characteristic whether individual or generic. With that in mind, the word *quality* will be used as the most generic when discussing about *spatial qualities*.

[2]Quality. (n.d.). In Oxford English Dictionary. Retrieved from https://www.oed.com/

Property ("property", n.d.)[3] implies a characteristic that belongs to a thing's essential nature and may be used to describe a type or species. In physics, a *property* is intrinsic and objective and a *characteristic* is extrinsic and subjective. Etymologically, *character* ("character", n.d.)[4] originates from the Greek "kharaktēr" meaning, "mark, distinctive quality" used to identify someone or something. In chemistry, a primary group of chemical elements like metal has a series of *properties* e.g. malleable, shiny or ductile, which are common to all metals. As for the word *attribute* ("attribute", n.d.)[5], it carries the notion of belonging to a thing or a being.

To sum up, from an architectural point of view, the word *characteristics* will be used to analyse spaces from a quantitative point of view, as well as when considering the design process. Otherwise, *Spatial Quality* will be used principally throughout the dissertation.

4.2.3 Four Spatial Properties: Theories and Evaluation

Theories on spatial qualities and studies about how the built environment affects its inhabitants emerged in the 1970s, within the field of environmental psychology (see an overview by De Young, 2013). The methodology used in these studies has always been controversial. Reproducing live environment situations in a laboratory is rarely possible and it is complicated to design effective measurements of people's real-life behaviours. Nonetheless, findings from this interdisciplinary field have had a wide range of implications, not only for psychology, but also for social science, cognitive science, and education. In the context of this project, only a few specific studies were addressed for their relevance to various spatial quality theories. In one study using the two models of space methodology, Wiener and Franz (2005) notably developed a framework that combines three spatial qualities: *spaciousness, clarity, and complexity*. The fourth quality was inspired by Dosen and Ostwald (2017) studying spatial *enclosure* and exposure. Here follows a brief summary of each quality and its origin.

Spaciousness: One way to understand *spaciousness* is to look at the concept of proxemics, proposed by anthropologist E. T. Hall (1963) and shown in figure 4.1b. Proxemics deals with the way humans make use of space and the effects that population density has on behaviour, communication and social interaction. Typically, anything within a radius of 1.2 meters of the individual is considered personal space, and anything greater is part of the public space. Entering one's personal space can quickly cause feelings of discomfort or anxiety. Still, from an interpersonal relationship point of view, this personal space is highly variable, depending on cultural differences and personal preferences. However, this theory brings valuable insights into the effects of spatial

[3]Property. (n.d.). In Oxford English Dictionary. Retrieved from `https://www.oed.com/`

[4]Character. (n.d.). In Etymonline.com dictionary. Retrieved from `https://www.etymonline.com/word/character`

[5]Attribute. (n.d.). In Oxford English Dictionary. Retrieved from `https://www.oed.com/`

surroundings on one's perception of proximity, depending, for instance, on how close the walls are. This is where an isovist measure can provide valuable information to determine if a space is large enough, or too small, in relation to the observer's position and path of movement (Benedikt, 1979).

Recent results from Alper and Erincik (2019), indicate that isovist area highly correlates with *spaciousness*, meaning that wider spaces are perceived as more spacious. Higher connectivity values, having more possibility of expansions, lead to an idea of perceptual spaciousness. Furthermore, other types of parameters can be taken into account such as light or colour (Franz, 2005). Indeed, a space that receives more light will also be perceived as more spacious than a darker equivalent.

Clarity: *Clarity* refers to another widely studied theory from environmental psychologists Kaplan et al. (1989). This theory postulates that the two most basic needs that dictate people's environmental preferences are understanding and exploring (Stamps, 2004). Understanding refers to predictability, legibility or clarity. Exploring refers to complexity, mystery, or an unclear surrounding. Figure 4.1d shows a comparison between a predictable fractal, and an irregular and complex neighbourhood.

Enclosure: Historically, after World War I, the evolution of industrial materials, combined with Mies van der Rohe's new style *free plan*, exemplified in the Barcelona Pavillion (1929), allowed the development of *open space*, now a key concept of modern architecture (see Figure 4.1a), transforming the concept of inside/outside. In turn, in the 1970s, architect and urban planner, Oscar Newman, proposed a series of principles to design *safer* spaces with his "Defensible Space Theory". In 1975, English geographer Jay Appleton developed the "Prospect and Refuge Theory" (cf. Sailer and Psathiti, 2017). In his book, "the Experience of Landscape", he explains the origin of humans desires as based upon the type of landscape we evolved in, always looking for opportunity (prospect) whilst being safe (refuge). This stems from evolutionary survival, where the predator must be able to see their prey without being seen. Examples of *prospect* views are: a distant vista or an elevated view. Examples of *refuge* places are: a tree, a bench with a wall behind, or a cave.

Furthermore, neuroscientists Epstein and Kanwisher (1998) have demonstrated the importance of such features in our environment. Indeed, when exposed to different stimuli, a specific region of the brain shows (using fMRI) high levels of response for surfaces (like walls) and low levels of response for objects (like furniture) within the same space. Having a dedicated region in the brain that responds to perception of enclosure in our environment demonstrates the importance, in human spatial cognition, of such an ability. Based on this finding, Stamps (2005) explored the use of isovists to calculate the level of spatial enclosure, a method which will be described in more detail in Section 4.2.4.

From a design point of view, the choice of surfaces that create our environment has a strong impact on the degree of enclosure. For example, by replacing a wall with a couple of columns, the sensation of *openness* will increase, and the room will feel more open.

Layout Complexity: The perception of *enclosure* is linked to the structure of the spatial layout one has to navigate when assigned a task of moving from one location to another. To effectively perform that task, one has to understand the configuration of the space, also known as *layout complexity*. The structure of the environment can have a significant influence on individuals' ability to orient within it, which is referred to *wayfinding performance* (see Section 2.4.3). Studies demonstrate that performance in wayfinding decreases with the level of complexity of the layout that participants have to navigate (Slone et al., 2015). The complexity of a layout is one of the most important factors to take into consideration in regards of user spatial experience. So, how should one evaluate the degree of *layout complexity*?

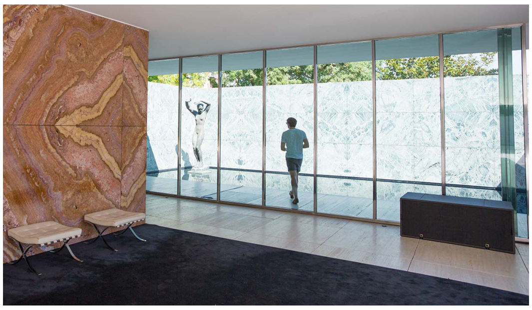
In the preliminary experiment of Chapter 3, Archimemory, participants had to sketch on paper the experienced layouts from memory. This was based on the idea that plan complexity significantly influenced sketchmap accuracy (cf. O'Neill, 1991). Even though participants' drawings presented clear insights into the different modes of representation used to draw each layout, they failed to provide any objective measure of the degree of complexity for the experienced environments.

In general, aforementioned studies required their participants to evaluate the spatial qualities by rating them using a Likert-scale, or by drawing sketch-maps of the experienced environment. Comparison of results between studies is hard because the environments never share the exact same layout, and there is no standardised evaluation method. The lack of objectivity in these methods makes an extrapolation to design principles insubstantial.

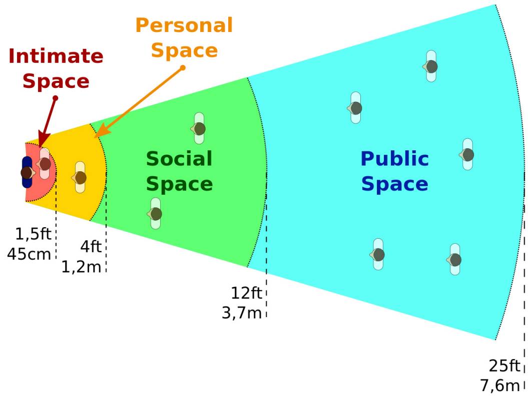
In the pursuit of developing an objective method to measure layout complexity, as well as many other spatial features, it is necessary to look at what architects and urbanists have been working on since the late 1970s. Hillier (1996) developed a set of theories and techniques for the analysis of spatial configurations, called *Space Syntax*. These serve mainly as tools to help urban planners simulate the likely social effects of their designs. However, in the digital age, these tools, turned into software, can easily be adapted and used for smaller scale projects such as buildings, interior architecture, and virtual environments.

4.2.4 Spatial Analysis

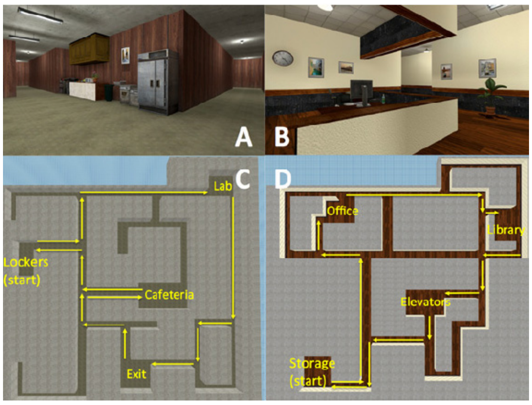
The process of designing and building an architectural space is long and expensive. Testing an architectural solution in a real setting is not an option. Once constructed in concrete, metal and glass, there is very little that can be modified. Because of these



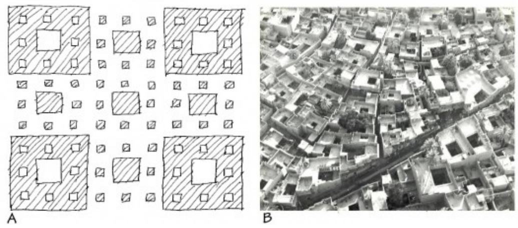
(A) In the Barcelona Pavillion (1929), Mies Van de Rohe demonstrates the possibility of *openness* by using thin metallic columns and frames that let the light bounced off the marble walls.



(B) Diagram showing the different distance of communication conceived in Proxemics (Hall, 1966). Distance has a direct impact on the sense of spaciousness.



(C) Two virtual environments with different degrees of layout complexity. Panels C and D show layouts of the simple and complex environments with starting locations and paths taken during the learning phase. Image from Slone et al. (2015)



(D) Clarity. On the left is a simple fractal pattern called a "Cantor Gasket". On the right is a much more complex and irregular pattern with recognisably similar fractal properties, a traditional urban neighbourhood in Baghdad, Iraq. Images from by Nikos A. Salingaros (left), Image from G. Eric and Edith Matson Photograph Collection, Library of Congress (right)

FIGURE 4.1: Example of studies analysing different spatial properties.

constraints, architects have been using physical models at different scales to verify the adequacy of their designs. More recently, the advent of computer-generated images and simulations offers more flexibility to modify the three-dimensional models and explore the virtual buildings.

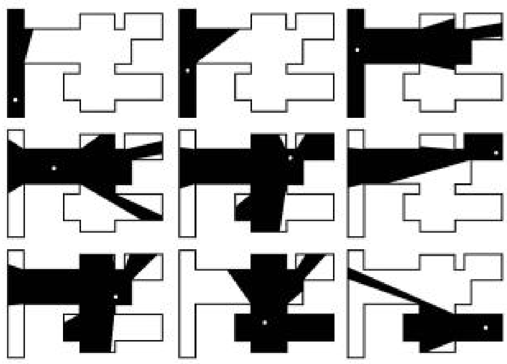
In parallel with the development of three-dimensional visualisation, in an attempt to quantify these spatial qualities, architects and urban planners have been working with analytical tools, using the power of computers to provide complex analysis. In a pivotal study, M. Benedikt (1979) demonstrates how to use an *Isovist* to measure spatial characteristics of small-scale environments. He explains that:

> An isovist is the set of all points visible from a given vantage point in space and with respect to an environment. The shape and size of an isovist is liable to change with position (Benedikt, 1979).

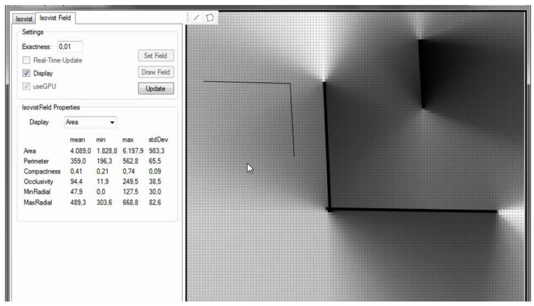
In other words, an isovist is a viewshed polygon projected onto the environment at 360 degrees around a single observational point of view (see Figure 4.2a). Sitting or standing in one location does not cover the range of ways humans navigate, and perceive their spatial environment. Hillier and Hanson (1984) converted spatial layout into graph representation in the 1980s (see Figure 4.2c). Later on, in an attempt to measure people's behaviour in the built environment, M.Batty (2001) suggested that a set of isovists taken along one's path, forms a visual field whose extent defines different *isovist fields*, based on different geometric properties.

> Isovists can be defined for every vantage point constituting an environment, and the spatial union of any particular geometrical property defines a particular isovist field (Batty, 2001).

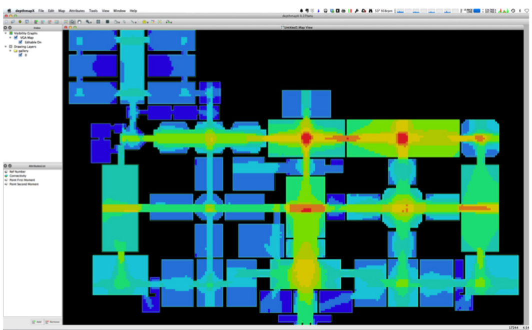
An *isovist field* shows an interaction between geometry and movement (see Figure 4.2b), represented by a series of polygons from which several quantitative descriptors can be derived that reflect local physical properties of the corresponding space, such as area, perimeter length, number of vertices, length of open or closed boundaries. These quantitative descriptors are also called *measurements* (Turner and Penn, 1999).



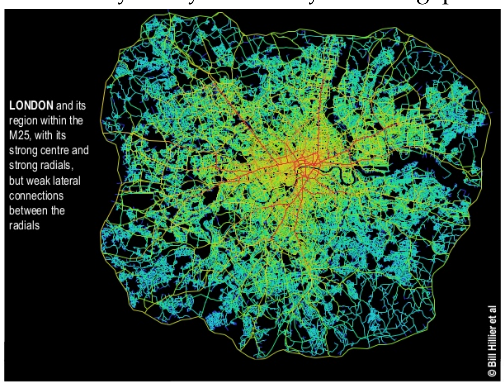
(A) Isovist Analysis from different locations



(B) An isovist field - extract from the application "visibility Analysis Tool" by DecodingSpace



(C) Typical Space Syntax Analysis of a building from SpaceSyntax.net.



(D) Typical Space Syntax Analysis of London by Bill Hilier et Al.

FIGURE 4.2: Example of studies applying different Spatial Syntax for different use-cases.

More recently, in an attempt to understand how spatial qualities affect human perception (see Section 4.2.5), Franz and Wiener (2008) proposed a series of isovist descriptors that are assigned to each spatial quality. A visual explanation of the different measurements taken with the isovist is proposed in figure 4.3. A series of measurements is listed below, followed by a selection of isovist descriptors.

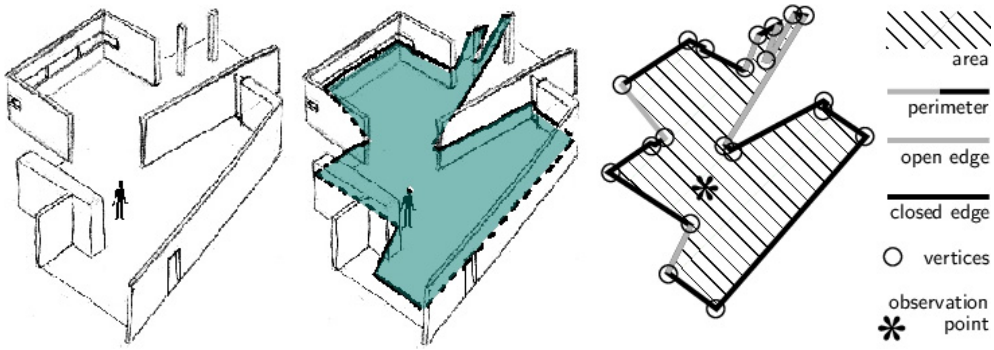


FIGURE 4.3: Isovist Explained (Wiener and Franz, 2005)

- Measurements
  - Number of Vertices
  - Neighbourhood Size
  - Isovist Perimeter Open
  - Isovist Perimeter Closed
  - Isovist Open Edge = Iso Open - Iso Closed
  - Isovist Area Open
  - Isovist Area Closed
- Isovist Descriptors
  - Openess (O) = length open / length close
  - Jaggedness (J) = iso peri sq / iso area
  - Roundness (R) = iso area / iso peri sq
  - Vertice Density = N vert / iso Area

The studies presented thus far provide evidence of using isovist techniques to analyse a variety of spatial qualities, as well as the wide range of potential variables. Although it requires a specific framework to deploy such a method, the potential for development is vast. For instance, an isovist is only a two-dimensional section taken on a horizontal plane at a given height, and for a particular location, without considering the state of the field in other areas. Isovists give only a partial description of any given spatial characteristics. To address this issue, Turner and Penn (1999) came up with a first solution to integrate these isovists in one syntactic solution, known as *visibility graph analysis* [6].

An other promising area of development in spatial analysis is the possibility to produce three-dimensional isovists, or *3D isovists*, which can produce a more realistic view of one's spatial environment. However, *3D isovists* present a couple of challenges. Firstly, in a review of existing *3D isovists*, Dalton and Dalton (2015) confirmed the difficulties of representation of such an approach. Indeed, reducing three-dimensional information to a two-dimensional medium, such as paper or screen, will always be challenging.

Secondly, while it is computationally possible to process three-dimensional isovists, it requires powerful computers and servers, with dedicated databases, to capture the vast amount of three-dimensional spatial data collected, and process into three-dimensional visibility analysis. Furthermore, the computational cost of using a three-dimensional solution needs to bring a substantially more informative solutions than for the two-dimensional method, otherwise the effort is not worthwhile. (Dalton et al., 2015).

Bhatia, Chalup, and Ostwald (2013) used a traditional ray-casting technique to generate *3D isovists* to evaluate spatial saliency from a CAD model of the Villa Savoye [7]. While this work was a significant advance in the field, it failed to explore experimentally the relationship between the spatial saliency captured by three-dimensional isovists and one's perceived experience. Using a different method, Varoudis and Psarra (2014) proposed using *visibility graph* analysis to clarify the relationship between *accessible* and *inaccessible* space. The best model of how space is perceived by *3D isovists* is still to be determined.

This brief introduction to isovist and visibility analysis has presented how architects are evaluating spatial characteristics to understand how spatial design affects human experience in the built environment. The next section gives a more detailed account of the association between objective measures of specific spatial qualities, and their experiential (subjective) equivalent.

4.2.5 Reconciling the Two Models of Space

This section considers the few studies that have worked towards reconciling quantitative measurement of the geometric space using spatial analysis, with the subjective qualitative perception of identified spatial qualities. Each study has its own features and limitations. This thesis builds upon those limitations to propose a unified framework.

[6] Turner et al. (2001) published a follow-up paper about the software *Depthmap* to perform Visibility Graph Analysis

[7] Villa Savoye is a famous villa designed by architects Le Corbusier and his cousin, Pierre Jeanneret and built between 1928 and 1931 using reinforced concrete

Different Approaches

In a study by Wiener and Franz (2005), participants were asked to give feedback on their spatial experience. They were instructed to move to the location that felt most open or enclosed, as if playing hide and seek. This was a major step towards a more realistic way of reconciling both spatial models. They used a joypad to move around the virtual environment. This kind of setup offers more spatial feedback than in a study completed by Dosen and Ostwald (2017), in which participants had to answer a series of question about the quality of the space-based static images displayed on a monitor.

In a number of studies, Ostwald (2011) gathered the most interesting data on a variety of spatial qualities by testing different methodologies: Dosen and Ostwald (2017) explored the notion of *enclosure* and *exposure* by running the experiment online which afford gathering a lot of datapoints; Vaughan and Ostwald (2014) looked at *visual complexity* using a fractal analysis; Bhatia, Chalup, and Ostwald (2013) focused on *structural saliency* using 3D isovists.

In the experiment designed by Franz and Wiener (2008), participants' subjective feedback on their experience of the spatial qualities was collected using a semantic differential rating scale, designed to measure the connotative meaning of objects, events, or concepts. The connotations are used to derive participants' attitudes towards the given object, event or concept. The downside of this method is that it requires participants' observations of the perception of spatial qualities in real-time, which would distract them from other tasks. This can be a problem if the main purpose of the experiment is to measure participants' performances completing a specific highly cognitive task.

A couple of notions briefly introduced in the literature review (see Section 2) require further analysis at this point. The first useful concept comes from a well-cited paper entitled, "Automatic and Effortful Processes in Memory" by Hasher and Zacks (1979). Their insight was based on the amount of attention required to accomplish an encoding task. It ranged from a very limited capacity attention mechanism named *automatic* processes, to a very demanding attention mechanism referred to as *effortful* operations. Spatial and temporal information, frequency of occurrence, and word meaning are part of *automatic* processes. Imagery, rehearsal, organisation and mnemonic techniques are part of the *effortful* processes.

A second insight comes from more recent research in neuroscience that demonstrates the role of hippocampal place cells in the representation of spatial information in the brain (Moser, Kropff, and Moser, 2008). Similarly, Burgess (2006) identified dedicated place cells in a study of rats recording location of their spatial surrounding (see Section 2.4.2). Dangerous tasks require the full attention of humans: they don't want to be eaten by a lion or be poisoned by the wrong fruit. The development of dedicated place cells allows humans to give their full attention to these highly demanding cognitive tasks without losing their way or forgetting their location. Most of the time, one is not actively paying attention to one's surroundings, even less so when one is in a familiar environment (see Section 2.4.3).

These studies suggest that the perception of spatial qualities operates as an automatic process. Specific brain cells have evolved to manage one's spatial awareness, so one can focus on the task at hand. They have also shown that isovist-derived measurements can be effective predictor variables for human behaviour when performing certain tasks (e.g. Wiener and Franz, 2005; Slone et al., 2015).

This informs an experimental design in which participants perform specific cognitive tasks in different conditions (with different spatial characteristics), without asking them to evaluate these qualities in real-time.

Difference in the Level of Immersion

A final factor requires consideration in relation to the aforementioned studies: the level of immersion. The lack of consistency from one method to the next invalidates any comparison of the results.

Starting of the lower end of the spectrum of immersion, studies from Bhatia, Chalup, and Ostwald (2013) and Vaughan and Ostwald (2014) are purely theoretical, with no human feedback. Spatial analysis is obtained by running an isovist in a three-dimensional model, from specific locations. By presenting participants with a series of 24 still images on a desktop display, Dosen and Ostwald (2017) collected both types of data, although representing a very minimalist level of immersion as no movement was allowed.

In the study by Wiener and Franz (2005), participants had to navigate through a series of 16 virtual environments using a desktop monitor and a joypad. Franz (2005) justifies the choice of such methodology based on practical and economical considerations. In 2005, VR hardware was still expensive and three-dimensional models and realistic lighting solutions were also costly to render. Today, even though the VR technological landscape is more affordable, both factors still have to be taken into account in order to optimise the benefits of using IVEs (see section 2.5.6, p. 50). That being said, for the last couple of years, VR HMDs like the *HTC Vive*, and game engines such as *Unity3D*, give an affordable alternative to produce higher level of immersion.

Summary

Most of the studies provide a detailed account of the setup, and the type of hardware used. What is often poorly described is the realism of the visuals, as well as the quality of the architectural space. They are usually poorly designed for multiple reasons: a lack of computer power, a lack of time to model more detailed environments, or a lack of an architect or designer to hand. Another issue is the wide range use of virtual environments in different configurations. Desktop applications can render a more realistic environment but with a lesser level of immersion than HMD counterpart. This section has considered:

- The two different ways to measure spatial qualities: objective (the geometric space) and subjective (the experienced space)
- Definition and use of: quality, property, characteristics, and attributes
- Different types of spatial qualities affecting human behaviours: enclosure, spaciousness, complexity, clarity
- Measurement of spatial qualities using *Isovist*, *Visibility Graph Analysis*, and the potential of *3D Isovist*
- The analysis of different methodologies used to reconcile the objective and the subjective spatial quality measurements
- The difficulty of obtaining participant feedback within IVEs

These factors make the comparison between studies difficult. It also shows the lack of framework to design relevant immersive virtual environment in cognitive psychology, neuroscience, education, and in the effect of the built environment on human experience in particular.

4.3 Spatial Design Prototype

This section focuses on the spatial design of the different conditions that will be tested later in VR. When planning the design of physical buildings, architects first take into account the existing constraints of the site, functions, and budget. However, in the case of virtual environment design, the primary constraints emerge from the concept of natural movement and immersive user interaction. Pursuing the idea of embodied learning (see Section 2.4.4) and to encourage participants to explore their surroundings in VR by naturally walking through them, the architecture of the space is mostly limited by the actual dimensions of the physical room being used for the experiment.

Another critical distinction to make is the different approach to space between an architect and a person exploring a building. The architect uses pen and paper, rulers and compass, or Computer-Aided Design (CAD) and Building Information Modeling (BIM) software, to design and encode the space that a user will experiment with all his senses, body and perceptions. This distinction is critical to the evaluation of any form of spatial qualities.

4.3.1 Design Constraints and Mixed Reality

Locations and Settings

The VR/Mocap Studio in the Ben Pilmot building at Goldsmiths, London was the first location used to develop the prototype. With a large area of 14.8 sq m, this physical space offered a physical perimeter of 3.7m by 4m. A three-dimensional model following the same dimensions served as the boundary of the virtual environment. As such, the contour walls in VR would correspond to the real walls of the studio. All three-dimensional assets were modelled using the software 3DMAX from Autodesk, then imported into Unity, where user interactions are programmed. This virtual empty room was the foundation of the virtual studio. The following section explores how mixed reality can be used to improve the User eXperience (UX), and how it can assist in answering the research questions.

Mixed Reality and Props

The mechanism of *embodied simulation* has been explained briefly in section 2.4.4. Practically, it means that, like our brain, VR offers a way to build a model of the world. The closer both models align, the more believable they are (e.g. Clark, 1999; Riva, Wiederhold, and Mantovani, 2019). Thus, the *Virtual Studio* is implemented as a mixed reality system, matching part of the virtual environment to the physical location. Once the perimeter wall of the physical space aligns with the virtual walls, it anchors the virtual room into the physical location in a way that supports a smooth transition between the physical and the virtual world when HMD is worn.

Another well known VR issue that can be addressed with a mixed-reality solution is the underestimation of distance (see Section 2.5.4, p.45). Even though there is no specific solution from a technological point of view, many solutions have been explored (see Section 2.5.5, p. 46). The first mechanism that this prototype focuses on is *room scale locomotion*, in line with findings exposed earlier (see Section 2.5.5, p.48).

A second mechanism was proposed to increase the perception of co-location by placing physical objects as their virtual counterparts. In the spirit of film studio production, two props were placed on set to give participants "business": a small table was placed at the same location as the virtual table; a chair was placed at the same location as the virtual chair. Where participants see a virtual table and touch it with their hands (controllers), they actually hit the physical table. This type of input should increase the level of presence by providing a more realistic interaction.

First Set of Architectural Elements

The choice of the first set of architectural elements to be studied was based on the origin of architecture discussed in chapter 2, Background Theory (see Section A, p.187).

This study design focusses on ceiling (roof), columns (structure) and walls (enclosure). The modification of the ceiling height has a strong effect on the perception of the room. The number of independent variables is limited to the shape and size of each architectural element. Also, to encourage participants to navigate the space, the layout was divided into different zones, either using walls or columns. The three architectural elements selected with their variable were therefore:

- ceiling: changing the height of the room
- columns: can be changed in shape and diameter
- walls: can be changed in shape

4.3.2 Generative Design with Isovist

A generative design workflow supports the optimisation of a product based on a number of criteria defined by the designer. During the last decade, with the advent of 3D printing and a wider range of algorithms, generative design has seen a rapid expansion in the production of unique objects and unseen architecture. Without going too deeply into the fascinating ways architects and designers are using generative design - many examples can be found online - this chapter focuses on using spatial variables in an iterative loop, to allow rapid prototyping of the virtual architecture.

Spatial analysis can help to determine the qualities of the building's interior spaces, by proposing human-level measures. Different solutions exist to generate isovists, some more efficient than others [8]. To facilitate the implementation of a generative design workflow, the layouts were generated using the computer-aided design (CAD) software Rhino [9], in conjunction with Grasshopper [10], which provides a two-dimensional isovist component. The isovist is computed by projecting a series of vectors from any given point towards each intersection with the surrounding geometry. This series of (intersections) points can then be connected to form a perimeter or a surface of visible (horizontal section of) space. The decision to use Rhino and Grasshopper was mainly based on the fact that, in 2015, after having tested other available tools, it was the best fit with my design workflow and iterative process.

Notwithstanding the use of an isovist as a visualisation tool, the purpose of running this kind of spatial analysis is to provide a single metric for each spatial quality that can be used in a generative design workflow, as well as a way to later compare the effect of each spatial quality on users' performance. One of the earliest papers about the quantification of the architectural space (see Section 4.2.4), was the work of Benedikt (1979), who provided a set of measurements that could be extracted from an isovist

[8] See software like *DeCodingSpaces Toolbox*; *Isovists.org*

[9] Rhinoceros version 6, for Windows, is a three-dimensional modelling tool developed by Robert McNeel and associates

[10] Grasshopper, designed by David Rutten, is a graphical algorithm editor tightly integrated with Rhino

and be used to quantify spatial qualities. Two of the measurements on which Benedikt was most focused, were the *isovist area*, describing the total amount of area visible from a point, and the *perimeter length* of the isovist boundary, describing the complexity of the view. The area and length components integrated in Grasshopper, were used to calculate these two metrics respectively.

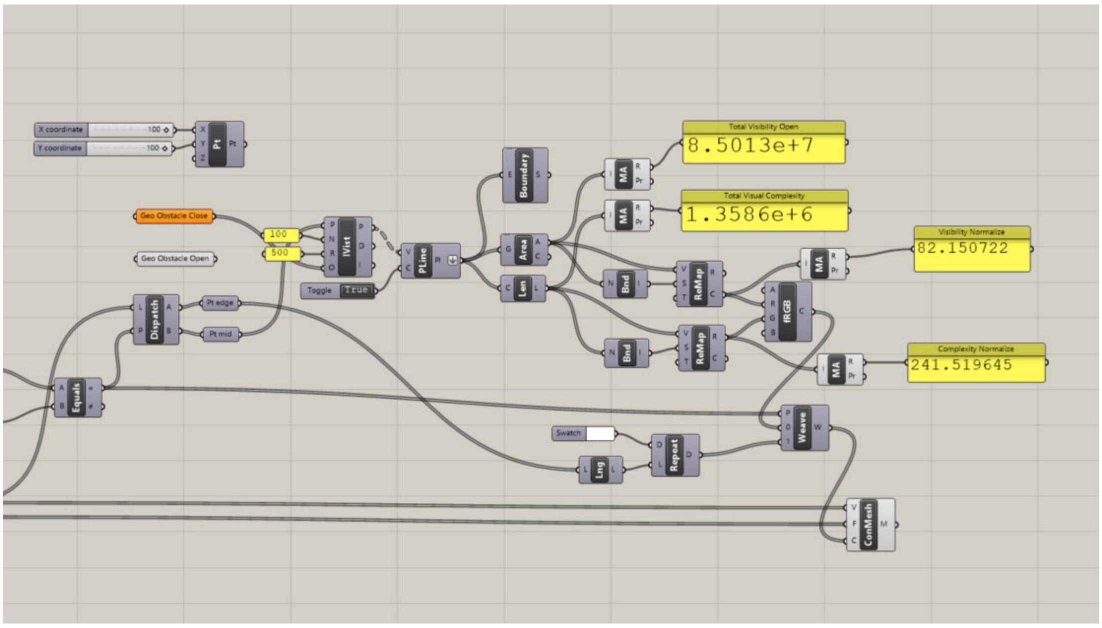


FIGURE 4.4: **Grasshopper Node-Based Isovist Descriptors.** The custom-made node-based program, made with Grasshopper, shows the two isovists descriptors: *visibility* based on the total area covered by the isovist and *visual complexity*, based on the full length of the perimeter of the isovist.

Two Spatial Qualities and their Isovist Descriptors

Taking the aforementioned elements into consideration (enclosed VR space and selected architectural elements), two spatial qualities were selected at this stage: *openness* and *visual complexity*.

The *openness* of a space is the opposite of the spatial quality *enclosure* explained earlier (see Section 4.2.3, p. 85). The word *openness* suits better the present investigation as it refers to the visibility afforded by the surroundings and can vary with the number of windows or the use of columns instead of walls. *openness* was measured by using the isovist area.

The *visual complexity* depends on the length of the perimeters as measured by isovist which varies with the number of windows and columns as well. It differs from the *layout complexity* presented earlier, which is calculated using a different method (see Section 4.2.3, p. 85).

The first step is to remap the area and perimeter length values to a range of 0.0 to 1.0 so that it can be used to create a range of colours for visualisation. This operation was done using the Bounds component provided in Grasshopper, which calculates the bounds of the data. The component remaps each number input to a normalised range of values with the largest area and largest perimeter length normalised to 1.0 and the smallest area and perimeter length normalised to 0.0.

Nine Conditions or Rooms

Based on the literature review about the essential elements that constitute the unit of interior space (see Section 2.3.2, p. 16), three series of layouts using each one of the three selected architectural elements (wall, ceiling, and column) were implemented as follows:

1. Rooms 1A: Round Columns - 1B: Square Columns - 1C: Twisted Columns
2. Rooms 2A: Straight Wall - 2B: Curved wall - 2C: Bulbed wall
3. Rooms 3A: Ceiling - 3B: Ceiling Low - 3C: Ceiling High

With this set of conditions selected (see Figure 4.5), an initial series of layouts were imported into Rhino to run the spatial analysis using the isovist method. These layouts were then extruded in three-dimensions using 3DSmax, before importing them into Unity, so that they could be experimented with within VR. This workflow was used a number of times until a set of conditions expressing a range of the spatial qualities was obtained. Figures 4.6 and 4.7 illustrate an example of the set layouts with the calculated isovists. Each option's visibility and complexity ratios are presented in Table 4.1.

Arch. Element	Variables	Rooms	Visibility ratio	Complexity ratio
Empty				
Column	square	1a	0.62	0.83
	round	1b	0.75	0.91
	twisted	1c	0.76	0.93
Walls	straight	2a	0.43	0.89
	curved	2b	0.32	0.70
	bulbed	2c	0.30	0.66
Ceiling	2.5m	3a	0.43	0.89
w/ straight	1.8m	3b	0.43	0.89
walls	10m	3c	0.43	0.89

TABLE 4.1: Shows each room visibility and complexity ratio

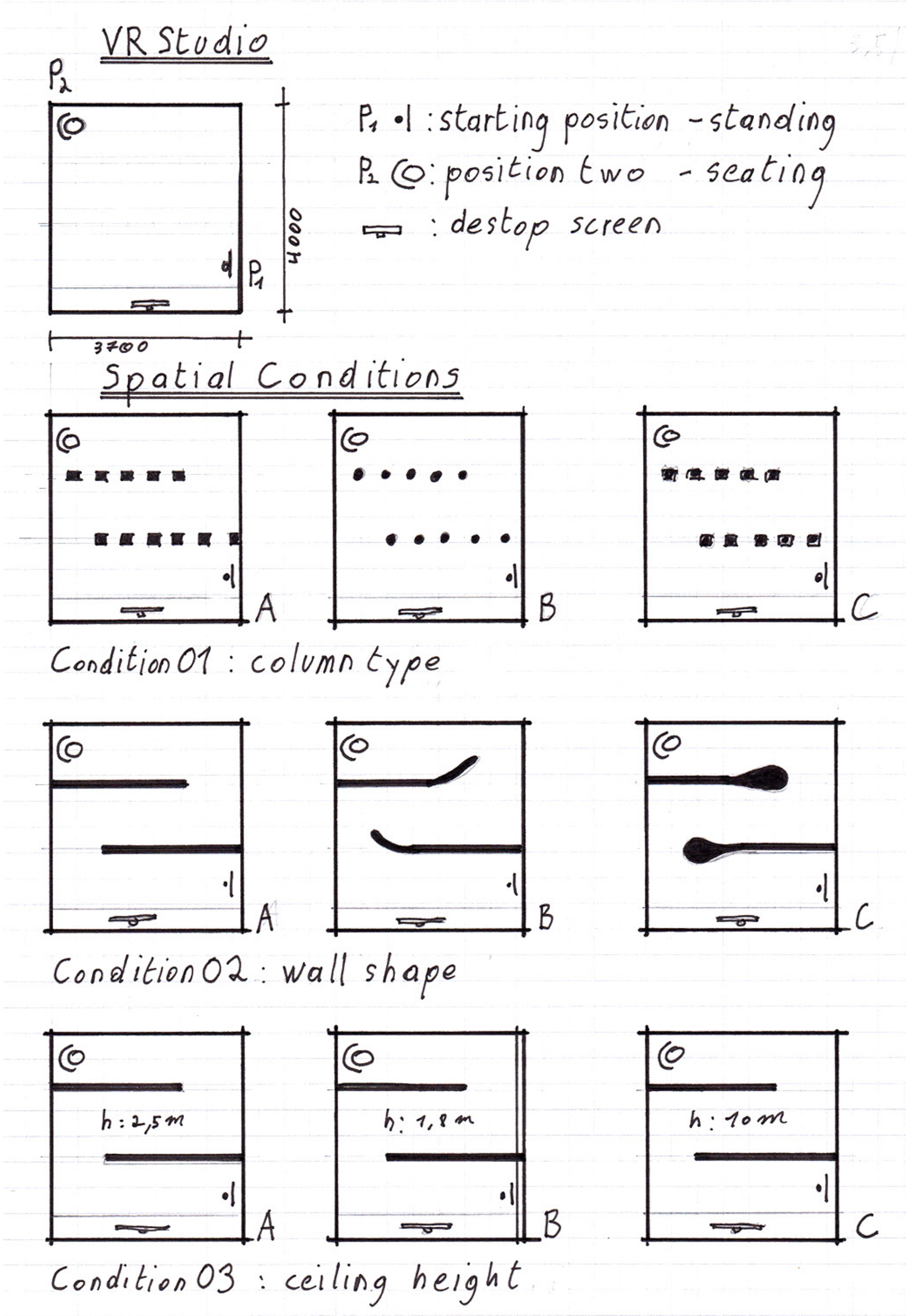
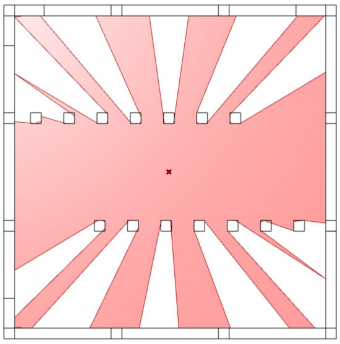


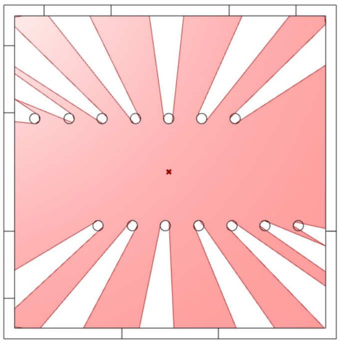
FIGURE 4.5: **Sketches of 9 Layouts.** Shows the three sets of three conditions as view in plan.

4.3.3 Spatial Analysis

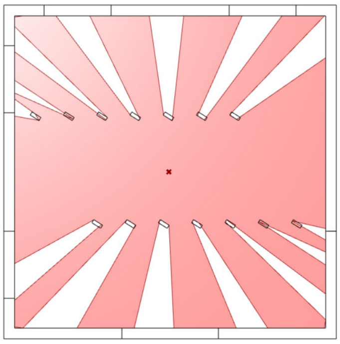
What are the different problems and take-aways from these settings? One problem was that the two-dimensional isovist did not relate the height of the ceiling. One solution



(A) Room1A square columns

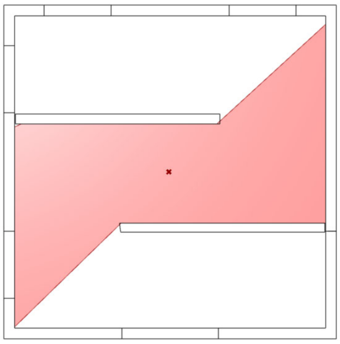


(B) Room1B round columns.

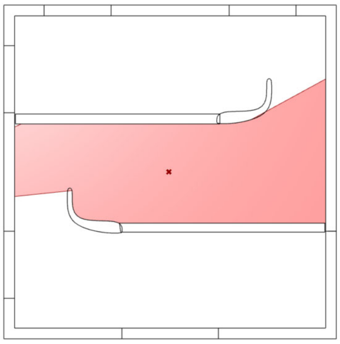


(C) Room1C twisted columns.

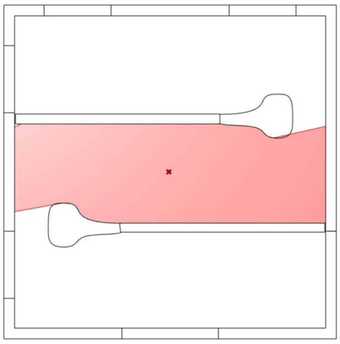
FIGURE 4.6: **Single Isovist - Columns.** Single isovist calculated in a set of rooms showing 3 variations of columns



(A) Room2A straight walls



(B) Room2B curved walls



(C) Room2C bulbed walls

FIGURE 4.7: **Single Isovist - Walls.** Single isovist calculated for a set of rooms with 3 variations of walls

would be to use a three-dimensional isovist. However, as explained previously (see Section 4.3), it would raise other issues: more variables to manage, slower processes with more calculations, and it may not work with other architectural elements. Even though variations in ceiling height conveyed a lot of reactions from participants when experimenting in VR (participants reported strong reactions with the change of height), it did not relate to the aforementioned spatial qualities from an evaluation standpoint.

In contrast, the two-dimensional isovist analysis brought some insight into the variations in columns and walls (Table 4.1). The comparison between the rooms with different column types (see Figures 4.6) showed that there was almost no difference, either in visibility, or in complexity, between the round columns and the twisted ones (0.75 and 0.76 respectively for visibility, and 0.91 and 0.93 respectively for complexity). These types of modification did not bring relevant comparisons when using an isovist. However, there was a difference between the square columns and the two other columns, 0.62 and 0.75 respectively (13% difference), which showed that an isovist is able to measure a certain level of difference, the square column added clear edges compared with the round ones.

With regards to the changes in rooms with different wall shapes (see Figure 4.7), the results differed from Figure 4.6, with a small difference between the curved wall and the bulbed one, of only 4%. However, there was a broader range of measurements, of both visibility and complexity, between the straight and the curved walls (0.89 and 0.70 respectively, a 19% difference).

Even though, differences were not always obvious between variations in the same element, there was an overall difference in complexity between the rooms with columns and those with walls. For instance, a complexity of 0.83 for the square column room compared with a complexity of 0.89 for the straight wall room. The comparison in visibility was more subtle with 0.62 in the room with square columns, compared to 0.43 in the room with straight walls. Introducing windows into the perimeter walls would accentuate the range in visibility.

To sum up, this analysis provided relevant insights into the correlational relationship between architectural elements and isovist descriptors. These results were taken into account to design the user study. This was just a glimpse of the possibilities of using generative design with isovists. More work is needed to build the foundations of a framework that could be used to design meaningful IVEs. Certainly, the means by which spatial qualities were experienced by the user, through locomotion and interaction, played an important role as well.

4.4 User Interaction Design

4.4.1 Room-Scale VR Locomotion

Aligned with theories of embodied cognition, as well as the level of immersion and the sense of presence described by Slater (2009), this section looks at how to increase the plausibility illusion. To increase the illusion of presence, as well as to fully experience the architectural environment, one has to be able to move around, as well as interact with one's surrounding as naturally as possible. Many studies have explored different ways to move around in VR (see Section 2.5.5). However, natural walking and the concept of congruency have shown the most promising results (Johnson-Glenberg, 2018).

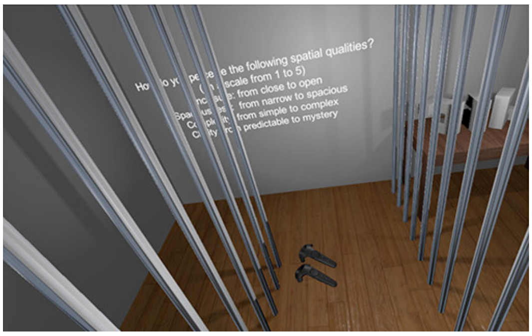
The physical limits are dictated by the room and the length of the cable that links the HMD to the laptop. Nevertheless, neither teleportation nor any other locomotion tricks are implemented as they all have their disadvantages (see Section 2.5.5). Based on the idea that spatial qualities are better perceived by physically walking through the space (cf. Siegel and Kelly, 2017), natural locomotion is implemented using a room-scale VR system in which one's ambulation is limited by the physical walls.

With the rapid advances in hardware technology, contemporary VR system specifications show evidence of significant improvements over earlier systems. For example, the Oculus Rift DK2 used for the Archimemory preliminary study had only a limited range of positional tracking (see Chapter 3). The HTC Vive (released in April 2016) comprises an HMD (tethered to a computer) and two wireless hand-held controllers, each of which allows 6 degrees of freedom of movement (6DOF); two 'Lighthouse' base-stations track users' head and hands movements, with a refresh rate of 90Hz. The device uses two screens, one per eye, each having a display resolution of 1080x1200 and a field of view about 110 degrees. This system offered the best VR experience commercially available at the time; offering a room-scale VR allowing users to freely walk around the play area, with their real-life motion reflected in the VR environment.

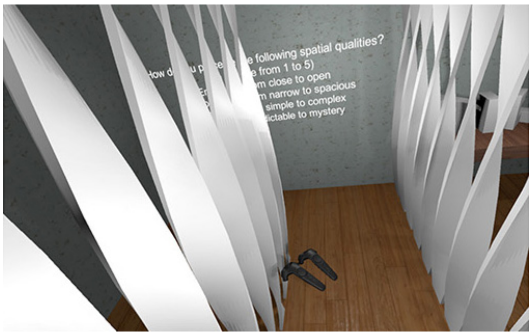
4.4.2 Immersive User Interaction

Changing Layout

Another challenge to address is to define how the user interacts with their surroundings, including different spatial configurations as well as object manipulation. A three-dimensional menu was created in Unity that allowed the selection of the different room/layouts. Pressing the *menu* button from the left controller brought a set of nine cubes representing each of the nine different rooms. Then, with the right controller, the user reached one of the cubes to swap the current layout to the corresponding one. Figure 4.8d shows the nine cubes attached to the left controller.

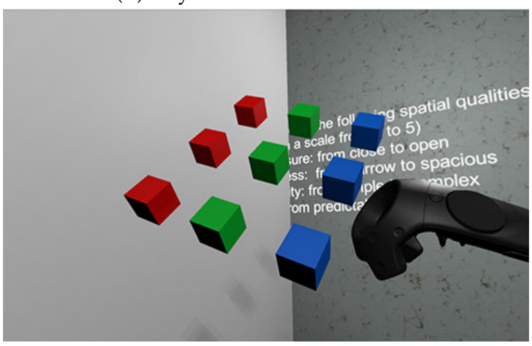


(A) Layout with round bars



(B) Layout with twisted bars

(C) Layout with walls



(D) Controller menu with the nine options

FIGURE 4.8: **Views from the different layouts.** The wrist-based menu is used to change from one layout to the next.

Object Manipulation

A series of shapes, programmed following physical laws, was used for the cognitive task, as explained below. The controllers were programmed to manipulate these shapes, and the user could pick the objects up by pressing the trigger button, examine them, drop them, and/or throw them around.

4.4.3 Potential Tasks

How humans process spatial information will dictate the design of the experimental design. What are the potential cognitive tasks that could be implemented to assess humans' spatial abilities?

Mallgrave (cited in Robinson and Pallasmaa, 2015) asserts that our initial emotional engagement with our surroundings is precognitive. The experience of the space builds up, thanks to a feedback loop of multimodal interactions, perceptions and embodied simulations. Only if a task requests the participant to pay attention to specific elements of the environment will they be using a conscious cognitive process to integrate that element into their internal model. Thus, to replicate realistic settings, if the purpose is to use spatial design to enhance one's ability to perform a specific task, it should not be the main point of focus. The Dual Process Theory explains a similar phenomenon (see Section 2.4.2, p.26), without being specific about the way spatial information is processed.

Testing participants' memory performance in the preliminary study Archimemory (see Chapter 3) did not provide relevant information to evaluate how they processed the different spatial environments in relation to the task at hand. Another potential approach to evaluate human spatial abilities could be to design tasks based on the three scales of spatial abilities introduced in Section 2.4.2, p.37 (Montello, Golledge, and Org, 1998). A typical task to assess figural spatial ability could be the Mental Rotation Test (Shepard and Metzler, 1971). The Virtual Spatial Navigational Assessment (Ventura et al., 2013) could be employed to test the larger spatial environment processing ability. A perspective-taking task could be used to assess the vista ability to access different points of view from an internal model of the space (cf. Tversky and Hard, 2009; Surtees, Apperly, and Samson, 2013).

Mental Rotation Test (MRT) - Object

Shepard and Metzler (1971) published a seminal paper on the mental rotation of drawings of three-dimensional objects, which has led to further studies exploring humans' spatial thinking abilities (Ganis and Kievit, 2015). This particular test is used to estimate spatial ability through identification of rotated objects. Figure 4.9 shows an example of the stimuli used in Ganis and Kievit's experiment. Hauptman (2010) proposes a description of the task, The MRT is used to estimate 'test-takers' three-dimensional cognitive capacity and spatial ability through identification of rotated objects. The test contains 20 items. Each item comprises a criterion figure, two correct alternatives, and two incorrect ones or "distractors".

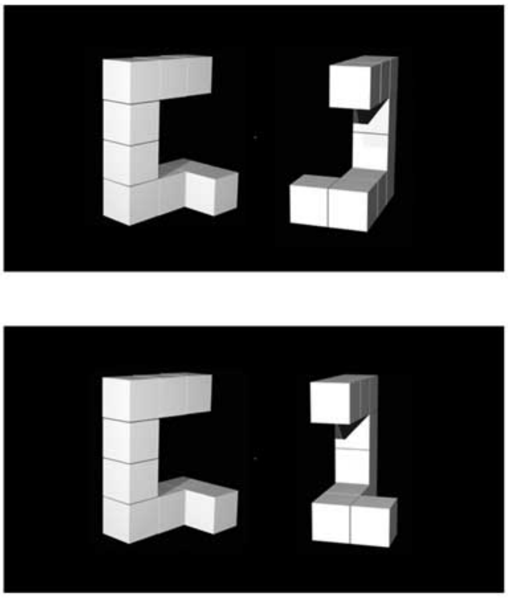


FIGURE 4.9: **Mental Rotation Test - Stimuli.** Mental Rotation Test Stimuli 13-113-1 as presented in the updated version made by Ganis and Kievit (2015).

The original test was carried out using pen and paper. For the purpose of this research, a three-dimensional adaptation of the MRT was proposed so that the user could interact with the figures within the IVE. In this test, with the incentive of using natural movement, participants could grab a three-dimensional target figure from the table. Four other test figures were placed on the table as well. They had to determine which of these were rotations of the target figure and which were "distractors". The test had two correct answers for each of ten proposed figures. The total score was based on the total number of items where both correct objects were found. A higher score indicated higher figural spatial ability.

Perspective Taking Task (PTT) - Vista

Vista spatial ability is useful when trying to understand how the arrangement of objects or a scene will look from different viewpoints. Hegarty and Waller (2004) undertook a study providing further evidence that generalises the distinction between figural spatial abilities (e.g., mental rotation) and vista (e.g., perspective taking).

In a more recent study, Chang et al. (2017) used a perspective-taking task to assess the effect of using a VR system in comparison to mouse/keyboard to enhance spatial cognition. In VR, changing viewpoint is as simple as swapping for another camera angle. Even though the experiment was not about spatial design, as the focus was on small scale object manipulation, it demonstrates the feasibility of such a task in VR.

Virtual Spatial Navigation Assessment (VSNA) - Scene

Ventura et al. (2013) designed this experiment to investigate a new way to assess spatial abilities. It was specifically designed to compare with previous experimental tasks in the field, and it proved to be as valid. The experiment was developed with Unity as a desktop-based virtual environment. Participants were instructed to collect three gems strategically located in four environments. They had to collect the gems twice. The first collection was the training phase and the second collection was the testing phase. Time taken to collect the gems in the training and the testing phase was recorded. The training phase was intended to measure one's ability to search and encode information in the environment, while the testing phase was intended to measure one's ability to retrieve and apply the encoded information (Ventura et al., 2013).

Spatial Quality Rating - Participants Feedback

Finally, the rating of experiential quality was inspired by Wiener and Franz (2005). It consisted of a semantic differential scaling technique. Subjects can differentiate their appraisal using a five-step Likert scale. The rating categories are selected to assess aforementioned properties of *enclosure, spaciousness, complexity and clarity*. The main challenge was to find the best time to get the participant's feedback. Four different ways were tested:

1. From inside the IVE, participants are presented with a text to read, asking them to rate the spatial qualities, and an assistant has to note down the answers.

2. From inside the IVE, participants are required to rate orally, and then an assistant has to note down the answer.

3. Participants wait until outside of the IVE to rate the spatial qualities from memory.

4. Implementation of an ExitPole tool as part of a tool set designed by "Cognitive3D" software.[11]

To be able to test the different possibilities, a display on one of the exterior walls of the virtual studio gave a brief explanation of the task, followed by table 4.2.

[11]This analytical tool provides position tracking, gazing and even surveys at a cost. See `https://cognitive3d.com/`

TABLE 4.2: Spatial Quality Rating Categories and Extremes

Category	Low Extreme (1)	High Extreme (5)
Enclosure	Close	Open
Spaciousness	Narrow	Spacious
Complexity	Simple	Complex
Clarity	Predictability	Mystery

4.5 User testing and Feedback

4.5.1 Proposed Procedure

Participants start inside an empty virtual space with a square floor, four walls, and one button on one of the walls. The walls are aligned with the physical walls which suggests a smooth transition between the real and the virtual world. The press of the button is an incentive to bring the participant to the starting point of the experiment. It also loads the first room. Then it runs as follow:

1. **First task (2 min)**: collect coloured gems on the way to location B where the chair is positioned.
2. **Second task (3 min)**: sit on the chair, follow instructions to complete the MRT.
3. Once done, go back to location P1.
4. **Third task (2 min)**: Do the SQR by replying orally to the questions.
5. **Repeat for each of the nine rooms**: when completed, push the first button again to call the next condition and repeat for the nine conditions, recommencing at step 1.
6. Take the headset off.
7. **Questionnaire (5 min)**
8. **Recall (3 min)**: sketch of the last condition and recall the sequence of colour gems

4.5.2 User Testing

User-testing at Soapbox

The feedback of 7 participants was gathered at this location over two afternoons.

User-testing at Future Mind Exhibition

I had the opportunity to test the virtual studio during the Future Mind Event at Goldsmiths, London on 18 September 2017. A 3 x 3 sq m space was enough for people to experience the demo. 12 participants gave a range of comments and reactions about the prototype.

Dragon Hall Techday

The team from the Dragon Hall Trust, a charity that organises event for young children, set up a Techday event in June 2017 to give the opportunity to young people who would otherwise not usually have the chance to try out new technologies, such as robotics, 3D printing, VR and AR. With overall responsibility for the VR side of the event, I presented a prototype of my research. Of the 232 young people that participated, around 25 experienced the demo, and gave a positive overall feedback on the experience, based on the level of enthusiasm from all participants. This evinced that the application was robust and had potential.

4.5.3 Feedback

Here follows a list of comments, remarks and ideas collected along the many conversations with a wide range of people that tested the VR prototype. Each point will be addressed in the following chapter.

Presence and Room Scale Locomotion: participants reported a strong feeling of presence in the virtual room. They were always placed next to the physical table before putting the headset on. Once the virtual environment was loaded, they were able to grab the controllers from the table, which worked in both the virtual and physical environments following the mixed-reality principle. Most participants reported positive feedback for this feature. It acted well as an anchor between the two realities and reduced the disorientation than can occur in VR (cf. Riecke et al., 2010; Riecke and Schulte-Pelkum, 2015). The main structure of the layout consisted of three corridors. Because of the limited space available in the room, these were quite narrow (less than 90cm). Some people expressed a feeling of claustrophobia. Object manipulation was restricted at times.

Immersive User Interactions: participants' responses were positive to the sense of agency afforded by the object manipulation mechanism using the controllers. They enjoyed grabbing objects, observing them, and throwing them around. However, in regards to changing the layout, some issues arose using the three-dimensional menu attached to the left controllers. Participants found it difficult to find the correct angle of the controller with the menu. When reaching out with the right controller, most users could not access the desired cube easily because the cubes were positioned too close to each other. Often, the same room layout was loaded more than once. It was difficult to track in which room the participant was running the task.

Spatial Quality Rating Task: a series of potential implementations of the Spatial Quality Rating were tested (see Section 4.4.3).

1. From inside the IVE, a text to read: only two participants, from a total of 19 (between the two user-testing sessions), read the questions once inside the IVE. The HTC Vive display resolution did not allow enough precision for a comfortable reading experience.

2. Participant stay inside the IVE, and reply to the questions. This worked well. Asking questions orally seemed to be the most effective way to obtain real-time feedback from the participants. However, the timing of these questions remains problematic. Is it better to ask them as soon as they enter the room or at the end?

3. Participants wait until exiting the IVE before being asked the SQR from memory. This creates other challenges due to the complexity of being able to remember all the different rooms at once. It would not be practical to put on/remove the headset between each room.

4. *Cognitive3D, Exit Poll* tool allowed participants to complete a rating task from inside the IVE. Even though this tool looked promising, following the demo period, some difficulty in its implementation as well as the cost of the application led to a decision not to use it.

VSNA: using nine rooms represented too many conditions, over-complicating the experiment. A two-by-two experimental design would be more manageable.

PTT: this psychological test was supposed to provide a solution to test participants' capacity to imagine another point of view of a situation in their mind's eye. It required a specific protocol that was not implemented at the time of the demos for logistical reasons.

MRT: participants reported difficulties manipulating the three-dimensional figures with the controllers.

4.6 Findings and Conclusion

4.6.1 Findings of Research Goals

Prototyping and testing brought many insights into the design of the user-study experiment. This section summarises the findings for each research goal. The insights gained from these have been taken into account in the design of the main experiment (see Chapter 5).

G1: Define the spatial qualities of a room.
The use of isovists provides objective measures of the different spatial qualities of the built environment. Four spatial qualities were explained in Section 4.2.3. After testing and discussion, only two spatial qualities were selected: *complexity* and *openness*.

G2: Take objective measures of these spatial qualities.
Section 4.3.2 presents the two isovist descriptors that served to calculate the spatial qualities as follow:

- Spatial Quality *Openness*: Isovist Descriptor "Visibility"
- Spatial Quality *Complexity*: Isovist Descriptor "Visual Complexity"

G3: Test the effect of different architectural elements on these spatial qualities.
Table 4.1 shows all the measures taken for each room. Preliminary results were promising.

G4: Find a method to obtain subjective feedback about these spatial qualities.
The Spatial Quality Rating task was used to ask participants to differentiate their appraisal of the different spatial qualities using a five-step Likert scale. Asking questions orally to the participants while inside the IVE seemed the most promising way to implement this. Answers can be noted down in a spreadsheet. However, the optimal moment to ask the question still needs to be determined. Overall, users' feedback was encouraging. For instance, the difference in height made participants react strongly. They reported feelings of vertigo for the very high ceiling, or feelings of claustrophobia for the low ceiling.

G5: Implement immersive interaction like (a) room-scale locomotion, (b) changing layouts, and (c) physical interaction with task-related object.
As explained in section 4.4.1, all the room-scale locomotion functionalities were implemented. This was a testing, demanding phase to understand all the pros and cons of the different possible settings. For the purpose of this phase:

- (a) Room-Scale Locomotion was implemented successfully. Participants were able to walk around the room from corner to corner even though the HMD was tethered to a laptop.
- (b) Participants could experience different rooms by using the three-dimensional menu as shown in figure 4.8d. The menu was attached to one of the controllers. It did not work in the context of our experiment: users got confused about which room they were selecting.

- (c) Object manipulation. Users were able to grab objects by pressing the triggers of both controllers simultaneously. Then, they were able to manipulate, drop or throw the objects away. This increased immersion by giving a higher sense of agency to the user.

G6: Test different tasks and tools to measure users' spatial abilities.

- The Mental Rotation Task was not as promising as anticipated. It turned out to be a challenging dynamic to implement in VR. On the one hand, participants reported difficulties manipulating the three-dimensional figures with the controllers due to the learning curve (cf. Fox and Schubert, 2018). On the other hand, it would have required extensive programming skills to implement a task efficient in measuring users' performance. (Lack of feasibility in the context of this research.)
- The Perspective Taking Task was not implemented at this stage as it would have required more control settings than possible at the time of user-testing.
- The Virtual Spatial Navigation Assessment was a good example of a demanding spatial cognition task. However, some problems arose: if we wanted to test participants' memory performance on a sequence of items in each condition, either they would have to exit the IVE after each condition to recall the sequence, or they would have to recall each sequence one after the other, at the end. The first option would require only working memory. The second option would make it confusing post-experiment to recall different sequences from different rooms all at once.

4.6.2 Answering the research questions

The findings of this experimental research helped to provide some answers to the research questions. The following partial answers supported the implementation of the main experiment.

RQ2: How to evaluate the correlational relationship between architectural elements and spatial qualities?
The correlational relationship between architectural elements and spatial qualities was evaluated using a design iterative process. This process consisted of proposing the first design, then measuring the desired spatial quality by running the isovist. With the spatial quality variable calculated, any modifications to the model had an effect on the variable. This process was run in real-time using the software Rhino and Grasshopper.

For this research, two spatial qualities were selected and calculated using two isovist descriptors: *openness*, also known as visibility, was quantified by calculating the isovist area; and *visual complexity* was quantified using the perimeter length as measured by the isovist method. One problem encountered by this method is to obtain a value that could be used to compare different spaces, not just variation of the same layout. This will be explored in chapter 5.

RQ3: How do perceived spatial qualities correlate to those measured by isovist techniques?
This question relates to one of the main topics discussed earlier in section 4.2. On the one hand, spatial qualities were measured using isovists; on the other hand, participants gave their experience of these same spatial qualities on a rating scale (SQR). User feedback showed an overall consensus aligning their experience to the isovist measurements.

RQ4: What tasks can be implemented to evaluate the spatial performance of an immersive virtual environment?
In line with Montello, Golledge, and Org (1998) and Hegarty et al. (2006), three different scales were proposed to assess users' spatial abilities: *figural, vista, and environmental*. The MRT and the PTT turned out to be complicated tasks to implement in VR. Room-scale locomotion and immersive interactions were implemented with partial success to support the VSNA. A new proposition could be to merge both the scale of figural and environmental into one navigational task; instead of collecting gems, one could collect MRT-style figures. Then, to encourage participants to navigate the whole space, they could be incentivized to gather the figures in one place, and maybe to solve a puzzle. As for the vista and users' ability to remember and manipulate a spatial object/scene in the mind's eye, this could be implemented as a post-virtual experience task, which would lean towards a more memory-related measurement. These questions will be further investigated in chapter 5.

4.6.3 Summary

This chapter has offered insights into various aspects of the research project. Spatial analysis using tools like isovists and visibility graphs can be used to objectively evaluate specific spatial qualities, and to design different spatial layouts. Preliminary user testing showed promising results using a natural user interaction approach to design cognitive tasks, although, further development is still needed. It has also raised a number of issues that provide avenues for exploration, such as finding an adequate task to measure memory retention (see Figure 4.10.

Virtual Architecture Studio - Design Principles
Four constraints dictated the design of a general layout which would serve as the foundation of the different rooms. These constraints could become four design principles applicable to the design of the next iteration of the virtual studio.

1. **Flexibility:** to ensure the same experiment can be run in both locations and eventually anywhere else, the dimension of the virtual studio had to fit at least in the smallest of the two locations mentioned above, the smallest of these being 3.2m by 3.8m. A basic layout used repeatedly in architectural analysis and space syntax in particular is the 3x3m square cell "building" (Hillier and Hanson, 1984), also called a "perfect grid".

2. **Rotation:** using a square perimeter affords the rotation of any internal layout by 90 degrees so that the sequence of rooms can be randomised. By rotating or mirroring the rooms, the next room will propose a different layout.

3. **Trajectory:** each room has to offer the same distance to travel from the table to each item's location so that participants' time spent in travel are comparable.

4. **Line of Sight:** each space is composed of an interior perimeter corresponding to the physical room and delimiting participant locomotion and an exterior perimeter delimiting the participant's view. This is important, as even though confined in a limited physical space, the visible space can be increased virtually as much as necessary.

This chapter has provided the building blocks for the development of an appropriate method to design the IVAS that will be used for the main user study detailed and discussed in chapter 5.

Virtual Studio Prototype	VAga	Geometric Space	Experienced Space
	Design	**Architectural Design** Architectural elements tested: Columns round, square and twisted Walls straight and curved Ceiling height 1.8m, 2.2m and 5m	**Immersive User Interaction** Room-scale VR (HTC Vive) VR Locomotion: natural walking Hand controller interaction with physics Hand controller attached GUI
	Measures	**Spatial Qualities** Using isovists field technique Openess Complexity (Enclosure) (Spaciousness) (Order)	**Objective** Head and hands position Mental Rotation Task Perspective Taking Task **Subjective** Spatial Qualities Rating Open questions

FIGURE 4.10: Virtual Architecture Analysis Grid - Virtual Studio Prototype

Chapter 5

Immersive Virtual Architecture Studio - A User-Study

His vision crawled with ghost hieroglyphs, translucent lines of symbols arranging themselves against the neutral backdrop of the bunker wall. He looked at the backs of his hands, saw faint neon molecules crawling beneath the skin, ordered by the unknowable code. He raised his right hand and moved it experimentally. It left a faint, fading trail of strobed afterimages.

William Gibson, Neuromancer, 1984

5.1 Overview

This chapter presents the design and development of the Immersive Virtual Architecture Studio, hereafter IVAS, which is used to conduct a quantitative study comparing the effects of different architectural designs on participants' cognitive performances within the immersive virtual environment. A full VR application is built and detailed hereafter.

This user study comprised the evaluation of the effectiveness of two spatial qualities - *visual complexity* and *openness* - in relation with participants' cognitive performance enhancement. Although an open questionnaire was included, it was used as a secondary source of information to help understand some potentially unexpected results from the objective measures. To run this quantitative research-driven study, a set of distinct variables were isolated as independent variables, and two new cognitive tasks were implemented: a Navigational Puzzle Game and a Visuo-Spatial Memory Test. Two main types of analysis were used to evaluate the relationships between these variables:

a spatial analysis using isovist fields, and a statistical analysis based on a randomised within-subject experiment.

Explanatory Strategy: The research methodology is based on a sequential explanatory strategy. Following the insights acquired from the Archimemory experiment (Chapter 3), and from the Virtual Studio Prototype (Chapter 4), the design of the main user-study was driven primarily by a quantitative approach. However, some issues required further user testing and feedback before the user-study was fully operational. Also, after the experiment, participants' feedback was recorded.

The three research questions formulated in the previous chapter (Chapter 4) were mainly concerned with the "how?". The next step is to formulate different goals to complement the answers with evidence-based facts. In the context of this specific study, a new set of goals, and their hypotheses, are presented for each research question.

RQ2: How to evaluate the correlational relationship between architectural elements and spatial qualities?

- **G1:** Evaluate the correlational relationship between columns and visual complexity. **Hypothesis: added columns increases the level of visual complexity.**
- **G2:** Evaluate the correlational relationship between windows and *openness*. **Hypothesis: added windows increases the level of *openness*.**
- **G3:** Evaluate the interaction between the two. **Hypothesis: adding columns and windows produce changes in both levels of *complexity* and of *openness*.**

RQ3: How do experienced spatial qualities correlate with those measured by isovist techniques?

- **G4:** Do participants experience a higher feeling of openness with added windows? **Hypothesis: human perception of *openness* confirms results obtained by isovist measures.**
- **G5:** Do participants perceive more visual complexity with added columns? **Hypothesis: human perception of visual complexity confirms results obtained by isovist measures.**
- **G6:** Is there an interaction between the two? **Hypothesis: humans perceive *openness* as visually more complex.**

RQ4: What tasks can be implemented to evaluate the spatial performance of an immersive virtual environment? Following the previous chapter's findings, this question was divided into **RQ5** and **RQ6**. To help answer each question, a number of goals were presented with their corresponding hypotheses.

RQ5: What is the effect of a specific spatial quality on participants' spatial cognitive performances? Spatial qualities have been proposed in Section 4.2.3 and 4.3.3. Spatial cognitive performance refers to the theory of spatial abilities explained in Section 2.4.3, p. 34 (Montello, Golledge, and Org, 1998; Hegarty et al., 2006; Ventura et al., 2013). The term performance is used as the development of a metric, like Recall Accuracy used in Chapter 3, Section 3.4.1, p. 67. The main task to assess the effects is the Navigational Puzzle Game (see Section 5.2.2, p. 123). The following goals were set to answer the question:

- **G7:** Evaluate the effect of *complexity* on user performance. **Hypothesis: conditions in which the spatial quality *complexity* is higher, yield higher puzzle assembly time as participants have more spatial features to attract their gaze when navigating the room.**
- **G8:** Evaluate the effect of *openness* on user performance. **Hypothesis: conditions in which spatial quality *openness* is higher, yield lower assembly time, as participants have fewer features from the outside world to attract their gaze and slow their progression in the room.**
- **G9:** Evaluate the interaction between the two. **Hypothesis: there is an interaction effect between *openness* and *complexity* on participants' assembly time.**

RQ6: What is the effect of a specific spatial quality on participants' memory performances? The comparison between isovist measures and participants' visuo-spatial memory success rate will show a correlation between Spatial Quality and memory. The visuo-spatial memory task replaced the Perspective Taking Task and is explained in Section 5.2.3, p. 128.

- **G10:** Evaluate the effect of *complexity* on memory performance. **Hypothesis: the rooms in which the spatial quality *complexity* is higher, yield higher memory retention because of more memorable features.**
- **G11:** Evaluate the effect of *openness* on memory performance. **Hypothesis: conditions in which the spatial quality *openness* is higher, yield lower memory retention because of the lack of memorable features.**
- **G12:** Evaluate the interaction between the two. **Hypothesis: there is an interaction effect between *complexity* and *openness* on participants' memory retention.**

As a result, and to inform the answers to these research questions, the remainder of the chapter presents the design and evaluation of the IVAS. Its experimental design was divided into three phases: spatial design and analysis, the design of immersive user interactions, and the tasks.

5.2 Experimental Design

5.2.1 Spatial Design and Analysis - Geometric Space

Employing the four design principles laid down at the conclusion of the previous chapter (see Section 4.6.3) - *flexibility, rotation, trajectory, and line of sight* - a square of 3m by 3m was used as the main canvas with which to design the different rooms. An outer perimeter was also included to repeat the same interior features visually accessible through the windows. Before creating the rooms in full detail, however, a set of architectural elements was chosen to work with the selected spatial qualities.

Architectural Elements and Spatial Qualities

The selection of a first set of architectural elements to implement in the user study has been discussed (see Section 4.3.1, p.95). The elements selected were: wall, window, and column.

A wall is a fundamental element to create a room. It blocks the movement and the vision of an inhabitant. Columns can also be used to create space. The main difference between a wall and a column is that the latter delimits a space without blocking vision or movement, adding visual complexity to the space with edges and surfaces. Adding a window increases the openness of a room, by offering more visibility to the outside world; moreover, a window is an obstacle and increases the level of complexity slightly. Adding windows in the perimeter wall means that one can look through the windows to see what is outside. Therefore, something has to be present outside to introduce a point of focus. So practically, for this study, a few architectural elements, only visible through the openings (windows or between columns), were added to the layout. They replicated the same elements used in the internal perimeter, also called navigable space.

Two spatial qualities, *openness* and *visual complexity*, were selected among the four tested in the previous chapter (see Section 4.3.2, p.97).

Four Conditions, Four Rooms

Many draft sketches were necessary before finding a solution that encompassed everything learned so far. Figure 5.1 presents the sketches of the layouts used for this study. Figures 5.2 show views of the three-dimensional models taken from Unity (more sketches are presented in appendix D). The design of the rooms is based on two assumptions:

1. Adding columns increases the complexity of the room
2. Adding windows increases the openness of the room

The four layouts, based on a two by two design with two sets of two conditions, were as follows:

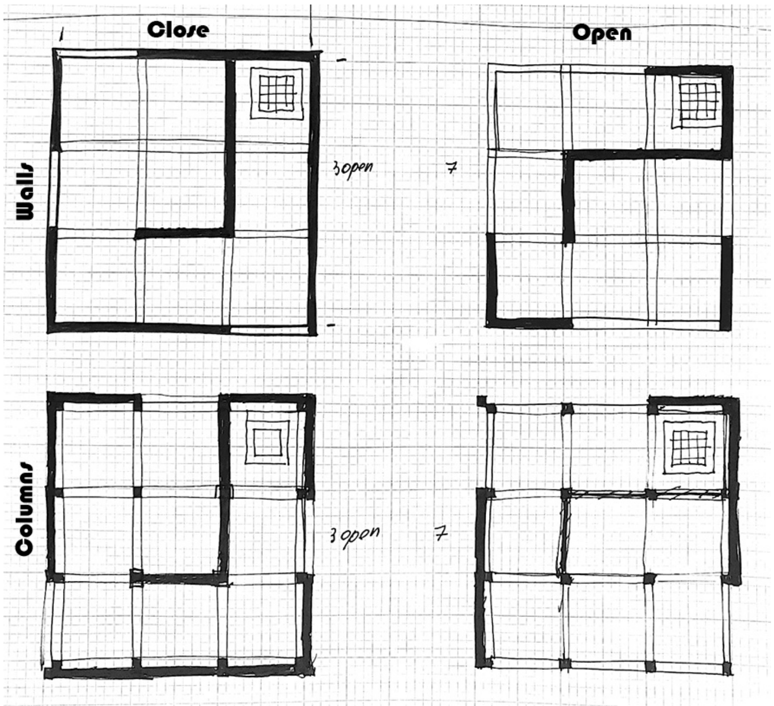


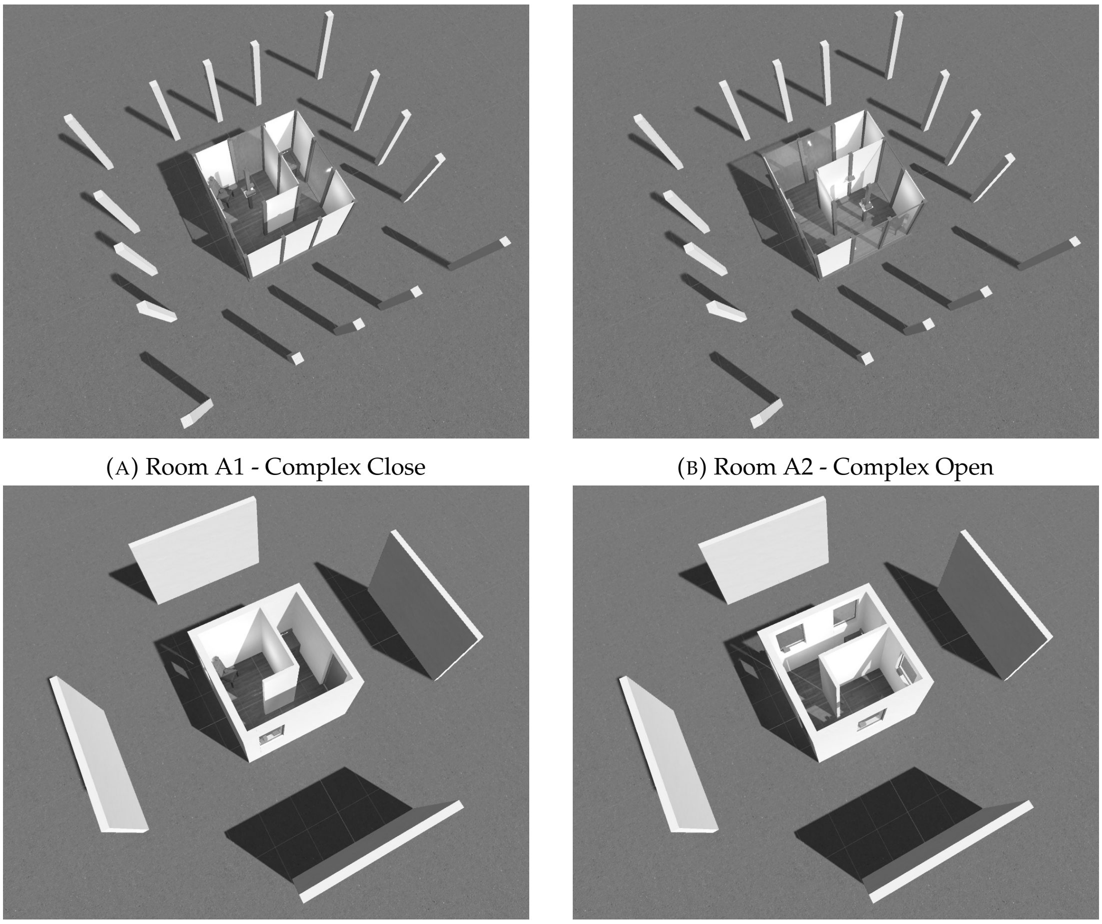
FIGURE 5.1: Sketch layout of the four rooms

1. Room A1 (ComplexClose): Walls and Columns (More Complexity) with fewer windows (More Close)
2. Room A2 (ComplexOpen): Walls and Columns (More Complexity) with more windows (More Open)
3. Room B1 (SimpleClose): Only Walls (More Simple) with fewer windows (More Close)
4. Room B2 (SimpleOpen): Only Walls (More Simple) with more windows (More Open)

Spatial Analysis with Isovist Field

In the previous chapter, spatial qualities were evaluated using a single isovist. The *generative design* workflow (see Section 4.3.2, p.96) is a fast and efficient method. It allows for a change in design and sees how variations in architectural elements properties affect different spatial qualities in real time. A new series of layouts were produced for this experiment, using the same method.

There was an essential difference between the layouts of the rooms used in Chapter 4 and the new series. In the latter, internal perimeter walls were fitted with windows, which afford participants an exterior view, providing a longer line of sight. Figure 5.3 presents a single isovist taken in one of the rooms. On the left, the isovist does not take into account the windows. The room is entirely enclosed, like the one from the



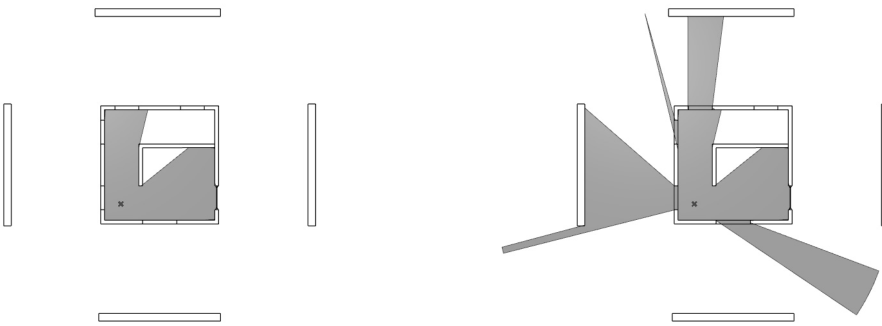
(A) Room A1 - Complex Close

(B) Room A2 - Complex Open

(C) Room B1 - Simple Close

(D) Room B2 - Simple Open

FIGURE 5.2: Perspective Views of the 4 Conditions



(A) One Single Isovist, interior only

(B) One Single Isovist with a radius of 900cm

FIGURE 5.3: One Isovist in Room B1 - Simple Open

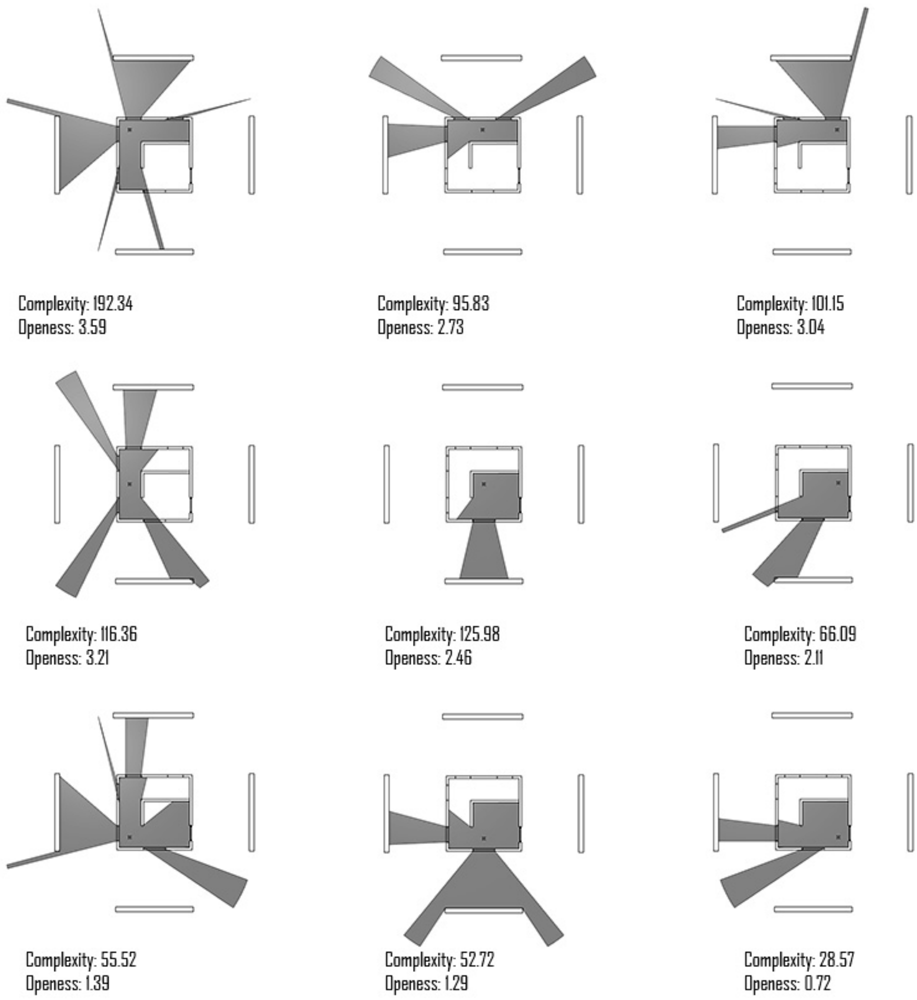


FIGURE 5.4: Nine Isovists for Room Simple Open

prototype. On the right (Figure 5.3b), the single isovist takes into account the windows, and extends the visibility into the external space of the room.

Inquiries into interior-exterior relations in architecture is an ongoing subject of research. Koch (2013) questioned how the arrangement of space can be facilitated through material boundaries and spatial connections. The intention of this experiment was to focus specifically on the way added windows affects one's experience navigating a small space. A window's intrinsic purpose is to offer a view between an interior and exterior. This also requires an external space to be defined and limited.

> It has been proposed that this 'limit' can be considered as when further addition no longer affects internal relative distribution of spatial measures inside the building, which also seems to consistently provide rather high correlations. However, exactly where this 'limit' is becomes a case of judgement,

and trial and error, and also becomes a problematic point for comparisons (Koch, 2013).

The purpose of the outside perimeter is multiple: it comprises the same architectural elements used in the room as shown in Figure 5.2; it shows that the virtual space does not have to be restricted to the physical space; in that way, the feeling of claustrophobia reported by some of the users in the previous experiment was reduced; more importantly, it permitted testing with a more significant range of the spatial quality of *openness*.

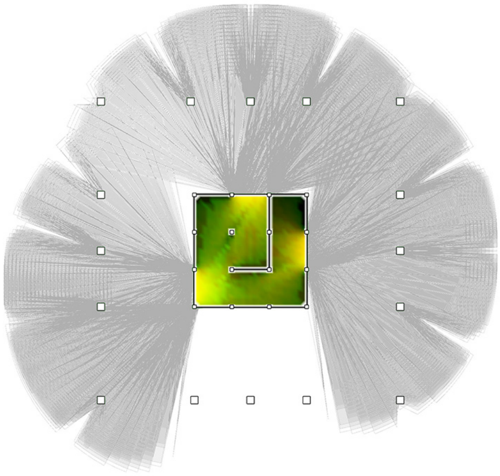
Using the generative design method, the architectural elements were placed at a distance that offered enough visual space, but still in range of sight. Consequently, the radius of the isovist was set to 900 cm so that it reached the outside perimeter from any internal point. If no surface was reached, it closed its boundaries following that radius. As Koch (2013) explains, this practice is not without problems as it works relatively to a specific design and can become a problematic point for comparisons between different buildings. However, following the design principles described above (see Section 4.6.3, p.111), the isovist measures obtained were consistent throughout the different layouts.

Once the layout complied with all the feedback and principles, a more advanced analysis was run, integrating a series of isovists. A test with nine single isovists looks like Figure 5.4. One single isovist is calculated from the centre of each one of the nine squares dividing the floor. Besides indicating the different possible views looking out the window from these specific locations, it did not provide a way to evaluate each spatial quality for the whole room. The *isovist field* was more promising in that regards (see Figure 5.5).

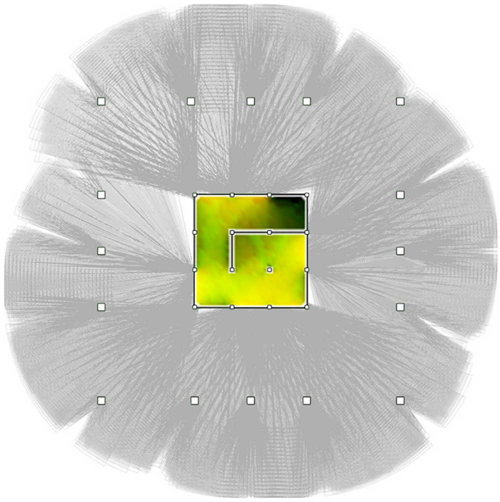
The *isovist field* is calculated by using a grid instead of a single point. The denser the grid, the more accurate the *isovist field*, but also the slower the computation. A grid with a total of 799 points, one every 10 cm (N=799) was found to be optimal to reduce computation time, but maintained sufficiently high accuracy for the visual to be readable. The shape of the grid follows the shape of the floor, subtracting any columns, thresholds or walls it crosses. The normalised value for each spatial quality is calculated by dividing the isovist descriptor value by the number of vertices (see table 5.1).

In Figure 5.5b, each room shows a very different visualisation of both spatial qualities, complexity and openness. Before zooming in to analyse what is happening in the internal space, it is worth noting the clarity expressed by the *isovist field* outside of the walls in grey. For instance, the most enclosed room appears straight away as in the bottom left image (Figure 5.5c) in contrast with the most opened room as shown in the top right image (Figure 5.5b).

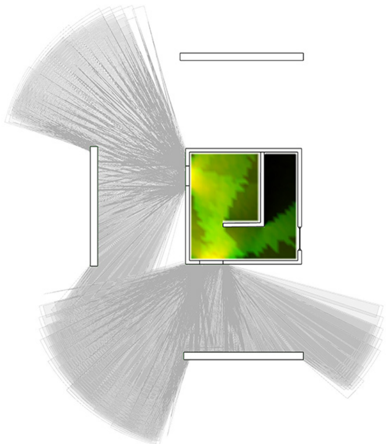
A test was also made with a *isovist field* limited to the internal space. Because of the similarity and intricacy of these small spaces, these measurements did not provide significant differences in regards to the level of *openness*. It does show a difference in



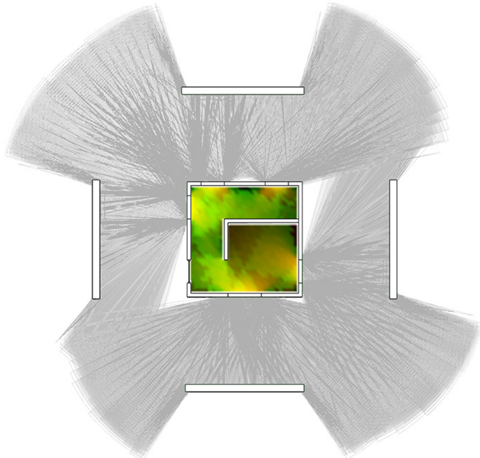
(A) Room A1 - Complex Close



(B) Room A2 - Complex Open



(C) Room B1 - Simple Close



(D) Room B2 - Simple Open

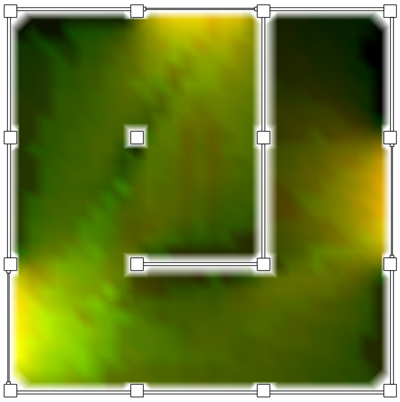
FIGURE 5.5: The Four Rooms Isovist Field

regards to the *complexity* of the space with a value of complexity averaging 0.44 for the rooms with the columns against a value averaging 0.39 for the rooms without columns.

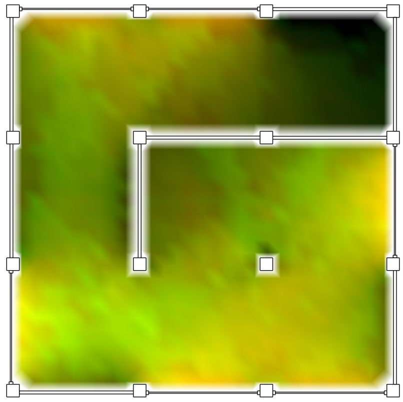
The interior visualisations (see Figures 5.6) show the *isovist field* taking into account the permeability of the internal perimeter. It offers a clear visualisation of the level of *openness* and *complexity* of the space.

TABLE 5.1: Isovist field and Normalised Openness and Complexity

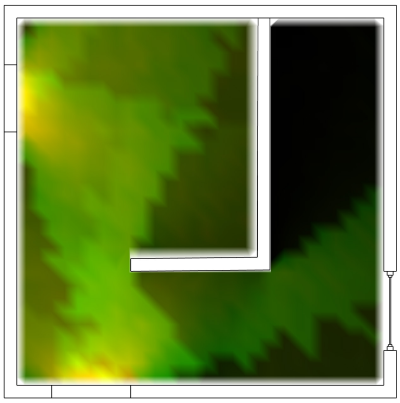
	Openness (sq cm)	Complex (cm)	Openness	Complex
A1 ComplexClose	105,050,000	2,315,900	0.31	0.40
A2 ComplexOpen	180,420,000	3,767,400	0.50	0.57
B1 SimpleClose	50,943,000	1,331,400	0.22	0.33
B2 SimpleOpen	96,380,000	2,280,100	0.31	0.40



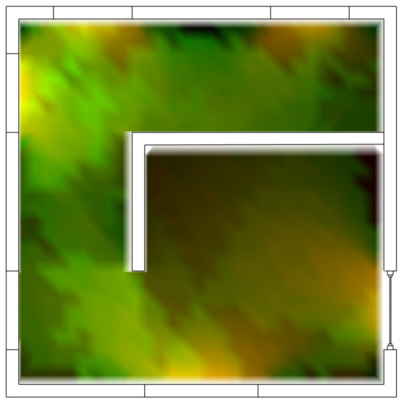
(A) A1: Openness: 0.31 - Complexity: 0.40



(B) A2: Openness: 0.50 - Complexity: 0.57



(C) B1: Openness: 0.22 - Complexity: 0.33



(D) B2: Openness: 0.31 - Complexity: 0.40

FIGURE 5.6: The Four Rooms with Internal Perimeter Isovist field

Interpreting the visualisations and the normalised level of spatial qualities: When looking at these visualisations using a gradient from light to dark, lighter regions of the floor plan are more open while darker regions are more enclosed, as measured by the area of the isovist generated at that location. Also, lighter regions have higher visual complexity, while darker regions have lower visual complexity, as measured by the length of the isovist's perimeter. When looking at the gradient in colour:

- Yellow areas (high red and green channels) are areas which are both very open and visually complex, for example, the area around the column in the top right room (figure 5.6b). This is related with the highest level, between the four rooms, of both *openness* with 0.50 and *complexity* with 0.57.

- Orangeish areas (higher red than green) are areas which are open but have lower visual complexity, for example, the main area in the bottom right room (Figure

5.6d)

- Darker yellow/mustard (higher green than red) are areas which are less open but have high visual complexity; for example, the area in the top left room behind the column (Figure 5.6a)
- Black areas (low red and green channels) are areas which are both very close and visually not complex, for example, the areas at the end of the corridor in the bottom left room (Figure 5.6c). This is conveyed by the lowest level of *openness* (0.22) and the lowest level of *complexity* (0.33)

The visualisation offers a real advantage over the use of numerical data to analyse the spatial qualities of the rooms. Indeed, both rooms, ComplexClose with the columns and SimpleOpen with the walls, show the same level for both spatial qualities (Openness: 0.31 and Complexity: 0.40). These two rooms are designed with different features. It shows that, by reducing a spatial quality to a one dimension variable, an isovist descriptor loses some information. However, the *isovist field* shows clearly the differences in how these spatial qualities come into play in similar spaces.

5.2.2 Immersive User Interaction - A Navigational Puzzle Game

Leaving aside the two factors (independent variables), the design of the dependent variable is considered. The main task focuses on the user experimenting the different spatial layouts in VR. To encourage participants to walk through the rooms, objects must be placed and interactions must be programmed. The key interactions and gameplay mechanics deployed to produce the main cognitive task of the experiment are detailed below.

The main event of this experiment is the Navigational Puzzle Game (NPG). Its primary focus is to evaluate users' spatial abilities. The task is a synthesis of a series of studies and video games design (Vandenberg and Kuse, 1978; Ventura et al., 2013; Murcia-Lopez and Steed, 2018). In a study investigating the potential of using VR to assess spatial abilities, Ventura et al. (2013) designed a virtual spatial navigation assessment. In line with their findings, NPG consists of a navigational task in which a user has to collect items, along their path. The design of the task, and the chosen items, was the conjunction of three well known designs: the Burr puzzle, Tetris (video game), and the Mental Rotation Task (Vandenberg and Kuse, 1978, see also Section 4.4.3). The exact origin of the Burr puzzle is unknown but it has been used effectively by Murcia-Lopez and Steed (2018) to compare virtual and physical training transfer skills . The popular video game Tetris, renowned for its addictive game play, was the overall inspiration for the design of the puzzle blocks. The design of these puzzles started with sketches as shown in Figures 5.7 and 5.8.

A series of colourful three-dimensional figures was designed, called blocks. They were based on a 10 cm sided cube unit. Each block had its own colour. The blocks were

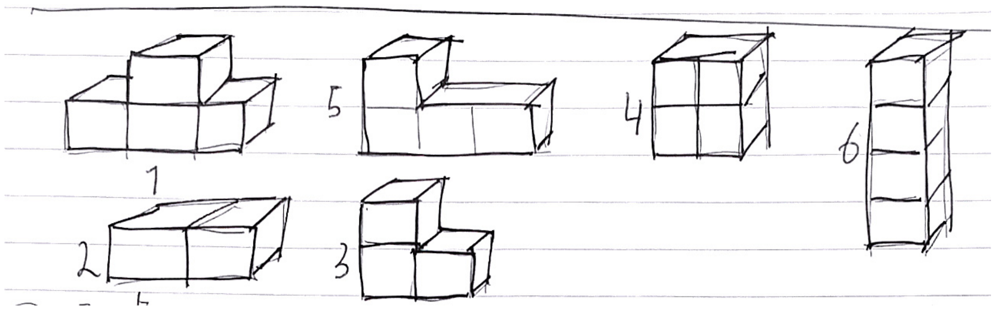


FIGURE 5.7: Tetris Shapes Inspired Sketches

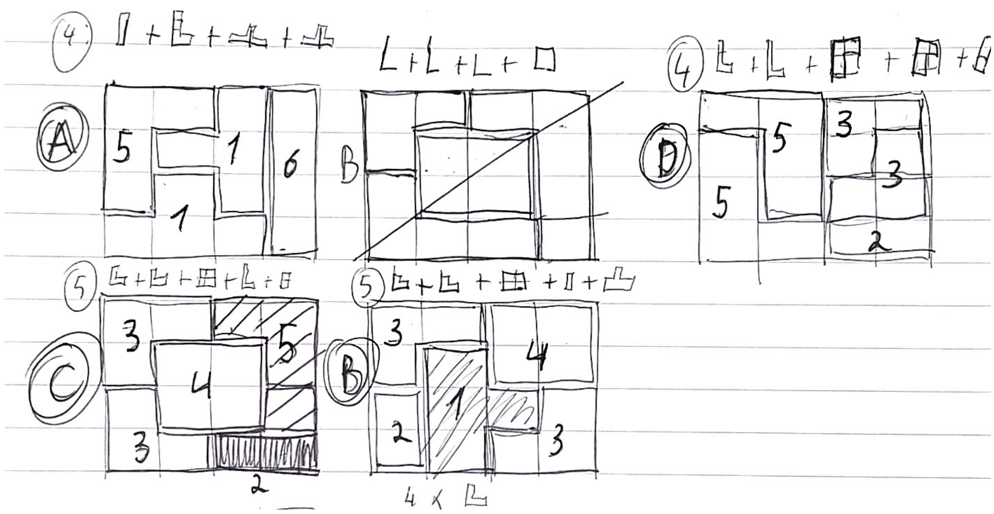


FIGURE 5.8: Puzzle Layout

placed around each room in different locations, either on the floor or on the window sills. Only the combination of all the blocks placed flat in a way that fitted in the horizontal surface on the table allowed participants to access the next room.

A series of virtual props was designed to bring structure to the task. A starting mechanism was designed to give participants control of the commencement of the task. It was made of a red cube-key block and a green U-shape block. Once inserted into the green U-shape block, the red cube-key block became green as well, announcing the start of the timer to complete the NPG. Both items were set on a chair that was located at the maximum possible distance from the table, in a corner of the room. The purpose for this was to encourage participants to explore the room before starting the task. The table served as an anchor, and starting position, for the user in each room. Both the chair and the table had their physical equivalent co-located at the same position of their virtual counterpart, in a mixed reality approach (see Section 4.3.1, p.95).

Task Objectives

1. **Increase sense of presence:** the table and the chair served as an anchor in the physical world as well as in the IVAS, mixed-reality prop (see Section 5.3.1).

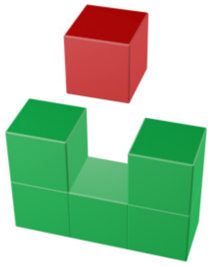


FIGURE 5.9: Starting Keys

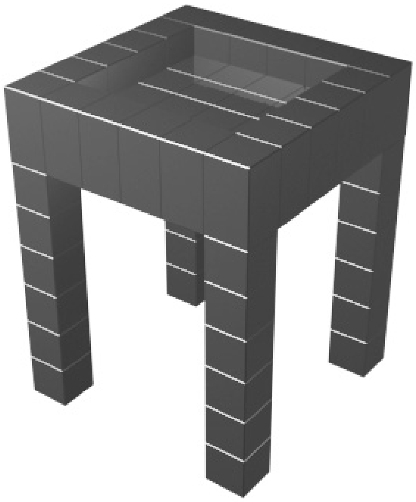


FIGURE 5.10: Reset Table

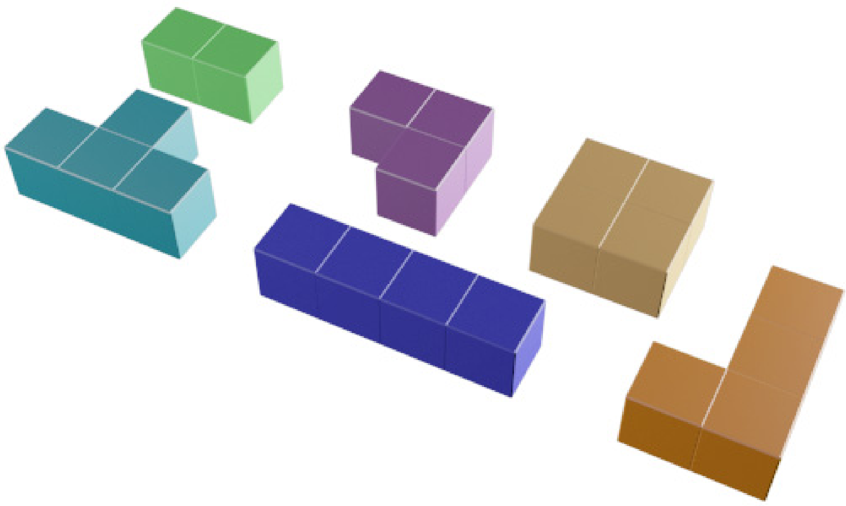


FIGURE 5.11: 3D Tetris Blocks

2. **Navigate equivalent distance:** the chair was located at the maximum distance possible from the table to encourage the participant to cover the best part of the layout. Having to pick up the items at specific locations ensured each participant

covered an equivalent distance.

3. **Address the dual processing theory:** subjects were required to focus their attention on solving a puzzle made of objects on a table, and not paying attention to their surrounding specifically. Following the dual processing principle, it is assumed that the spatial information about the environment was evaluated as a secondary process (see Section 2.4, p.25).

4. **Measure user performance** completing the task.

5.2.3 Tasks and Performance Metrics

The main task was the NPG, preceded by a Free Exploration mode to give every participant the chance to familiarise themselves with the layout. The third task was a visuo-spatial memory test to assess memory retention and vista spatial ability. Before going into the description of each task, a series of performance metrics are defined.

Performance Metrics

Metrics are used in different industries, in a wide variety of situations, depending on what types of performance need to be assessed: from an employee or company productivity point of view, looking at the efficiency of a system, or how to improve the design of a task or a product.

Different industries approach performance metrics with slightly different methods. The two main influences were from user experience (UX) design and supply chain productivity. UX designers base performance metrics on users' behaviour rather than what they say. Participants' subjective experience will be assessed with different measurements (see Section 5.2.4). Tullis and Albert (2013) propose five types of performance metrics: task success, time on task, errors, efficiency, and learnability.

- **Task Success Rate**: can be used to know if users are able to complete tasks using the product. It can be used to look at whether a user is successful or not, based on a strict set of criteria.

- **Time on Task**: to measure how quickly users can perform a task. It can also measure the proportion of users who can complete a task within a desired time limit.

- **Errors**: based on the number of mistakes users make while attempting to complete a task. A task might have a single error opportunity or multiple error opportunities.

- **Efficiency**: to evaluate the amount of effort (cognitive and physical) required to complete a task in a specific context. Efficiency is often measured by the number of steps or actions required to complete a task or by the ratio of the task success rate to the average time per task.

- **Learnability**: involves looking at how any efficiency metric changes over time. Learnability is useful to examine how and when users reach proficiency in using a product. It will not be used in the scope of this research as it would require longer exposition to the virtual experience, requiring 5 to 10 opportunities for each participant to repeat one task in each condition/room.

In chapter 3, card cycle time (the duration of a process) was used to compare users' performance between the two different memory palaces. The next step is to evaluate the system performance efficiency of each room with regards to a specific task. Indeed, the main research question is how to enhance user performance by developing a more adapted spatial environment.

Performance efficiency is used in many industries as a way to define the performance of a worker, a machine, or a system. For instance, a factory robot performance efficiency can be defined by the number of tasks complete, multiplied by the average task cycle time, divided by the total amount of time taken to complete the tasks. This could be measured for each participant. However, this project is more interested in the performance efficiency of the virtual environment with regards to the NPG, or the spatial performance efficiency.

Free Exploration Mode

The main idea behind this first task is for the user to familiarise oneself with the new environment. Participants have the opportunity to explore each new room, with no time pressure, before commencing the main task.

Navigational Puzzle Game

The NPG, described above, was the main means by which participants' performance inside the IVAS was measured. In this particular design, one had to assemble a puzzle in one room to access the next one. Neither task success rate nor errors were relevant, as the task had to be completed to activate a new room. The main measure was the time to complete the puzzle in each room, or Cycle Time κ. As an incentive to perform faster, a timer was visible on the table where the blocks were assembled. **Performance efficiency** P is defined as the ratio of the number of completed tasks (NPG) multiplied by the average cycle time K to the total time T to complete all the tasks.

$$P = Tasks * K/T$$

Visuo-spatial Memory Test

A two-alternative forced-choice (2AFC) approach was adapted to evaluate visuo-spatial memory. This type of experimental design is commonly used to test speed and accuracy of choices between two alternatives given a timed interval. It was developed by Gustav Theodor Fechner (1889) and has been used since as a standard to test animal and human behaviour. In well-cited study on cognition that examines the attention in the visual space, the designed task uses a 2AFC approach to present two stimuli representing two given locations (Posner, 1980). A threshold of 75% of correct responses has been demonstrated over many experiments.

A more advanced test could have been used to assess visuo-spatial memory, such as the Brief Visuo-spatial Memory Test - Revised (BVMT-R) that has been commonly used to evaluate visuo-spatial memory abilities in neuro-psychological populations (Benedikt, 1997). However, this kind of test requires a multiple exposition and response from the participants at time intervals, which was not possible logistically in the context of this research project.

Some adaptations were applied in the context of this experiment to develop the Visuo-Spatial Memory Test (VSMT). To test memory retention without using short-term memory (cf. Miller, 1956), a certain lapse of time has to run between the exposure to the stimuli, that is, the virtual environments, and the memory test. Because it is not practical to enter and exit VR to run a memory test after each room, the test was given at the end of the experiment. Once the HMD was removed, participants had to answer a few questions as part of the questionnaire (see below, Section 5.2.4) before completing the task. The main purpose was to measure the memorability of each room. A series of 16 pairs of images were created. For each pair, one of the images was taken from one of the explored room and the other image was taken from a room not visited, although very similar in layout. One had to identify which image related to the scenes one had experienced. The pairs of images were displayed on a desktop monitor (two sample pairs of images are shown in figure 5.13). The 16 pairs of images are shown as thumbnails in figure 5.12 (the 16 pairs can be found in higher resolution in Appendix D.5). Results were noted down in a spreadsheet during the experiment.

5.2.4 Subjective Measures

Spatial Quality Rating

The spatial analysis can be confirmed (or not) by using an equivalent evaluation from a human experience self-reported measure. Evaluating *lived space* can be done by asking participants to rate their experience for each spatial characteristic. Wiener and Franz (2005) suggested a similar approach to human subjective experience. Using a semantic differential scaling technique, subjects were able to differentiate their appraisal using

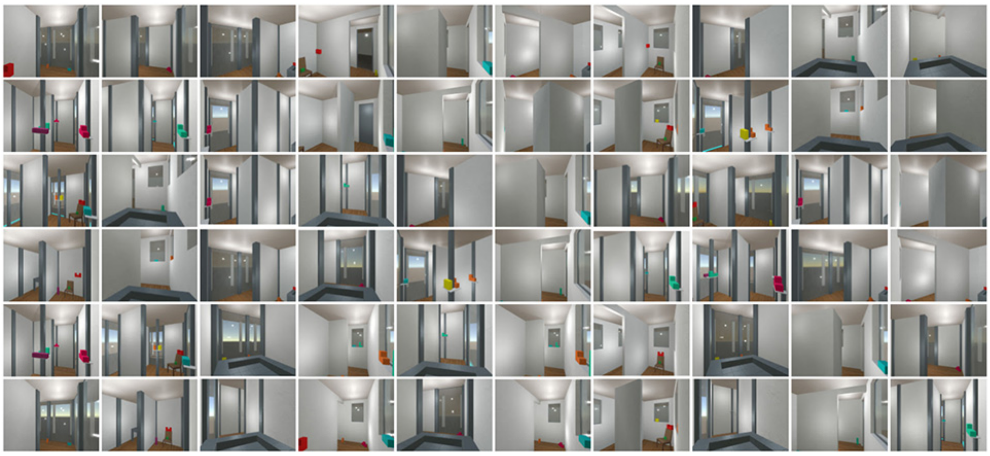
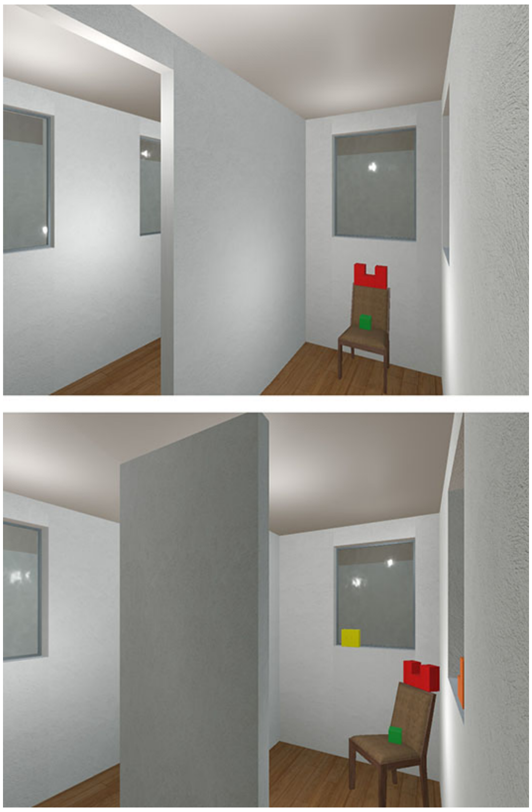


FIGURE 5.12: Visuo-Spatial Memory Task - the 16 pairs of images



(A) Visuo-Spatial Memory Task - 4AB pair 03

(B) Visuo-Spatial Memory Task - 4AB pair 11

FIGURE 5.13: Visuo-Spatial Memory Task - Images Sample

a five-step Likert scale. The rating categories were selected to represent previously mentioned properties: *openness* and *complexity*.

Questionnaires

The questionnaire had two purposes: gathering information about participants' backgrounds, and distracting them for long enough so that they would not use their working

TABLE 5.2: Spatial Quality Likert Rating Scale from 1 to 5

Spatial Quality	1	2	3	4	5
Openness	Very Open	Open	Neutral	Close	Very Close
Complexity	Very Simple	Simple	Neutral	Complex	Very Complex

memory to complete the last task. There were five questions, of which two had the potential answer on a linear scale from 1 to 5, one question used multiple choice, and two were open:

- How much experience do you have playing video games? On a linear scale from 1 to 5 from no experience to playing every day.
- How many times have you experienced Virtual Reality? Multiple Choice: Never, Once or Twice, many times, every week or every day.
- How immersive would you scale your experience? On a linear Scale from 1 to 5 from not immersive to fully immersive.
- Could you describe in a short paragraph how you felt when you were experiencing the IVAS today? Open question.
- Here is a good place for any questions, comments or suggestions you might have. Open Question.

5.3 Materials and Method

5.3.1 Materials

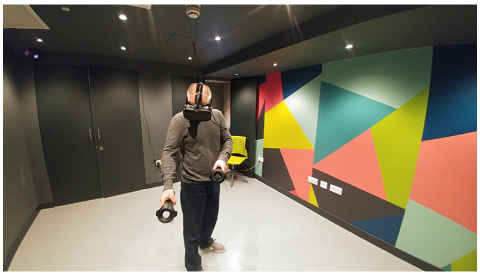
Physical Locations

The study was conducted at two different locations (see Figure 5.14):

1. **Location A** Goldsmiths, St James, Hatcham House, London, the top floor where the available space in the room measures 3.5m x 4.2m
2. **Location B** Soapbox, 238 Old Street, London, VR room, where the dimensions of the room measure 3.2m x 3.8m.

The motivation of having two different locations to run the experiment was to attract a wider variety of people. Usually, experiments that are set in universities attract mostly students, which creates distributional bias towards a specific group. The following VR system specifications were set up similarly in both locations with minimal differences.

(A) Location A



(B) Location B

FIGURE 5.14: IVAS - Two Locations

Implementation

The three-dimensional models designed for this experiment were created first in 3Ds-Max, then imported into Unity3D, the main software used to produce the VR application. All the behaviours and interactions were designed with Unity 3D (see Figure 5.15). A series of custom-made scripts were programmed in CSharp: one to describe the "start button"; one to describe the collisions between blocks and table; another one to collect the positional data as well as timestamps.

Collision with Button

```
Get parents Component
DataCollection
    Function OnTriggerEnter(Collider collision)
    if (collision.gameObject.name == "startKey")
        dc.isStart = true;  //Set the start button enabled
        this will trigger the Task script to run
```

Collision with Item

```
clc = new Collection
Function OnCollisionEnter(Collision col)
clc.onCollision (col)
```

Data Collection

```
Interval at which the User's position will get recorded
Last recording time
userNum
Update is called once per frame
```

```
        if Start /// 2 Minutes of free will exploration
        fname = "Free.csv"
        else
        fname = "Task.csv"
    Record and write the user position in a file
    userActivity/UserNum.txt
    Function initVariables
        interval = 0.25f
        timeFreeWillExplore = 120.0f
        lastTime = curTime
        isStart = false
    Getting current loaded Scene information
    Write the current Scene name
```

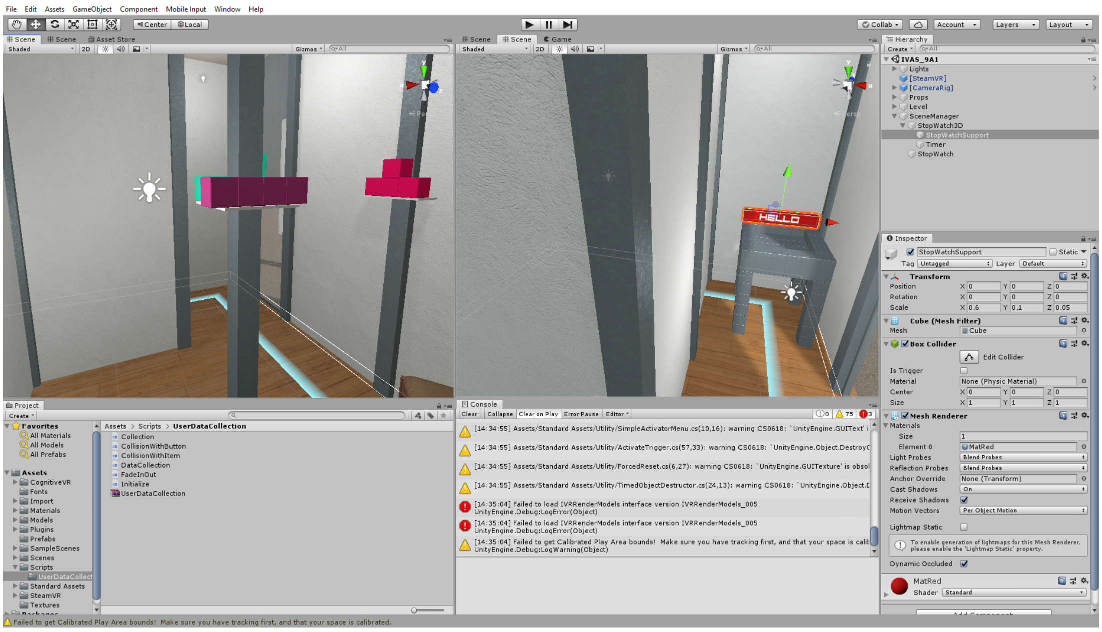
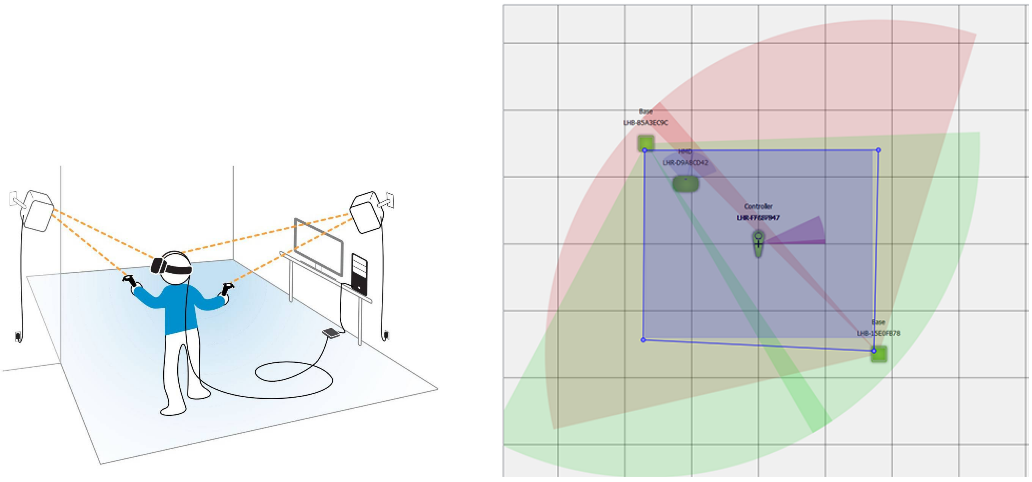


FIGURE 5.15: **The IVAS in Unity.** This image is a screen capture taken from Unity to show the different elements involved in the programming of the IVAS. A couple of blocks used to solve the NPG are present in the scene on the left. The table on which the blocks are gathered is shown on the right. The red shape with the word "Hello" is where the timer is displayed during the task.

Room-Scale VR Specifications

The VR system was composed of an HTC Vive head-mounted display (HMD); two wireless hand-held controllers; two 'Lighthouse' base-stations that track user's head and hands movements, with accuracy at a refresh rate of 90Hz. The device uses two screens, one per eye, each having a display resolution of 1080x1200 and a field of view of about 110 degrees. This system offered the best VR experience commercially available at the time of testing in 2017. It was tethered to a laptop computer Dell Alienware 15r3 equipped with an Intel i7-7820HK, 2.90GHz, dual-core processor, 16 GB of RAM and an Nvidia GeForce 1070 graphics card.



(A) HTC vive Setup (B) Room Scale Calibration, HTC Vive

FIGURE 5.16: How to setup and calibrate the HTC Vive System

The range of locomotion of the room scale VR is dictated by the position of the two lighthouses that track the HMD and the controllers' movements. The two lighthouses are placed as far apart as possible in opposite corners of the available space (see figure 5.16). At location A (Hatcham house), one lighthouse was placed on top of a shelf, the other was mounted on the opposite wall; at location B (Soapbox) they were hooked to the ceiling. In both configurations, the floor was free of any object apart from the "reset table", and the cable linking the HMD to the laptop.

The cable is the main limiting factor of the installation, as it gets in the way of the person immersed in VR. It can break the "place illusion" and reduces the feeling of presence as it reminds the user of the physical world (see Section 2.5.3, p.42). However, because only perceptual, the "place illusion" is only temporally broken. The cable was hooked from the ceiling to reduce the friction. During the experiment, I also followed the participants' movements closely and when necessary moved the cables to avoid participant interaction.

Perimeter Wall Calibration: The ideal settings would be to have a three-dimensional model following the same dimensions of the physical location as the boundary of the virtual environment. However, adhering to the first design principle of flexibility (see Section 4.6.3), a standard model of 2.6m x 2.6m was designed to adapt the experiment easily between the two locations. In that way, a minimum of two of the contour walls in VR can be aligned to the real walls of the room. When the user reaches a virtual wall and tries to touch it with the controller, he or she would feel the actual wall. Using a standard model to fit in different rooms had downsides. The calibration was far from accurate. At least two virtual walls did not correspond with the real walls. A more accurate calibration would improve the illusion of place.

Table Calibration: The table was another key feature of this experiment, serving multiple purposes. It was the starting point, when entering the VR environment for the first time. Participants also picked up the controllers from the table. They had to stay close to the table once the puzzle was solved because it was the only object that remained at a constant point when the next room was loaded. Moreover, when they touched the table in VR with their controllers, they were also hitting a real table. Aligning both table, virtual and physical was straightforward once wearing the HDM. Overall, it increased the level of presence perceived by participants.

5.3.2 Participants

A total of 35 participants (26 male, 9 female; average age 33.34 years, *SD*=10.92) were split between the two locations with 19 participants at Hatcham house, and 16 at the Soapbox [1]. Participants at the former were mainly computing students with experience of playing video games. Those at the latter had diverse educational backgrounds and had almost no experience with VR. More details on participants' backgrounds are detailed in the questionnaire section further down.

5.3.3 Procedures

This section describes the user-study procedure step-by-step. Figure 5.17 shows an outline of the experimental task.

1. **Online Consent Form + Instructions:** at the beginning of the session, participants were asked to sign an online consent form, to read an information sheet with written instructions describing the experimental task and to fill in a background questionnaire (see Appendix E.1).

2. **Start of Virtual Experience - Tutorial:** once the participant puts on the headset, they can take the time to familiarise themselves with the different levels of interactions. By walking around and grabbing (trigger button with the index finger on either or both hands) the different Tetris shapes, they will be able to complete the first puzzle by filling the surface on the table.

3. **Transition:** once the puzzle is solved, the participants find themselves in a neutral environment - the transition area. The only thing remaining is the wooden floor

[1] Comparing the effect of gender difference is not part of this study; however, enough studies support gender-related differences in visuo-spatial ability Bosco, Longoni, and Vecchi (2004)

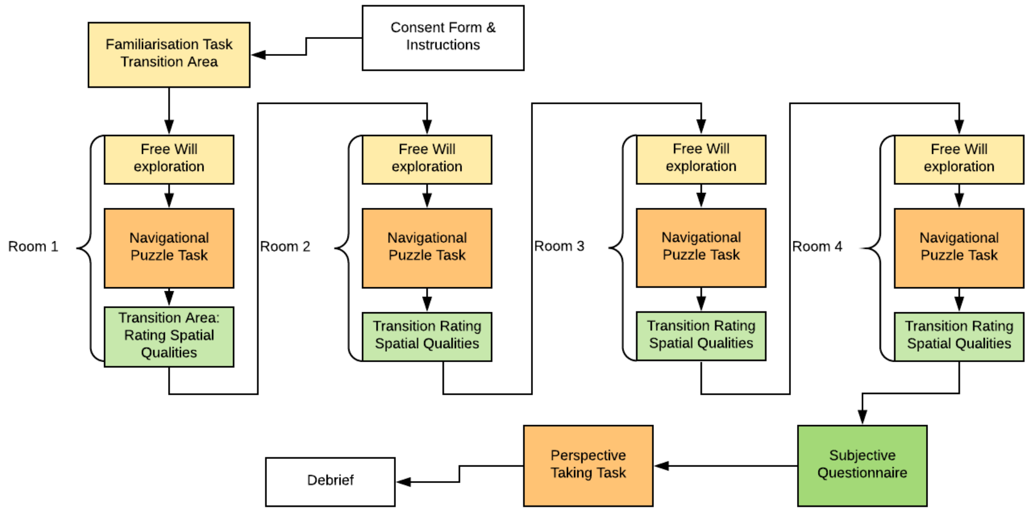


FIGURE 5.17: Overview of the Experimental Procedure

and the table, next to which the participant should remain. A countdown timer sitting on the table shows how many seconds remain before the new room is loaded.

4. **First Room:** once the first room is loaded, the participant is in exploration mode, at which point they should have a good look around to find their way. When they feel comfortable and ready to proceed with the NPG, they have to find the green cube and place it in the U-shape starting key holder. As soon as the key holder turns green, the stopwatch sitting on the table commences. The participant has to collect all the Tetris shapes and solve the puzzle by fitting each one of them in a certain position so that it fills up the horizontal grid positioned flat on the table.

5. **Transition - SQR:** once the NPG is solved, the environment resets to the *transition area* for 40 seconds, during which time I ask the questions about spatial qualities. Participants have to answer on a scale from 1 to 5. I take note of their answers on a spreadsheet. The next room loads as soon as the time is up.

6. **Repeat last two steps for each room - four times**

7. **End of Virtual Experience:** once participants have replied to the last couple of questions, they can then leave the VR experience by leaving the two controllers on the table and removing the HMD.

8. **Subjective Questionnaire:** participants are asked to come back in front of the screen to fill in the subjective questionnaire. It serves as well as a spacer and a diversion before the last memory-related task.

9. **Visuo-spatial Memory Test:** still in front of the screen, participants have to run through the VSMT. Their answers were noted on a spreadsheet.

5.3.4 Generalisation, Ethics, Limitations and Validity

This chapter has thus far described the set of tools that were used to measure spatial qualities and to evaluate how they affect a user's performance completing a cognitively demanding task. Spatial analysis method like *isovists* and *isovist fields* were used to support the numerical evaluation of the independent variables, that is, room *complexity* and *openness*.

The dependent variables were extracted from three different tasks. The first was the time taken to explore each room. The second was the time taken to perform the NPG in each room. The third was the accuracy of recognition, identifying which image originated from each of the experienced rooms. The SQR gave a subjective feedback using a rating five-step Likert scale. A final questionnaire completed at the end of the experiment served to collect information on participants' backgrounds and feedback on their experience.

Generalisation

Differences between people with experience of playing video games and VR, and those who do not, were found in questionnaire answers. Understanding the effect of this experience on their ability to perform the task was not evaluated in this study. However, with the concept of natural interaction motivating the design of the experiment, a short learning curve for each participant to get used to the VR system was expected, regardless of the participant's background. It was also noticeable that young participants acquired the necessary skills faster than older ones. With participants representing a range of all ages, and genders, it was expected that results could be generalised to a broader range of the population.

Ethics

An ethical approval form was submitted to the College Research Ethical Committee, which agreed to the present experiment. Each participant filled in the consent form as per Appendix E. The form explained the risk of the experiment, as well as matters of confidentiality and protection of data.

Limitations

As with the majority of studies using VR, the design of the current study is subject to limitations. New types of human-computer interaction require new user-experience design, which is time-consuming to develop. Even more importantly, there is a lack of previous research studies specific to the evaluation of the effect of spatial design on user performance in VR.

The existing studies used a variety of hardware setups, pre-dating the recent wave of more affordable immersive VR systems released since 2014. As such, most of the experimental design had to be imagined and tested with the new hardware. VR requires a lot of different components to be taken into account in order to obtain a valid experimental design. As a part-time PhD student, my time was quite limited, so I had to reduce the number of variables and conditions to be tested to ensure the project was manageable. The consequence is a limited range of architectural elements tested with only two spatial qualities.

The limited time available also had an impact on the number of participants in the experiment. Each participant needed approximately an hour to run through the presented protocol. 35 participants offers only a limited range of individual variability, which can limit the potential to generalise the findings and extrapolate onto the wider population. However, having the opportunity to run the experiment in two different locations, attracting different profiles of participants, helped to mitigate the cultural bias.

Validity and Confounding Variables

One of the aims was to limit the amount of confounding variables. As a field of investigation, VR is still in its infancy. A wide variety of parameters have to be taken into account when using such a multi-modal medium to simulate reality. Many more trials and errors will be necessary before it reaches maturity.

Confounding variables were limited by starting with a simple experimental design to establish a valid framework to build upon. Then, once this proved to work as a controlled and reliable tool, more conditions could be added, such as other architectural elements and features, on the one hand, and experimentation with different cognitive tasks, on the other.

5.4 Results

This section presents the data collected and subsequent analysis. The process of collecting, managing and analysing each set of data is explained in details. The correlation between the data is explored in the following discussion section.

The first and second set of data were collected during the Free Exploration Mode and the Navigational Puzzle Game (NPG) using the same method. The data collected for the Visuo-Spatial Memory Test (VSMT) were collected post-VR experience, and are addressed in the third section. Next, the subjective evaluation from the Spatial Quality Rating (SQR) is analysed. The appearance of the rooms during the experiment is randomised to reduce the bias that would result from the order in which the rooms are experienced. Indeed, because of the learning curve, if every participant set out from the same room, following the same sequence of rooms, they would perform more slowly in the first room. This would reduce the validity of the measure taken in that room. Randomised was preferred over counterbalancing because, without knowing the number of participants ahead of starting the experiments, it would have been difficult to create groups of equivalent size. Randomness was integrated into the software. Each set of data is unified, and additionally put back in order to have all the data organised per conditions.

From that data, two different analyses were produced: the first one looks at the data taken in the randomised conditions (rooms in random sequence) as experienced by each participant; the second analysis looks at the data for each room (condition) to understand the effect and interaction of the two spatial qualities.

The tables of raw data, created with Google Sheet, were then imported into the software SPSS to run a statistical analysis. Next the raw data were plotted either into Google Sheet or BoxPlotR [2] to produce the graphs (Weissgerber et al., 2015). The last set of data comprised all the replies to the questionnaire.

The main objective of the Free Exploration Mode was to familiarise users with the different rooms before having to focus attention on the task at hand. By doing so, participants were already building a representation of the space in their mind's eye, which meant they would not be confronted with an unfamiliar environment (see Section 2.4.3), when asked to complete the NPG.

Two different nomenclatures were used to discuss the rooms: "Room" is followed by a number (like in "Room 1") when talking about rooms experienced in random sequence, or "condition" is followed by its characteristics (like in condition Complex-Close). Thereafter the following terminology will be used:

- ComplexClose: Walls + Columns with few Windows
- ComplexOpen: Walls + Columns with more Windows
- SimpleClose: only Walls with few Windows
- SimpleOpen: only Walls with more Windows

Data Processing

The type of data collected during these two tasks is time taken to explore each room and participants' position encoded every quarter of a second. The data were saved in a CSV file for each user and each room. Every quarter of a second a line following the format, "(x,y,z) mm/dd/yy hh:mm:ss", was added to the file. For the Free Exploration Mode, the time stamp was collected as soon as a new room was loaded, and ended when the NPG started. For the NPG, the time stamp was activated when the participant entered the *starting key* in the *starting slot* (see description in Section 5.2.2). The elapsed time in each room, as experienced by users in random sequence, was extracted from the CSV files and inserted into a Google Sheet table (see Appendix E).

[2] BoxPlotR is a web-based tool develop using SHINY app (Spitzer et al., 2014)

A second table was then created to rearrange the timestamps for each room, organised by condition. The first column shows time spent in room ComplexClose, the second in room ComplexOpen, the third in room SimpleClose, and the fourth in room SimpleOpen. Both tables were processed to be imported into SPSS, as they lead to two different analyses: rooms in random sequence and rooms per conditions.

5.4.1 Rooms in Random Sequence

Free Exploration Mode: the descriptive statistics are presented in table 5.3 with the mean and the standard deviation for each room as experienced in random order by the 35 participants. The mean time spent exploring the first two rooms is around 31s, with 30.24s in Room 1 and 31.50s in Room 2. The mean time goes down in the next two rooms with 21.28s in Room 3 and 20.62s in Room 4.

TABLE 5.3: Free Exploration Time Random Seq. - Descriptive Statistics

	Mean	Std. Dev.	N
Room1	30.24	10.85	35
Room2	31.50	15.73	35
Room3	21.28	7.37	35
Room4	20.62	8.20	35

A repeated measures ANOVA with a Greenhouse-Geisser correction determined that mean time differed statistically significantly between rooms ($F(2.30, 78.50) = 15.27$, $p<.05$). Post hoc tests using the Bonferroni correction revealed that the mean time spent exploring Room 3 and 4 is reduced in comparison with the two first rooms with a statistically significant effect ($p<.05$). Note that there is no effect between the two other pairs of rooms ($p=1$).

Navigational Puzzle Game: participants' task completion time was used to measure their performance (see Section 5.2.3). The only type of data used for this task is the time taken to complete the puzzle in each room. Table 5.4 presents the descriptive statistics with the mean and the standard deviation for each room as experienced in random order by each participant.

TABLE 5.4: Navigational Puzzle Game Completion Time in Random Seq. - Descriptive Statistics

	Mean	**Std. Dev.**	**N**
Room1	76.86	29.69	35
Room2	63.22	22.29	35
Room3	56.95	24.03	35
Room4	60.88	27.89	35

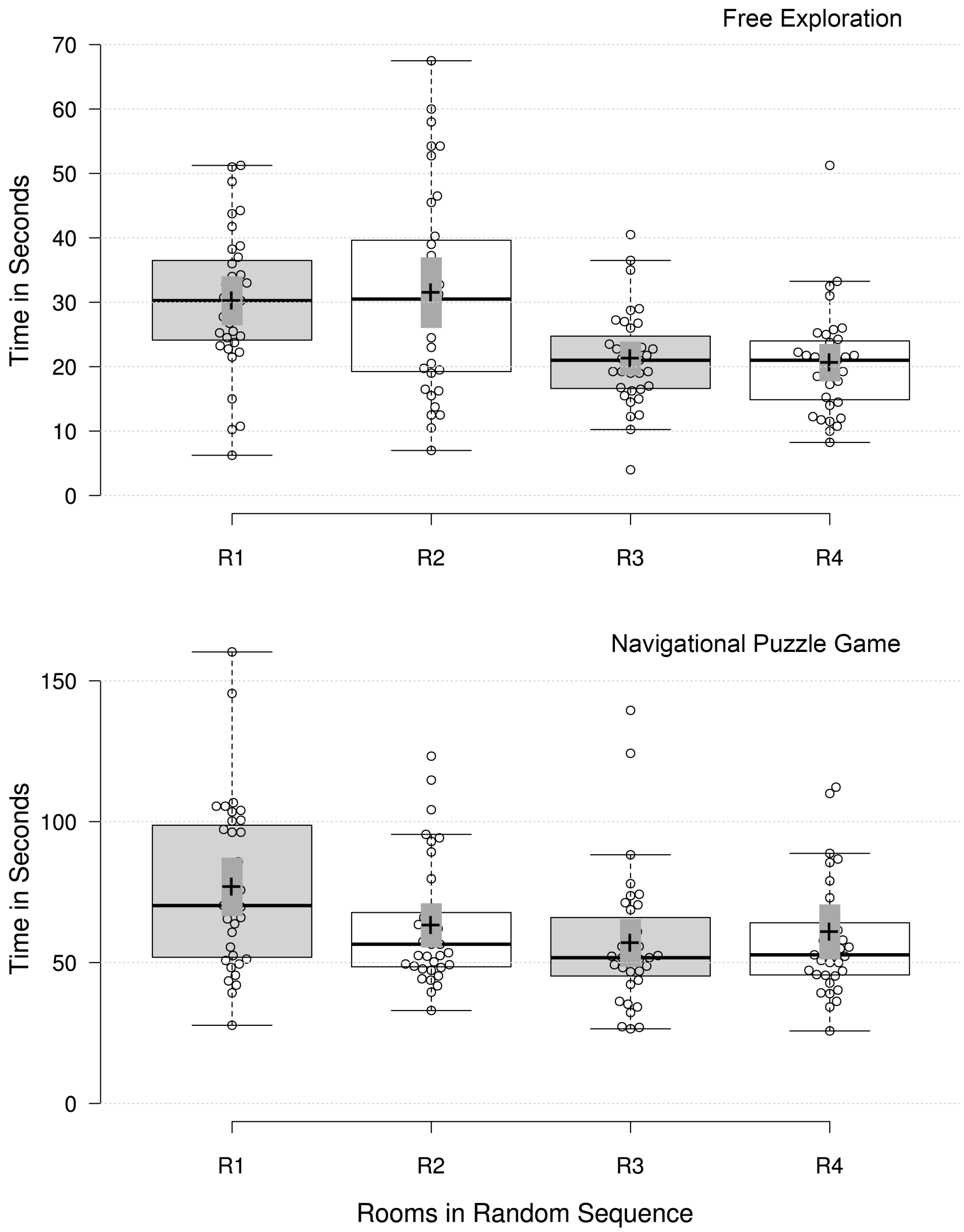


FIGURE 5.18: **Time spent in the four rooms as experienced in random sequence, during both Free Exploration Mode (top) and Navigational Puzzle Game Task (bottom).** Y-axis shows time spent in seconds. X-axis present the four rooms in random sequence. Centre lines show the medians; box limits indicate the 25th and 75th percentiles; whiskers extend 1.5 times the interquartile range from the 25th and 75th percentiles, outliers are represented by dots; crosses represent sample means; bars indicate 95 % confidence intervals of the means; data points are plotted as open circles. N = 35 sample points

A repeated measures ANOVA with a Greenhouse-Geisser correction determined that mean time differed statistically significantly between rooms ($F(1.93, 65.57) = 5.66$, $p<.05$). Post hoc tests using the Bonferroni correction revealed that the first room elicited a longer completion time compared to the following rooms, which was statistically significant for room 2 ($p<.05$) and room 3 ($p<.05$) but not for room 4 ($p=.22$). However, there was no effect comparing Room 2, 3 and 4 together ($p=1.00$).

A comparison between both tasks is presented in Figure 5.18. Each participant's time is plotted as an open circle using a BeeSwarm method [3] in a way that allows every data point to be viewed. The top box plot shows, for the Free Exploration Mode, how participants spent more time in the first couple of rooms. This could mean they needed some practice to get used to the VR system as well as the virtual environment. It also could mean that, once the second room confirms the spatial knowledge acquired in the first room, they were able to move faster in the following rooms.

With regards to the NPG, the bottom box plot shows that the mean time spent exploring the first room is at least 13 seconds longer than for the three other rooms. Therefore, we can conclude that even with some time spent exploring the rooms freely, participants still take still longer to complete the puzzle in the first encountered room than the following ones. This effect seems independent of any spatial characteristics and may be due to the time taken to get used to the controller and the way they have to grab the different blocks to solve the puzzle.

5.4.2 Rooms per Condition

Free Exploration Mode: the descriptive statistics are presented in table 5.5 with the mean and the standard deviation for each room characterised by their spatial qualities. At first glance, the mean time spent exploring the two rooms ComplexClose (M=28.39s, SD=13.06) and ComplexOpen (M=30.60s, SD=22.18) is higher than for the two other rooms, SimpleClose (M=23.50s, SD=9.89) and SimpleOpen (M=23.86s, 11.30). The standard deviation for the room ComplexOpen is much higher than for the other rooms.

TABLE 5.5: Free Exploration Time per Room - Descriptive Statistics

	Mean	**Std. Dev.**	**N**
ComplexClose	28.39	13.06	35
ComplexOpen	30.60	22.18	35
SimpleClose	23.50	9.89	35
SimpleOpen	23.86	11.30	35

The repeated measures two-way ANOVA shows a statistically significant effect of the mean of *complexity* ($F(1, 34) = 6.96$, $p<.05$), but not of the mean of *openness* ($p=.57$).

[3] The bee swarm plot is a one-dimensional scatter plot like "stripchart", but with closely-packed, non-overlapping points.

A trend towards an interaction (F(1, 34) = .20, *p*=.66) between *openness* and *complexity* is presented in the top plot from figure 5.20; both lines are not strictly parallel. In the case of the rooms that have only walls, Room SimpleClose (23.5s) and Room SimpleOpen (23.86s), the number of windows does not have an effect on participants' exploration time. However, the mean time spent exploring these two rooms was shorter than the mean time spent in the two more complex rooms with the added columns. This suggests that a higher *complexity* level slowed down participants' progression; however, the level of *openness* had little effect on exploration time.

Navigational Puzzle Game: a quick look at the descriptive statistics (see table 5.6), shows the main difference occurred in mean time completing the task between the fastest performance in the ComplexClose condition (M=54.48s, SD=25.04) and the slowest performance in the ComplexOpen condition (M=71.32s, SD=28.28).

TABLE 5.6: Navigational Puzzle Game Completion Time for each Room - Descriptive Statistics

	Mean	**Std. Dev.**	**N**
ComplexClose	54.48	25.04	35
ComplexOpen	71.32	28.28	35
SimpleClose	66.60	24.07	35
SimpleOpen	65.50	28.32	35

A repeated measure ANOVA, with the assumption of sphericity not violated, *p*=.72, shows that the mean time completion of the NPG task differs statistically significantly between the four conditions (F(3, 102) = 3.65, *p*=.015). Post hoc tests using the Bonferroni correction reveals a faster performance within the room ComplexClose in 54.49s compared to the three others. However, from the three other rooms, only room ComplexOpen (in 71.33s) shows a statistical significance ($p < 0.05$). The two other rooms show only a slight improvement with room SimpleClose in 66.60s and room SimpleOpen in 65.50s, which is not statistically significant (*p*=.18 and *p*=.22, respectively). The SPSS general linear model output can be found in Appendix E.

A two-way repeated measures ANOVA with complexity (simple, complex) and openness (open, close) as a within-subjects factor was run. No outliers were found in the data, as assessed by inspection of the box plot (see Figure 5.19). There was a statistically significant interaction between *complexity* and *openness*, F(1, 34) = 5.10, $p<.05$. Therefore, simple main effects were run. The main effect of *complexity* shows no statistically significant difference in participants' performance between trials, F(1, 34) = 0.99, *p*=.33. There was a trend in the effect of *openness*, even though the main effect did not show any statistically significant difference in participants' performance, F(1, 34) = 3.86, *p*=.06.

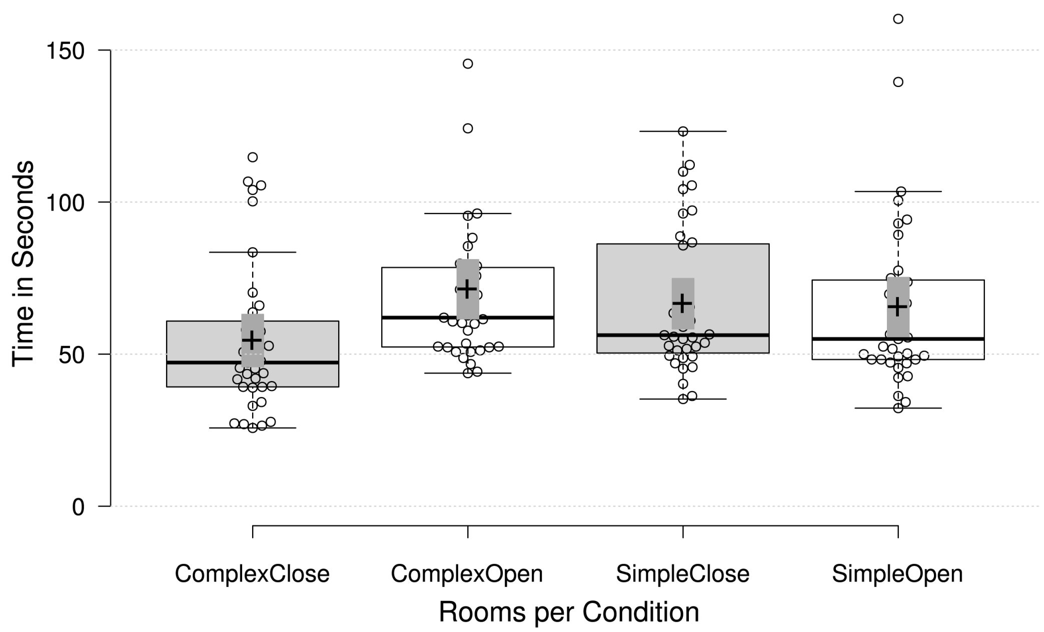


FIGURE 5.19: **Mean time spent in each condition during the Navigational Puzzle Game.** The Y-axis shows the mean time spent for each participant. Centre lines show the medians; box limits indicate the 25th and 75th percentiles; whiskers extend 1.5 times the interquartile range from the 25th and 75th percentiles, outliers are represented by dots; crosses represent sample means; bars indicate 95 % confidence intervals of the means; data points are plotted as open circles. N = 35 sample points

Therefore, we can conclude that the room with the most complexity and closeness (room ComplexClose) elicits a statistically significant improvement in performance, but the difference in the effect between the three other conditions is less obvious.

Another approach that was introduced earlier is to look at the performance efficiency of each room or Spatial Performance Efficiency P (see Table 5.7). That is the number of trials multiplied by the average cycle time K to complete NPG (M=64.48s, SD=26.43s), divided by the total time spent in each room. It shows that the room ComplexClose was 18% more efficient than the average.

$$P = Tasks * K/T$$

TABLE 5.7: NPG - Spatial Performance Efficiency

	Total Time in sec.	P	**N**
ComplexClose	1907.00	118%	35
ComplexOpen	2496.50	90%	35
SimpleClose	2331.00	97%	35
SimpleOpen	2292.50	98%	35

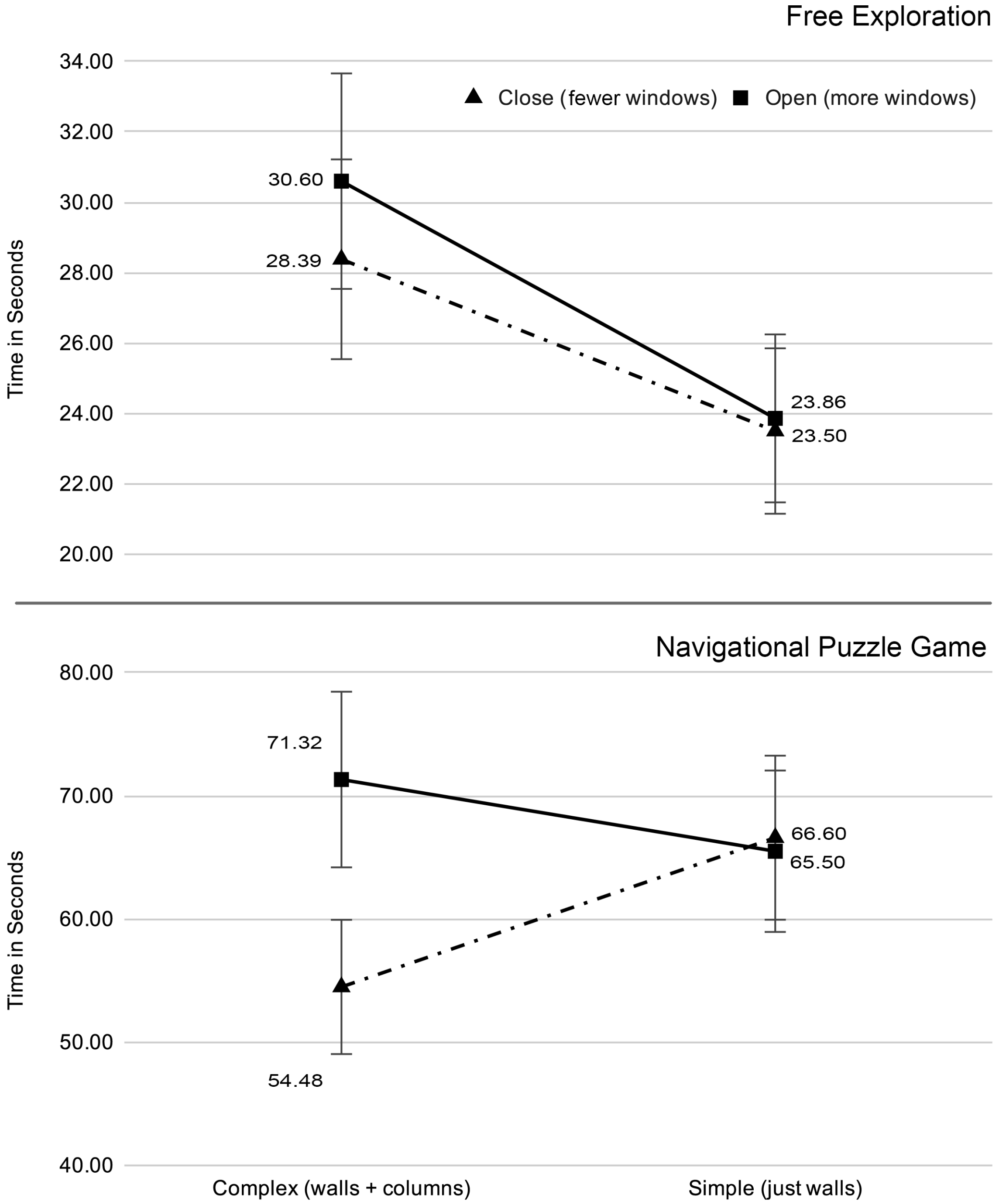


FIGURE 5.20: **Marginal means of completion time for both Free Exploration mode and Navigational Puzzle Game.** X-axis represents the level of complexity; The Y-axis represents the mean time in seconds. Triangles represent the means of the *close* conditions (with less windows); Squares represent the means for the *open* conditions (with more windows); the two lines, not strictly parallels, suggest an interaction between the two factors; bars indicate 10 % error intervals of the means. N = 35 sample points

5.4.3 Visuo-Spatial Memory Test

The VSMT was based on the two-alternative forced-choice method. A binary type of data, either right or wrong, were collected during the task. Participants were presented with each pair of images (of 16 pairs), and had to choose which one they thought was part of the room they had visited. Their responses were copied into a table. A formula automatically added together the choices for each room and showed the total per room. The total per room was used for further analysis in SPSS and Google Sheet (see table in Appendix E.12).

Table 5.8 shows the descriptive statistics of the mean and the standard deviation for each room (score max = 4).

TABLE 5.8: Visuo-Spatial Memory Test - Descriptive Statistics

	Mean	**Std. Deviation**	**N**
ComplexClose	3.06	1.00	35
ComplexOpen	3.29	.89	35
SimpleClose	2.86	1.00	35
SimpleOpen	3.40	.88	35

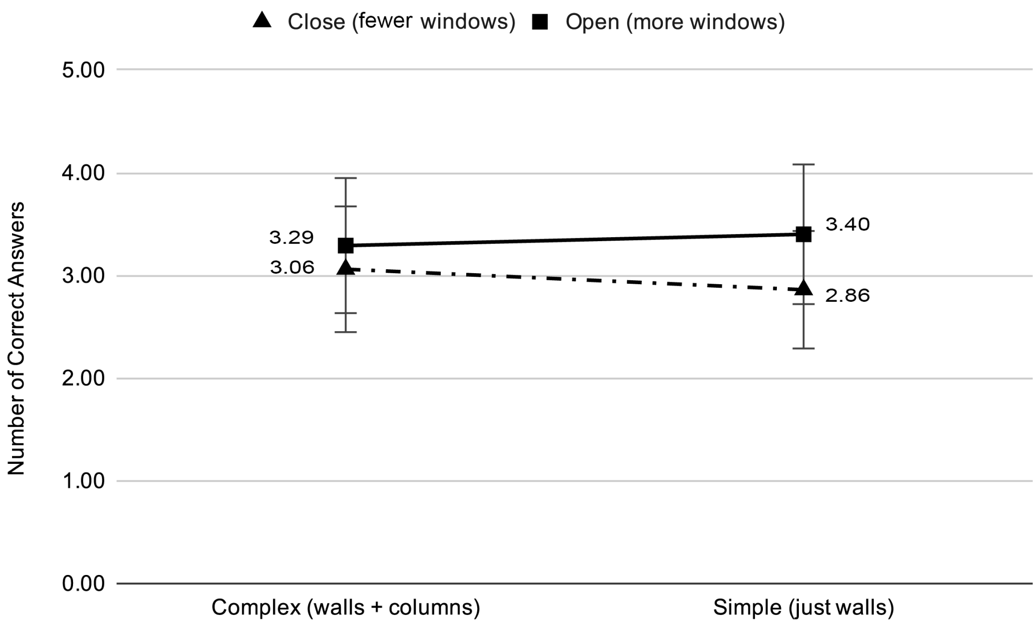


FIGURE 5.21: **Marginal means of retention to the Visuo-Spatial Memory Test.** Both lines are not strictly parallel, showing a trend toward the more memorable conditions. The level of complexity is represented along the Y-axis; Squares represent the means for the Open conditions (with more windows); Triangles represent the means of the Close conditions (with fewer windows); bars indicate 20 % error intervals of the means. Max score is 4. N = 35 sample points

A repeated measures ANOVA with a Greenhouse-Geisser correction determined that the mean of *memory* (images recognised) differed statistically significantly for spatial quality of *openness* ($F(1.00, 34.00) = 13.07$, $p<.05$) but not for *complexity* ($F(1.00, 34.00) = 0.07$, $p=.80$). The completed output of the statistical analysis can be found in Appendix D.

Looking at the means in Figure 5.21, a trend shows that participants remembered more accurately the room SimpleOpen with a mean of 3.40 images compared to only 2.86 for room SimpleClose. Following that trend, although with a lesser effect, they recognised more accurately the room ComplexOpen with a result of 3.29 images against 2.86 for room SimpleClose.

This analysis thus shows that the main effect on memory was due to the level of *openness* of the room. In both cases, participants remembered more accurately the more open room, that is, the room with most windows. The added columns did not seem to have an effect on the way participants remembered the rooms (SPSS general linear model output can be found in Appendix D).

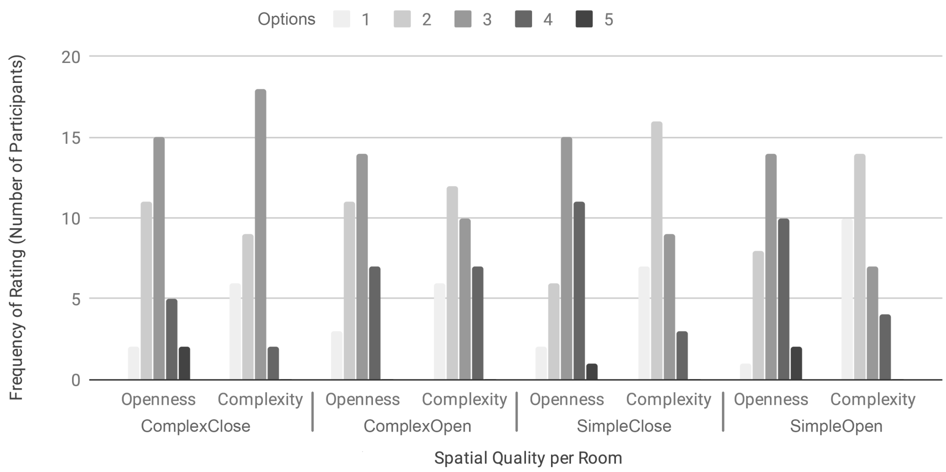
5.4.4 Spatial Quality Rating

The Spatial Quality Rating (SQR) task was conducted by asking each participant to rate their perception of *openness* and *complexity* for each room, using a five-step Likert scale. The rating option were set as follow; *openness*: 1-Very Open, 2-Open, 3-Neutral, 4-Close, 5-Very Close; *complexity*: 1-Very Simple, 2-Simple, 3-Neutral, 4-Complex, 5-Very Complex. The two questions were asked, in random sequence, during the *transition* period (see Section 5.3.3). Answers were collected orally and copied into a table (see Appendix E.5). The table was split into two (see Appendix E.6 and E.7), before being imported into SPSS to analyse their interaction. But first, the rating of spatial quality frequency is explored.

Overall, looking at the frequency rate per condition (see Figure 5.22a), for the spatial quality *complexity*, option "4-Complex" received the most number of votes for the ComplexClose condition with 18 participants. In contrast, participants had more difficulty evaluating the level of *openness* giving a majority of their vote to option "3-neutral" in the four conditions. This majority of 3-neutral votes is confirmed by the cumulative rating of spatial quality (see Figure 5.22b) with the longest bar adding up to 58 votes in total. The next most voted option was 2-Simple for the spatial quality *complexity* with 51 votes.

The descriptive statistics with the means for each spatial quality are presented in the bar chart (see Figure 5.23). The separated repeated measures of variance (ANOVA) for each spatial quality are presented next.

The descriptive statistics for *openness* show the means and the standard deviation for each room. The two rooms SimpleClose (M=3.09, SD=0.92) and SimpleOpen



(A) Frequency of Rating per Condition

(B) Cumulative Rating for *openness* and *complexity*

FIGURE 5.22: **Frequency rate of spatial qualities, *openness* and *complexity* in four conditions: Complexclose, ComplexOpen, SimpleClose, and SimpleOpen.** Figure (A) shows the most frequent options chosen for each condition. The Likert scale was as follows for Openness: 1-Very Open, 2-Open, 3-Neutral, 4-Close, 5-Very Close; for Complexity: 1-Very Simple, 2-Simple, 3-Neutral, 4-Complex, 5-Very Complex. Figure (B) shows the cumulative rating for each spatial quality in each condition. N = 35

(M=3.11, SD=0.93) have been perceived more **"close"** than the two other rooms, ComplexClose (M=2.83, SD=0.95) and ComplexOpen (M=2.71, SD=0.89). N = 35.

The repeated measured ANOVA shows no statistical significance in *openness* (F(1, 34) = 3.429, *p*=.073).

The descriptive statistics for *complexity* show the means and the standard deviation for each room. The two rooms SimpleClose (M=2.23, SD=0.88) and SimpleOpen

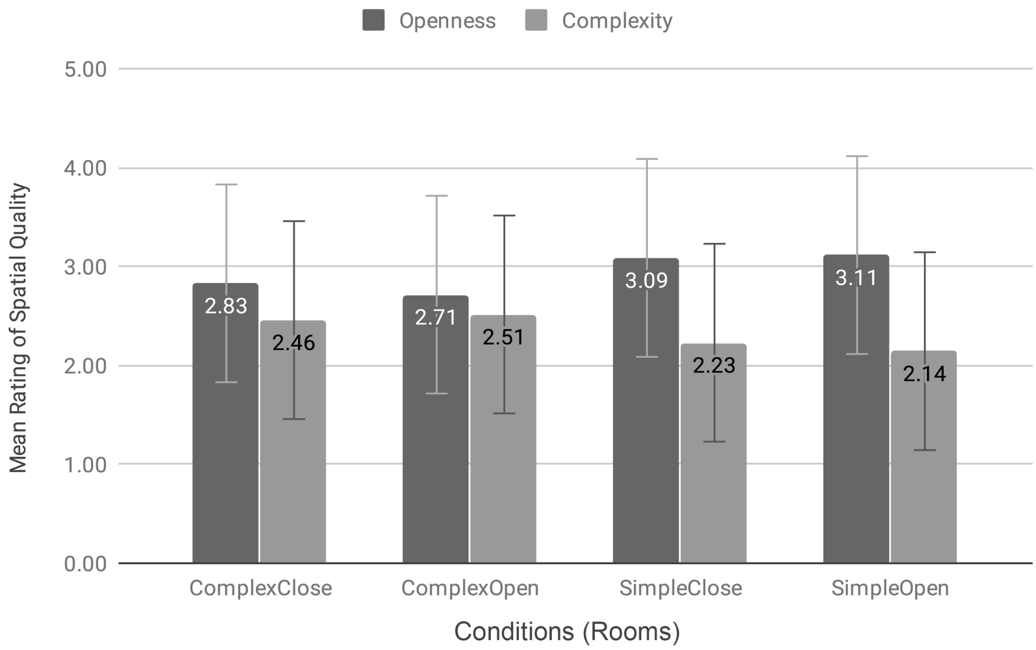


FIGURE 5.23: **Means of Spatial Quality Rating for *openness* and *complexity*.** X-axis represents the four conditions: Complexclose, ComplexOpen, SimpleClose, and SimpleOpen; Y-axis represents the mean rating of spatial quality; bars indicate 20 % error intervals of the means. Five step Likert scale. N = 35 sample points

(M=2.14, SD=0.97) were perceived as more **"simple"** than the two other rooms ComplexClose (M=2.46, SD=0.85) and ComplexOpen (M=2.51, SD=1.01). N = 35.

A repeated measures two-way ANOVA was conducted on the means rating of *complexity* and *openness* between the four conditions. There were no outliers, as assessed by boxplot. The mean of rating for *complexity* was statistically significantly different between the conditions (F(1, 34) = 5.61, *p*=.024). This effect means that participants recognised the more complex conditions with the added columns. The fact that the room had more or fewer windows did not seem to affect the way people perceived the complexity of the room (*p*=.92). The SPSS general linear model output can be found in Appendix E.

The plot from Figure 5.24 shows an interaction between the perceived *openness* and *complexity* of the room. It seems that people rate the feeling of *openness* based moreon the presence of columns or walls more than based on the number of windows. Even though not statistically significant, there is a trend in the data suggesting that the presence of columns drives the feeling of openness.

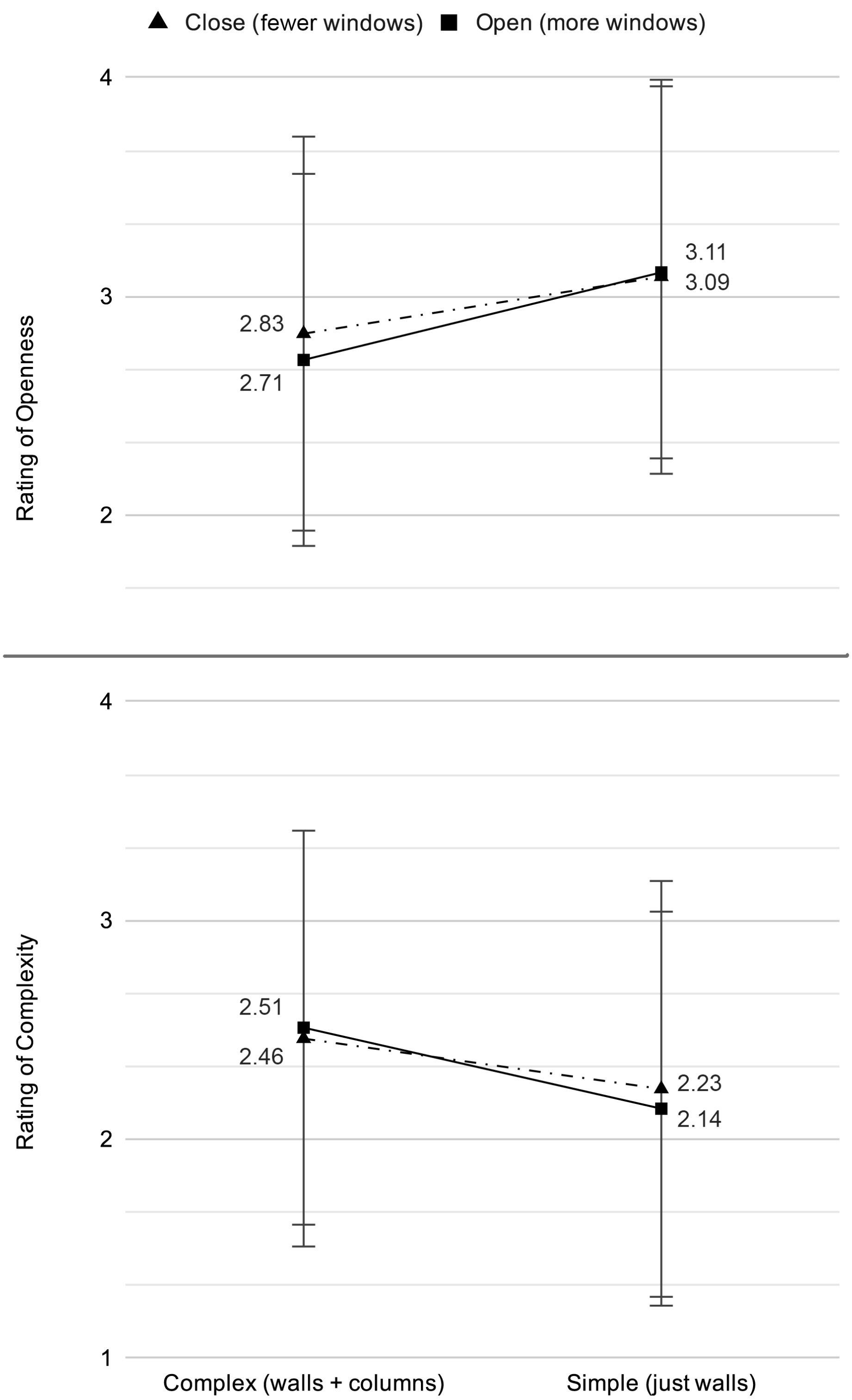
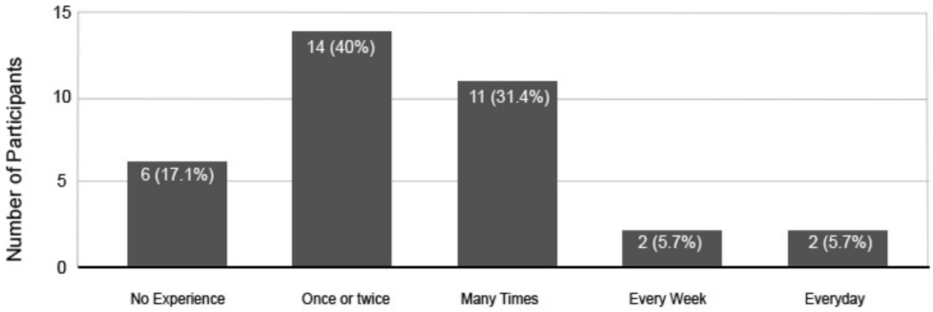
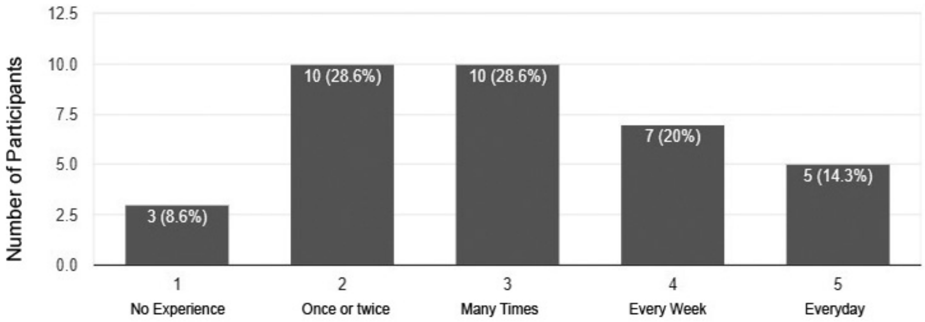


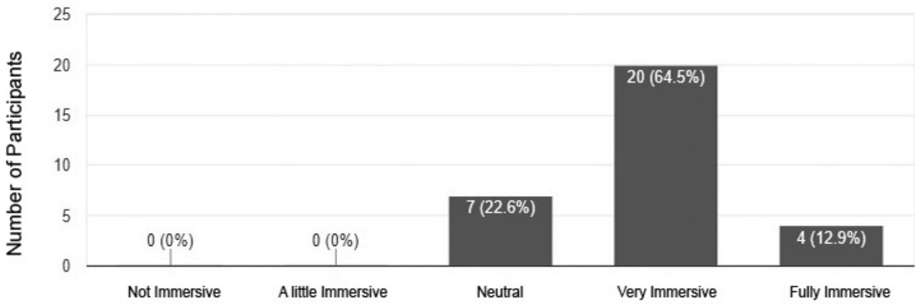
FIGURE 5.24: **Marginal means of rating between two spatial qualities: *openness* and *complexity*.** The level of complexity is represented along the Y-axis; Squares represent the means for the Open conditions (with more windows); Triangles represent the means of the Close conditions (with fewer windows); bars indicate 20 % error intervals of the means. Max score is 4. N = 35 sample points



(A) Participants' experience playing video games, N=35



(B) Participants' experience in VR, N=35



(C) Participants' feeling of immersion, N=31

FIGURE 5.25: **Participants' rating of video game and VR experience, and feeling of immersion.** X-axis presents the five options; Y-axis presents the number of participants.

5.4.5 Post-Questionnaire

Figure 5.25 shows the percentage of response [4] to the two multiple choice questions about participants' previous experience of VR and video games, and about their feeling of immersion during the experiment.

Overall, participants were not experienced video game players. Only four of them played on a regular basis (11.4%). By contrast, 9 participants (34.3%) used VR on a regular basis, either daily or weekly. Only 3 participants were trying VR for the first time. Although it did not have a huge impact in the case of this particular study, it is important to keep in mind for further development of VR applications, specifically for user interactions.

The third question was, *"How immersive would you scale your experience?"*, to which participants could choose between five options on a Likert scale (1-not immersive; 2-little immersive; 3-neutral; 4-very immersive; 5-fully immersive). The majority rated the experience as "very immersive" (64.5%; N=31).

5.4.6 Open Questions and Observations

Two open questions were set at the end of the online questionnaire to give the opportunity to every participant to describe how they felt during the experiment, and to leave feedback or suggestions.

Feeling of Immersion

Many comments mentioned the feeling of immersion. People were usually surprised by the extent to which they 'forgot' the real world. One participant commented (when asked "Could you describe how did you feel when you were experiencing the IVAS today?")

> *Even though the experience wasn't photorealistic, just being inside the environment became comfortable to the point where I began to accept the immersion*

However, people mentioned that the cable (that tethered the HMD to the computer) was the main factor which broke that feeling of being present. Two other comments to the same question were:

> *It was great felt like I was there until the cable had disrupted my movements.*

> *Involved and at ease with the task, it was fun! Would have felt more immersed without the data wire.*

[4] The questionnaire was designed using Google Form.

Agency and Object Manipulation

Another trend in participants' comments to the second question concerned issues interacting with the blocks. Three participants complained about the lack of control of the blocks (when asked, "Here is a good place for any questions, comments or suggestions you might have.)

> *It is difficult to rotate the objects or to try to keep more than one in one hand by piling them. Haptic feedback (don't know if the Vive controllers have) would be great to get more feeling of control when handling the cubes.*
>
> *Sensitivity on physics of blocs would be good to fix. Have open windows rather than gauze covered windows.*
>
> *The blocks tend to fly off if they're in your hand and you touch a wall, either than that its amazing.*

A big part of the object manipulation issue, identified by the participant, was already known to the experimenter. There was a bug in the programming of the physics using the Vive controllers, which was never resolved in time for the user study. Another problem, not specific to this experiment, is the way moving objects interact together, as well as between the controller and the stationary objects. There are many possibilities to program these kind of behaviours, which will be mentioned in the future work section.

Spatial Qualities

As expected, only a few participants made comments about the spatial qualities of the space. As the experiment was designed to have them focus on the puzzle game, the spatial characteristics were secondary. Only five comments explicitly mentioned spatial qualities from the the 54 answers to the two broad aforementioned questions (less than 1%).

> *One suggestion would be to increase the spatial complexity factor further.*
>
> *Enclosed within the spaces , walls very close*
>
> *I didn't feel very immersed into the space however once I got used to the main architecture of the room it was better.*
>
> *Good, became very task focused, looking for shapes. Tended to look at the floor. Liked looking through into other areas outside space. The overall space seemed quite small. Viewed space as part of puzzle (a maze).*

A copy of the questionnaire, and all the responses, can be found in Appendix D. Although a qualitative analysis was not run at this stage, the comments were helpful to confirm or disprove specific points during the discussion. Furthermore, they provided some valuable points for follow-up action (see Future Work Section 7).

5.5 Discussion

The discussion evaluates the IVAS in relation to previous research, in a series of subjects discussed earlier, mainly, level of immersion, spatial analysis, memory for familiar and unknown environments, and figural and environmental spatial abilities. Compared with previous research, the presented approach is unique in so far as it attempts to address all identified challenges of measuring the effect of spatial qualities on human's cognitive performance within IVEs, rather than singling out one aspect in isolation. In doing so, it also largely overcomes the limitations of previous research, but this is not without problems which should be duly acknowledged.

5.5.1 Benefits Over Previous Research

In contrast with the series of studies looking into spatial qualities evaluation, which focus mainly on spatial analysis (e.g. Chalup and Ostwald, 2010; Ostwald, 2011; Dosen and Ostwald, 2017; Varoudis and Psarra, 2014), or even Franz (2005) on affective responses to spatial qualities, IVAS not only proposes a more immersive experience, but also an advanced methodology to investigate the correlation between spatial analysis and perceived experience.

Franz and Wiener's methodology has been influential. However, their experiment settings were based on the desktop and joystick, which offer only a limited level of immersion and reduces participants' ability to fully perceive the spatial qualities of an environment. Indeed, the type of hardware used dictates the way one is moving (if moving at all) through the spatial environment. If the feedback appears only on small flat display, it offers only limited clues about self motion, which in return offers only a reduced ability to perceive the different quality of the space.

The approach by Dosen and Ostwald (2017) was more thorough regarding the number of isovist measures used to evaluate the different spatial qualities. Notwithstanding their encouraging conclusions about the reliability of those measurements to correlate with human perception of space, participants' responses were obtained by looking at still images (no motion) viewed on a monitor, which comprises a very low level of immersion.

With regards to spatial metrics, however, both Dosen and Ostwald (2017) and Wiener and Franz (2005) used a wide range of isovist measures to evaluate a broader set of spatial qualities. This range of isovist measures will have to be included in future work as part of a larger framework. Moreover, methods other than 2D isovists can extend the type of spatial information to evaluate elements such as 3D isovists (e.g. Bhatia, Chalup, and Ostwald, 2013; Varoudis and Psarra, 2014).

The first task, the free exploration mode, was designed to utilise an environment in which the participant was placed in a situation of familiarity, so that they could focus on the task at hand (the NPG) rather than using specific additional strategies to find their way around. Many studies have looked into human strategies to navigate unfamiliar environments (e.g. O'Neill, 1992; Baskaya, Wilson, and Özcan, 2004; Slone et al., 2015). Wayfinding performance in all these studies was evaluated by asking participants to draw a sketch map of the visited environment (see Chapter 3). That method did not provide a tangible way to evaluate the different effects between conditions (the different rooms). Instead, a new task was proposed to measure the memorability of each condition, the VSMT.

Another important factor to take into consideration when trying to evaluate the effect of a system on memory is the overall cognitive load of that system. Many studies have demonstrated the benefit of using a VR system to enhance memory; however, their settings have also imposed a high cognitive load on the participants. Based on information processing theory, during learning, information must be held in one's working memory until it has been processed sufficiently to pass into one's long-term memory [5]. This was addressed in the requirement of participants to fill in the questionnaire before completing the VSMT. However, a measure of the overall cognitive load created by the virtual environment was not taken into account. For example, in a study on multimedia learning by Skulmowski and Rey (2017), they used a dual-task performance as a measure of cognitive load. Maguire, Woollett, and Spiers (2006) used physiological measures which led to fascinating findings, measuring the difference in volume of grey matter between taxi drivers and bus drivers. Such measurements were beyond the scope of the present research, as specific equipment and a technician are needed.

The most successful part of the experiment resides in the NPG. It proposed a task that plays on both scale of figural and environmental spatial abilities (Montello, Golledge, and Org, 1998; Hegarty et al., 2006). It builds upon the VSNA experiment proposed by Ventura et al. (2013) in a way which includes the object manipulation inspired by the mental rotation test (Shepard and Metzler, 1971) and the more recent study looking at Blurr object manipulation by Murcia-Lopez and Steed (2018).

5.5.2 Findings of the Research Goals

This section presents the findings of the research goals defined earlier in this chapter. These findings will be used to answer the subordinate research questions.

G1: Evaluate the correlational relationship between columns and visual complexity. Hypothesis: added columns increase the level of visual complexity. One of the two assumptions in the design of this set of rooms was that adding columns would increase the level of complexity of the room. The spatial analysis confirms that is the case:

[5] *Cognitive Load Theory* (CLT) is an instructional design theory that reflects the way humans process information. Skulmowski et al. (2016) discussed whether embodiment approaches enhance learning processes by measuring that cognitive load.

- between the rooms with fewer windows: 0.33 in the room with no column, and 0.40 in the room with columns
- between the rooms with more windows: 0.31 in the room with no column, and 0.50 with the room with columns

Two of the measurements are very similar. Both rooms, with columns and fewer windows, as well as the room with no columns and more windows, show the same level of complexity of 0.40. This value was obtained by taking the original measurement of the ratio of the surface of the room rounded to two decimals. It also shows the limit of reducing a spatial concept, measured with a 2D Isovist, to a one-dimensional variable. The visualisation gives a much fuller understanding of the spatial quality.

G2: Evaluate the correlational relationship between windows and openness. Hypothesis: added windows increase the level of openness.
The other assumption prior to designing the rooms was that adding windows in the walls would increase the level of openness. The spatial analysis confirms that is the case:

- between the rooms with no column: 0.22 when fewer windows and 0.31 with more windows
- between the rooms with columns: 0.31 with fewer windows and 0.50 with more windows, a noticeable difference in this case.

A similar consequence, as in G1, is observed for openness between the two rooms Columclose and SimpleOpen.

G3: Evaluate the interaction between the two.
Hypothesis: adding columns and windows produces changes in both level of complexity and openness. The two previous evaluations point to some interaction between the two architectural elements and the spatial quality. The same level of complexity between the room with the column and fewer windows and the room with no columns and more windows is explained by the fact that adding windows in the wall multiplies the number of edges, therefore increasing the overall complexity. So even though there are no columns in the room, the isovist method measures the increase in the number of edges because of the three added windows. With regards to the same level of openness between the room with columns and fewer windows and the room with no columns and more windows, this seems more puzzling. It shows the limits of this kind of measurement, in the restricted context of this experiment at least. However, the visual from the isovist field method still gives valuable information of the spread of each spatial quality in the room.

G4: Do the participants experience a higher feeling of openness with added windows?
Hypothesis: human perception of openness confirms results obtained by isovist measures. The results from the SQR task give insights into this assumption. The statistical analysis does not provide a significant confirmation of people perceiving an increase of the level of openness when in a room with more windows. Although not significant, there is a trend. One concern was flagged by a couple of participants, about the translucency of the texture applied on the windows. The texture was not fully transparent. This could have caused some participants to perceive the glass as just another surface.

G5: Do participants perceive more visual complexity with added columns?
Hypothesis: human perception of visual complexity confirms results obtained by isovist measures. Results from the SQR task confirm that participants recognise the more complex room with the added columns.

G6: Is there an interaction between perceived openness and perceived complexity?
In contrast with the explanation from G3, the added windows in the rooms did not affect users' perception of complexity. However, results from the SQR suggest that the presence of columns drives participants' perception of openness. They rate the room with more windows and columns more open than the room with more windows but no columns.

G7: Evaluate the effect of *complexity* on users' spatial abilities. Hypothesis: conditions in which the spatial quality *complexity* is higher would yield higher puzzle assembly time as participants would have more spatial features to attract their gaze when navigating the room. The analysis does not show any statistically significant results of the effect of complexity on participants' performance.

G8: Evaluate the effect of *openness* on users' spatial abilities.
Conditions in which spatial quality *openness* is lower would yield lower assembly time as participants would have fewer features from the outside world to attract their gaze and slow their progression in the room. Even though not statistically significant, there is a trend showing the effect of *openness* on participants' performance, in which they performed faster in the room with fewer windows.

G9: Evaluate the interaction between the two.
Hypothesis: there is an interaction effect between *openness* and *complexity* on participants' assembly time. There is a significant interaction between the two spatial qualities. As with the VSMT, it seems that the opportunity afforded by the windows to look outside distracted participants and thus, slowed them down.

G10: Evaluate the effect of *complexity* on memory performance.
Hypothesis: the rooms in which the spatial quality *complexity* is higher yield higher memory retention because of more memorable features. The evaluation of the effect of complexity on memory performance is based on the results from the VSMT. Results do not show any statistical differences between the rooms with and without columns. This means that the added columns do not yield higher memory retention. Of course, this does not permit the conclusion that complexity did not work as anticipated. More tests exploring different ways of adding complexity into the rooms need to be performed.

G11: Evaluate the effect of *openness* on memory performance.
Hypothesis: conditions in which the spatial quality *openness* is lower would yield lower memory retention because of the lack of memorable features. A significant improvement in spatial memory is shown to be linked to a higher level of openness. Indeed, participants remember best the rooms with the most windows.

G12: Evaluate the interaction between the two spatial qualities.
Hypothesis: there is an interaction effect between *complexity and openness* on participants' memory retention. The analysis does not suggest any interaction between these two spatial qualities. However, it can be argued that the added windows affording higher visibility outside give participants more features to see. This actually increases the level of complexity through the increased openness.

5.5.3 Answering the Subordinate Research Questions

RQ2: How to evaluate the correlational value between architectural elements and spatial qualities?
Isovists and isovist fields are used to assess the relationship between architectural elements and spatial qualities. In particular, four rooms, each with a different layout using the three architectural elements, walls, columns and windows were designed to test their relationship with two spatial qualities: *openness* and *complexity*. This was evaluated using two isovist descriptors known as *visibility* and *visual complexity*. The spatial analysis confirms that: adding columns increases the level of complexity of the rooms; and, adding windows increases the level of openness of the rooms. Furthermore, it shows some interactions between the two. For instance, adding windows also increases the level of complexity. It also shows the limitation of the technique when displaying the same value in openness for two rooms with different layouts.

RQ3: How do perceived Spatial Qualities correlate to those measured by isovist techniques?
This question is undoubtedly the most critical question of all. The design of a geometric space assisted by generative algorithms and powerful computers is only worth the

effort in regards to the feedback of the people that experience those buildings or virtual environments.

In terms of gathering user feedback from their experience of IVE, the implementation of the SQR is far from optimal. Another type of scale with 7 steps could be used. Results showed only a trend confirming that participants recognise the room with more windows to be more open and the rooms with added columns to be more complex.

RQ4: What tasks can be implemented to evaluate the spatial performance of an immersive virtual environment
This question was split into RQ5 and RQ6.

RQ5: What is the effect of a specific spatial quality on a participant's spatial abilities?
The Navigational Puzzle Game (NPG) was designed to help answer this question. It is an embodied cognitively-demanding task requiring participants to use their environmental and figural spatial abilities to navigate the space and resolve the three-dimensional puzzle game by grabbing, rotating, dropping and swapping the pieces around (see Section 5.2.2). NPG was successful in so far as each participant succeeded in completing the task, and the level of difficulty was appropriate. However, most participants commented they would be happy to have more puzzles to solve, which seems to indicate that it was sufficiently challenging. A conclusion may thus be reached that this task would work in future iterations of the IVAS, testing other architectural element and spatial qualities.

NPG was used to measure participants' time to completion, which was then used to calculate a spatial performance efficiency P for each room with its different spatial qualities. This produced a single metric to compare the effect of spatial design on participants' performance when solving the NPG. The investigation comparing each condition showed that the puzzle was completed most quickly in the rooms with fewer windows and columns with a P of 118%. One explanation is that the closed walls reduce the visibility of the outside world, that is, reducing 'distractions', and the columns structure the space in a way that supports efficient navigation to find the different items. The second room with columns has more windows that afford more visibility of the second layer of columns outside, which seems to disturb participants' performance.

Another observation is that the inner wall that separates the corridor from the central space does not vary apart from the added column. The overall *openness* of one room could be increased by adding an opening in that wall. A comparison of the effect of more distinct features would probably offer more insight into the impact of each element on user performance. The right balance between design and limiting confounding variables is critical to improving the experimental design of IVAS. Many iterations are needed to understand the effect of each element.

RQ6: What is the effect of spatial qualities on a participant's memory performances? A new task was put to the test to answer this question. The VSMT was used to measure the success rate of participants' recognition of the rooms they had experienced from images presented, once participants were removed from the VR experience.

This task was based on the 2AFC task which demonstrate a consistent score threshold of 75% of correctness (e.g. Posner, 1980). Indeed, when presented with 16 pairs of images, participants' responses were 78.75% correct. Notwithstanding this high percentage of positive responses, participants demonstrated in their comments a lack of confidence in their ability to pick the right image.

Besides the positive results of this task, results did not show any statistical differences between rooms with or without added columns. However, they did show a significant improvement considering the room with the added windows (a higher level of *openness*). Indeed, participants remembered most accurately the rooms with the most windows.

5.6 Virtual Architecture Analysis Grid

Immersive Virtual Architecture Studio (IVAS)

VAga	Geometric Space	Experienced Space
Design	**Architectural Design**	**Immersive User Interaction**
	2 architectural elements: column and window 4 conditions tested	Room-scale VR (HTC Vive) VR Locomotion: natural walking Hand controller interaction with physics Feedback attached in the environment
Measures	**Spatial Qualities**	**Objective**
	Using isovists field technique Complexity Openess	Head and hands position Navigational Puzzle Game Visuo-spatial Memory Test
		Subjective
		Spatial Qualities Rating Open questions

FIGURE 5.26: Virtual Architecture Analysis Grid - Immersive Virtual Architecture Studio

Chapter 6

Virtual Architecture Framework

"All right. Now listen - a tesseract has eight cubical sides, all on the outside. Now watch me. I'm going to open up this tesseract like you can open up a cubical pasteboard box, until it's flat. that way you'll be able to see all eight of the cubes."

Robert A. Heinlein - And He Built a Crooked House, 1941

6.1 Overview

This chapter gathers all the lessons learned in previous chapters using the Virtual Architecture Analysis Grid and integrates them into a virtual architecture framework. This Virtual Architecture Framework supports further testing of a wider variety of spatial properties, qualities and architectural elements and may be used to support the design of virtual learning environments in general.

It is time to review the lessons learned throughout this process and compare them to what others researchers have produced in term of design guidelines, principles and frameworks. This section is structured in three steps: (a) define what an architecture framework is; (b) relate these to existing frameworks and guidelines in VR application design; (c) explain where this research is positioned in relation to the reviewed studies and propose a new framework.

The idea of an architecture framework is not new. The ISO Standards[1] has proposed the following definition:

> An architecture framework establishes a common practice for creating, interpreting, analysing and using architecture descriptions within a particular domain of application or stakeholder community (Standards, 2017).

[1]ISO Standards are internationally agreed upon by experts. Details can be found on the website `https://www.iso.org/standard/50508.html`

This definition is sufficiently broad to be used in different domains of application, (e.g. software engineering, computer architecture, cognitive architecture) but still defines a clear purpose: to establish a common practice for creating, interpreting, analysing, and using architecture descriptions. Of particular interest to VR is its coverage of both domains. A VR experience needs spatial design and software development, both of which can be described in terms of architecture. Architectural design was covered in chapter 2, but what is the role of architecture in software development?

In the 1990s, software engineers started to use the concepts of architecture of buildings as metaphors for software design, giving rise to the term 'software architecture'. For instance, Perry and Wolf (1992) proposed a new model for software architecture consisting of elements (process or data), form (properties and relationship), and rationale (system constraints). Using the term 'architecture' in software development provided an easier way to grasp the complexity of a software system. Over the years, this practice has evolved into a standardised approach defined under the ISO/IEC/IEEE 42010 Systems and software engineering — Architecture description (Standards, 2017). This document defines in detail the significance of each word to explain the 'architecture descriptions'. This kind of thorough documentation can only happen over time and use but the reasons for using such a framework are valid, considering the complexity of building IVEs, most of which revolve around cost-saving and risk-mitigation.

- It provides a basis for analysis of software systems' behaviour before the system has been built (Perry and Wolf, 1992).
- It provides a basis for re-use of elements and decisions (Perry and Wolf, 1992).
- It affords an opportunity to reflect on the early decisions, which subsequently may have the greatest impact.
- It facilitates communication with stakeholders, contributing to a system that better fulfils their needs (Bass, Clements, and Kazman, 2012 p.29-31). Architecture descriptions help to communicate about design decisions before they are implemented and at a stage in which they are still relatively easy to adapt.

These legitimate points should indeed be considered at the start of any project involving the development of software, including VR applications. And this is the main purpose of a framework - to structure and plan the work ahead, to analyse and reflect, and to communicate with stakeholders.

In the context of this research project, and considering the strong background in architectural design, the term 'architecture' is mostly used not as a metaphor but in its original sense and definition; that is, the art and science of designing buildings and other structures (Curl, 2006). Architecture also includes both the process and the product of planning, designing, and constructing buildings or other structures.

From a standpoint of definitions, this section aims to contribute to the establishment of a framework of common practices for the creation and analysis of IVE design, which will be termed the Virtual Architecture Framework (VAF). The VAF presents a model of the process of planning, designing and developing architectural design in VR.

6.2 Related Work

Bridging the domain of software engineering and UX design, J.Murray (2012) has produced an extensive work defining the specificity of the digital medium. She proposes "a methodology and principles of design for the collective effort of maximising the expressive power" of each of the four following affordances. [2]

1. Procedural: composed of executable rules
2. Participatory: inviting human action and manipulation of the represented world
3. Encyclopaedic: containing very high capacity of information in multiple media formats
4. Spatial: navigable as an information repository or a virtual place

The spatial affordance of the digital medium is subdivided into wayfinding, mapping and curating. She uses the term 'spatial' broadly as it includes the two-dimensional space of a display and further states that "appropriate spatial design should make obvious the space's functions".

6.2.1 Three-dimensional Learning Environments

The idea of using 3D games, simulations, and virtual worlds as an alternative method to learning is not new. Many applications, using various levels of three-dimensional graphics and interactivity have been created over the years. From an education standpoint, these developments also imply the need for new methodologies to evaluate the efficacy, benefits and challenges of learning in these new ways.

Considering virtual environments from the late 1990s to the early 2000s, Downey et al. (2012) found that students were better able to follow the flow of conversations in three-dimensional collaborative environments, such as "Second-Life" [3] than in two-dimensional environments, such as "Elluminate" [4], even though both are accessible on desktop computers. Students are also better able to recall the actual content of these

[2] Taken from Janet Murray's blog, visited on 22nd March 2020, `https://inventingthemedium.com/four-affordances/`

[3] Second Life is an online virtual world, developed and owned by Linden Lab, launched in June 2003, and still operational.

[4] Elluminate Live! is a web-conferencing program developed by Elluminate Inc. Elluminate "rented out" virtual rooms or vSpaces where virtual schools and businesses could hold classes and meetings. Elluminate was acquired by Blackboard Inc. and renamed Blackboard Collaborate.

conversations when they take place in three-dimensional environments. Moreover, drawing on published research spanning two decades, Dalgarno and Lee (2010) identify a set of unique affordances of three-dimensional virtual learning environments,

> The facilitation of tasks that lead to enhanced spatial knowledge representation, greater opportunities for experiential learning, increased motivation/engagement, improved contextualisation of learning and richer/more effective collaborative learning as compared to tasks made possible by 2-D alternatives.

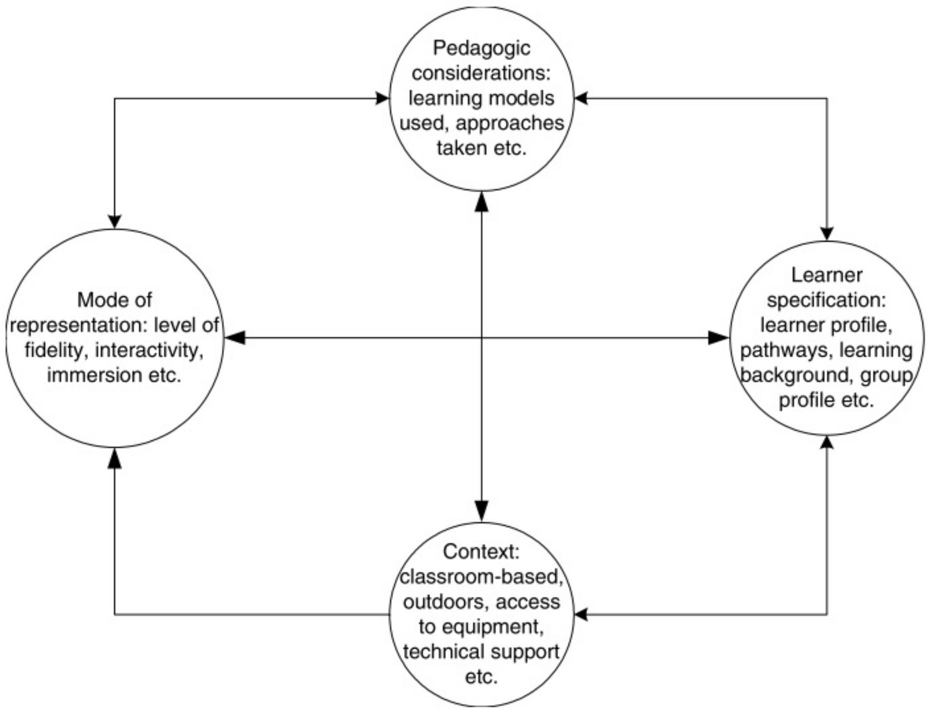


FIGURE 6.1: **The Four Dimensions Framework.** The first dimension focusses on the particular context where learning takes place, the second dimension on attributes of the particular learner, the third on the internal representation of the world, and the fourth on the process of learning or simulation. Image by De Freitas and Oliver (2006).

Recognising the lack of recommendations to design effective games for learning, De Freitas and Oliver (2006) proposed a framework to help educators and tutors evaluate the potential of using existing games and simulation-based learning in their practice. The framework, shown in Figure 6.1, presents four dimensions grounded in theories of education. Taking this a step further, De Freitas et al. (2010) undertook to evaluate the efficacy of using Second Life as a platform for supporting lifelong learners. They proposed a new approach to learning centred more upon experience and exploration. They took into account the role of multimodal interfaces and cognitive-based approaches, explaining that the interactions with the environment as well as the social interactions with others are part of "constructing learning experiences as a process of 'choreography', rather than based around data recall strategies" (De Freitas et al., 2010).

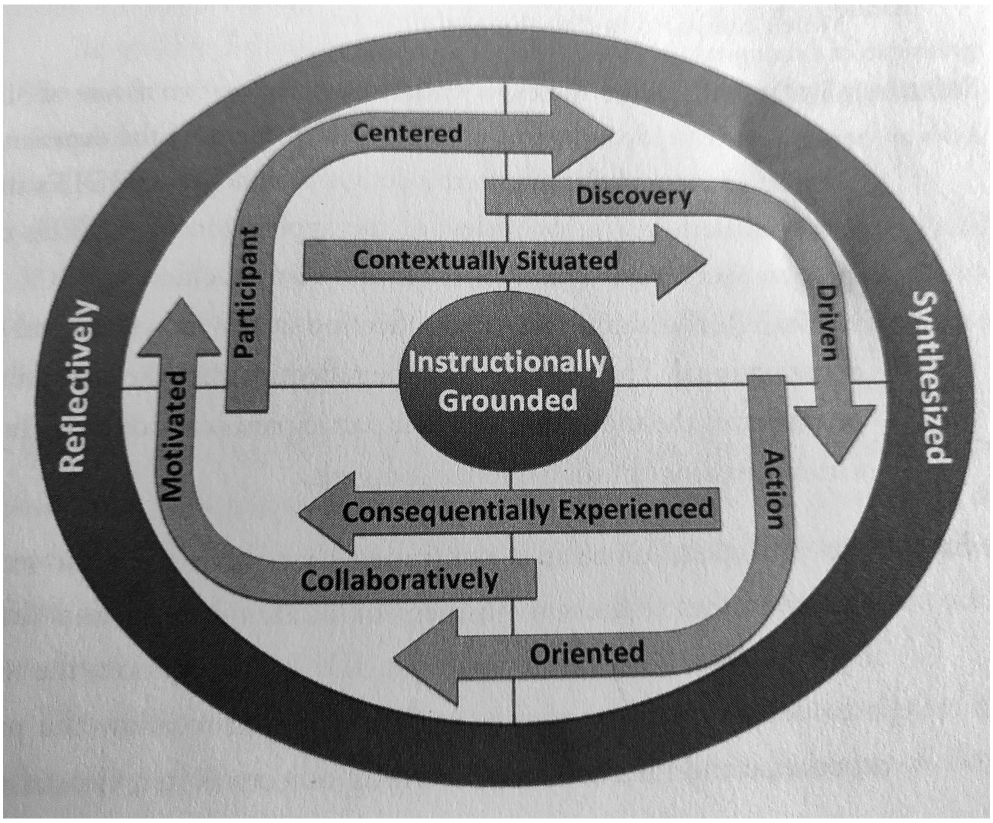


FIGURE 6.2: **3DLE Design Principles.** Participant Centred, Contextually Situated, Discovery Driven, Action Oriented, Consequentially Experienced, Collaboratively Motivated. Image by Kapp and O'Driscoll (2009)

In a seminal work about *learning in 3D*, Kapp and O'Driscoll (2009) present the benefits of using three-dimensional environments over the more established e-learning and web-conferencing platforms. Many practical example are used throughout the book to demonstrate various benefits of using three-dimensional environments for learning. They propose a relatively advanced framework comprising different layers to analyse existing applications. The most relevant layer is called "3DLE Design Principles", where 3DLE stands for Three-Dimensional Learning Environments, shown in Figure 6.2. The most relevant factors to take into account when designing a three-dimensional learning experience are listed. Even though written without the immersive level of experience we can achieve today, a couple of the main concepts presented throughout the thesis, such as the 'contextually situated' and the 'sense of space' are already presented.

Whereas the two aforementioned frameworks offer robust foundations with which to consider various factors when designing educative content using three-dimensional graphics and interactive materials in general, they do not provide clear guidelines on how to design effective immersive learning environments which take into account the advantages of the latest VR headset technology, mainly spatial awareness, sense of agency and congruency (as detailed in Section 2.4.4). These resources would benefit from an update in light of what has been learned in the last 5 years. The main advantages of immersive VR over the desktop-based virtual environments are the increased attention afforded using the HMD (no 'real-world' distractions like phone notifications or pop up windows) and the potential data which can be collected from HMD and hand controller positions.

6.2.2 Immersive Virtual Environment - Design Principles

Slater and Wilbur (1997) proposed a Framework for Immersive Virtual Environments (FIVE) in which they speculated about the role of presence in VR. They also suggested that the degree of *immersion* can be objectively assessed as the characteristics of the system used to run the virtual experience. In a more recent paper, Slater (2009) went further by establishing three important principles behind the realistic responses of participants to a VR experience: the *plausibility illusion*, the *place illusion*, and also, *body ownership* (see Section 2.5).

Still in the pursuit of establishing the foundations of this new medium, Bailenson (2018) explains that simulation-based learning in VR is well suited for to activities that are *impossible*, *dangerous*, prohibitively *expensive*, or *counter productive* to do in real life. The world's militaries put pilots through hours of flight simulator training for the obvious reasons that mistakes in the simulator are risk-free; errors in real planes are life-threatening.

Another benefit of using a framework is to enable the classification of the wide variety of existing virtual experiences. The following framework was proposed by Punchcut on their website.[5] It allows any virtual or augmented reality experience to be plotted along its four axes. The VR applications presented in this thesis are plotted in the graph (see Figure 6.3). A counter example of its validity, however, is demonstrated when trying to plot an application of remote surgery with an active participant, in a actual environment but from a fixed point of view. [6]

This kind of framework may be helpful in term of distinguishing between VR applications from a levels of immersion and interactivity, however it is limited in term of planning the design of immersive learning environments as discussed here. With that in mind, Punchcut recommends to consider the following three layers of sensory stimuli when designing a VR experience.

[5]Punchcut is a human interface design company specialising in mobile, connected products and services. The blogpost entitled, "An Experience Framework for VR" can be read at `https://www.punchcut.com/perspectives/`, accessed on 16 February 2020

[6]An example is the app developed by Medical Realities see `https://www.medicalrealities.com/`

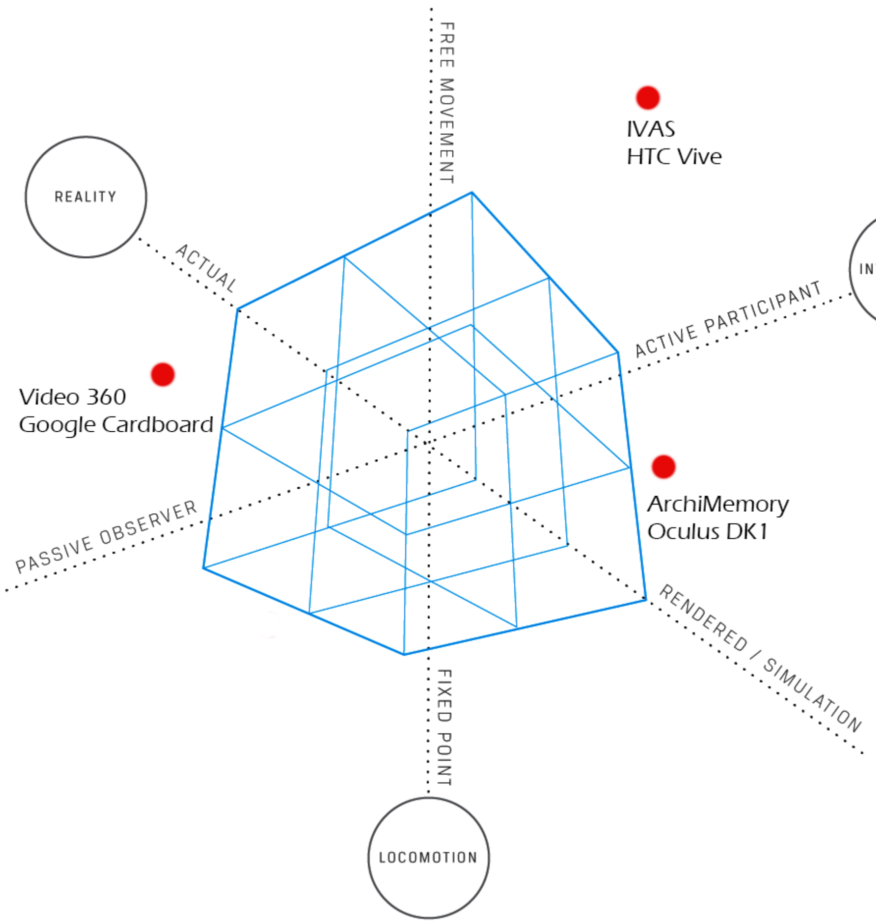


FIGURE 6.3: **Punchcut VR Experience Framework**. The three axes: locomotion (Fixed Point vs Free Movement), interactivity (Passive Observer vs Active Participant), and reality (Actual vs Simulation). The fourth axis is time. Images from blogpost, *An experience framework for virtual reality* by Punchcut.

The Environment: with relevance to this thesis, the design of the environment provides not only the atmosphere, but can also have a wider effect on user behaviour and affect user locomotion.

Directional Cues: these can be objects, or sounds, placed in the scene to attract users' attention to a specific location or to signal that an interaction is required.

User Initiated Events and Feedback: an event happens when the user interacts with an object in the scene visible or otherwise. Each event can be recorded in real-time to track users' progress as well as giving them feedback. These are the primary methods for indicating a user's presence within a VR experience.

In a paper on design guidelines for VR applications, Johnson-Glenberg and Megowan-Romanowicz (2017) proposed "The Necessary Nine: Design Principles for Embodied

VR and Active STEM Education". These guidelines are actually well aligned with the empirical experiences observed in the research undertaken for this thesis, even though published *a posteriori*. A list of the nine principles is illustrated below with the correspondent examples from the present research:

	Experienced Space - Immersive User Interaction	
	9 Embodied VR design Principles	**Applied in IVAS**
Design	Scaffold cognitive effort one step at a time	Tutorial (see Section 5.3.3 Procedure, p. 135)
	Use guided exploration	The starting key serves as the guide (see Section 5.2.2 NPG, p.125)
	Give immediate, actionable feedback	Once the NPG is solved, a new room was loaded
	Playtest often, with correct user group	Chapter 4 was dedicated to testing
	Build opportunities for reflection	A *transition space to reflect* on the spatial qualities (see Section 5.3.3 Procedure, p. 135)
	Use the hand controls for active, body-based learning	Hand controls were fundamental to the design of the NPG
	Integrate gestures that map to the content to be learned	IVAS was not developed for the purpose of learning a specific topic, but to study the effect of spatial design. See next point.
	Gestures promote learning, agency, and attenuate cybersickness	Natural walking was implemented to navigate the room in accordance with physics and nautral body movements.
	Embed assessment, both during and after the lesson	The equivalent in this case was the spatial quality rating task carried out between each room

FIGURE 6.4: **Nine Embodied VR Design Principles.** Looking at how these guidelines were integrated into the design of the Immersive Virtual Architecture Studio.

The VR application implemented in this research made good use of these principles. The positive responses from all the users who have tested the different stages of the application presented here are a testimony to the strong foundations of these guidelines. They should be followed to create effective immersive virtual learning environments. However, nothing is explained in the aforementioned principles about the design of the surrounding architecture.

6.3 A Virtual Architecture Framework

With due consideration of the previously mentioned frameworks in addition to the findings of the present research, a new extended framework is proposed. Based upon the practice of designing both Archimemory and IVAS (and many other VR applications) as well as guided by the Punchcut framework, Figure 6.5 represents a starting point, identifying the principal elements for consideration when designing a VR application: the user, the environment/scene and objects.

VR is a human-centred medium, (see Section 2.5, p.39) and thus the user is situated at the top of the triangle. In the review of spatial cognition related studies, a dichotomy between *space* and *object* was exposed (see Section 2.4.2, p.26). Indeed, *space* and *object*

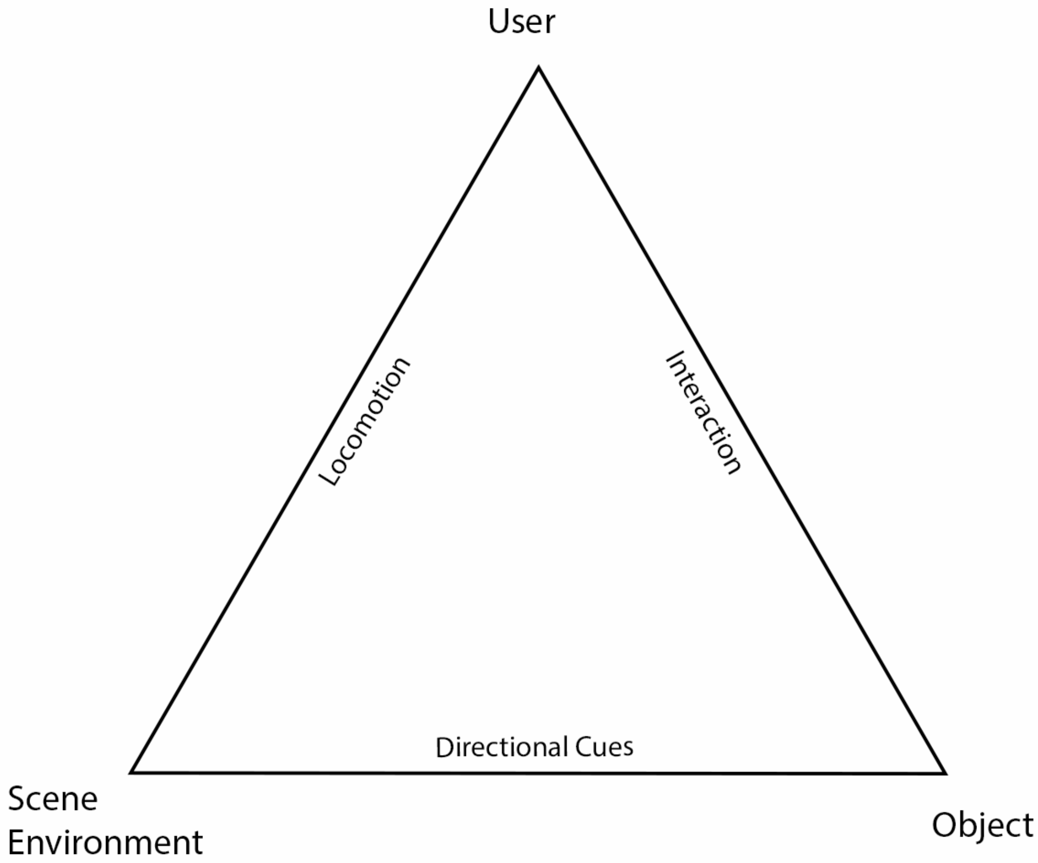


FIGURE 6.5: **Virtual Experience Triad.** The user is connected to the environment by potential locomotion, and to objects by potential interactions; object is connected to environment depending on their potential for cueing and direction.

engage different processes and, as such, should be considered discretely. This is a worthwhile framework to consider when designing virtual experiences. Nevertheless, it lacks a fourth element specific to the digital medium, and at the core of the present research, which is the ability to measure each action, and to use these measures to enhance the user experience.

The potential of tracking data in VR and measuring spatial qualities is often an afterthought when designing VR applications: VR companies are developing their own proprietary software to try to analyse these data but keeping their findings private [7]. Most of the data are captured by tracking user movement or object interaction (event). To my knowledge, none is evaluating the spatial qualities of the design environment and the potential effect it can have on user behaviours. Furthermore, most VR applications designed by such are simulation-based VR, which tend to replicate an

[7] VR training companies like Immerse `https://immerse.io/` and Innoactive `https://innoactive.de/` are developing a vast array of analytical tools to support the training of thousands of employees for different customers

existing environment.

In contrast, one of the early decisions was to focus on the design of virtual environments as a personal mnemonic device (see Chapter 3) that could potentially be used to complete different types of cognitive task, but which also adapts its architecture (see Chapter 5) to the users' modes of engagement (see also Chapter 7, p.183).

Taking into account the importance of metrics, analytics and feedback loops, a more complete representation of a potential framework to design and to optimise effective IVEs is proposed in Figure 6.6 and detailed below.

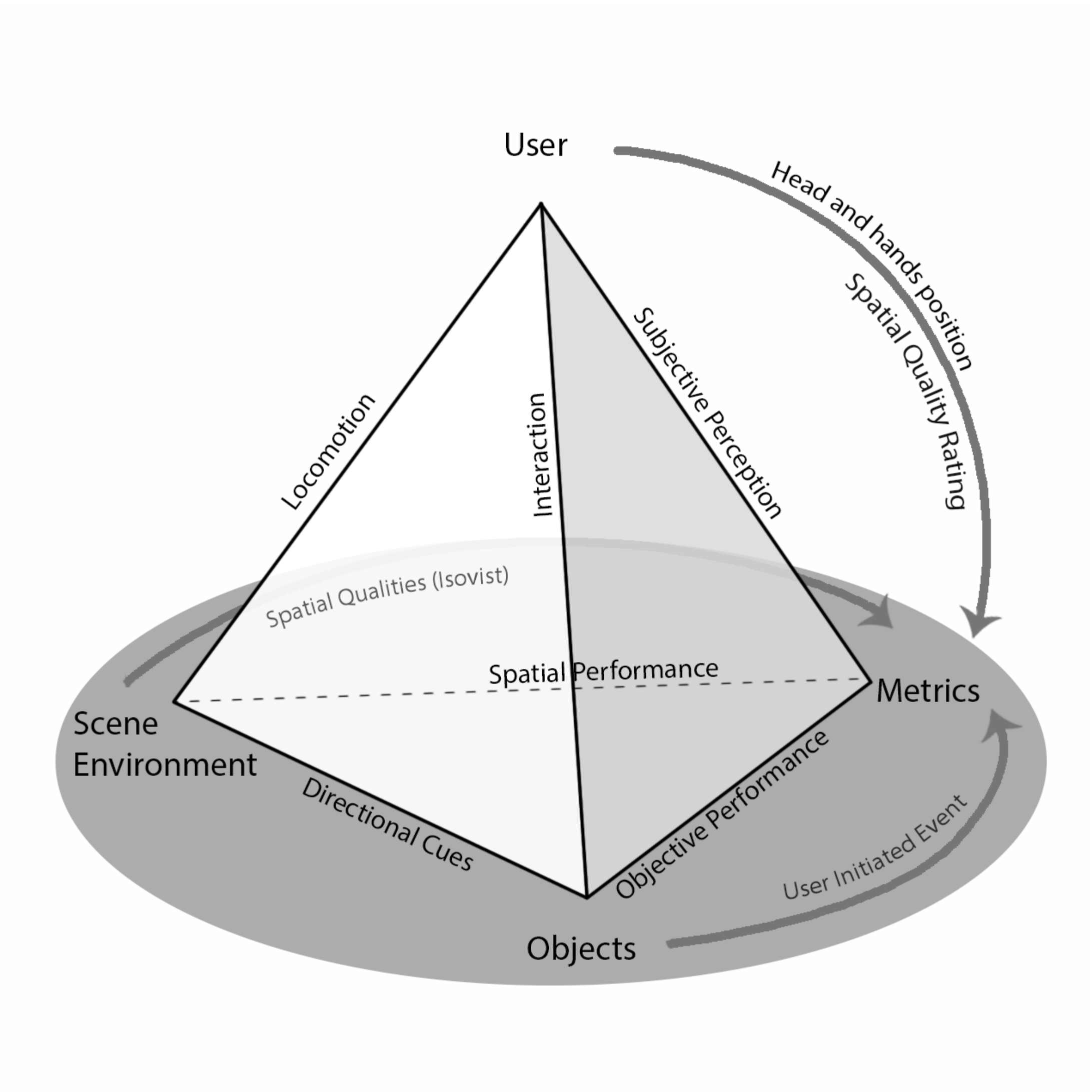


FIGURE 6.6: **The Virtual Architecture Framework.** The triad of user-object-environment is integrated in a framework that considers *measure* as a fundamental component in the design of effective VR experiences.

Vertex / Actors

- **User(s)**

- **Scene / Environment**: includes any form of spatial design, architecture or landscape
- **Objects**: static like furniture or dynamic like props
- **Metrics**: head and hands position, rotation, gazing, eye tracking, events, interaction, other physiological trackers.

Processes

- **Directional Cues**: created with Objects to attract users' attention to different places in the Environment and/or to guide the user along a storyline.
- **Locomotion**: determines how the user navigates the Environment
- **Interaction**: determines how the user interact with Objects

Performance Metrics and Analysis

- **Spatial Performance**: a room P is calculated by using the quantified spatial qualities determined by isovist methods in relation to the user and the task (object).
- **Objective Performance**: this analysis enables improvements on the design of the experiment based on task cycle time k.
- **Subjective Perception**: this analysis is run based on user feedback about spatial qualities and then compared with the spatial analysis run with the isovist method.

Typical Tasks

- **Spatial Qualities**: objectively measured by the isovist method (see Spatial Analysis, Section 4.2.4, p.87) and used to design the environment following user performance and subjectively measured by user rating task (see Spatial Quality Rating Task, Section 4.4.3, p.105)
- **User Initiated Event**: the design of the NPG with the starter key, the table and the puzzle block is a good example of a user Initiated Event (see NPG, Section 5.2.2, p. 123)
- **Head and Hands Position**: this was used in Archimemory to develop the interaction with the screen to browse through the images (see Screen Browsing Mode, Section 3.3.2, p.61) and to create the heatmaps (see Heatmap Visualisation, Section 3.4.3, p.70).

The pyramidal representation is a valuable way to encapsulate the key principles for the design of effective virtual learning environments. It offers a visual way to communicate to an audience, other scientists or VR developers. But it is somewhat limited in its scope. To fulfil the role of a framework as described above, and to plan and organise the various components used to design the virtual environments, Figure 6.6 laid out the different categories in an analysis grid-style template, the Virtual Architecture Analysis Grid (VAAG). This grid has been presented at the end of each chapter to summarise the main concepts discussed.

Virtual Architecture Analysis Grid		Geometric Space	Experienced Space
	Design	Architectural Design	Immersive User Interaction
	Measures	Spatial Qualities	Objective & Subjective

FIGURE 6.7: **The Virtual Architecture Analysis Grid** The analysis grid focuses on the spatial design of immersive learning environments. This is a template.

Chapter 7

Conclusions

> Writing has nothing to do with meaning. It has to do with land-surveying and cartography, including the mapping of countries yet to come.
>
> *Gilles Deleuze*

7.1 Answering the Research Questions

In order to explore the possibility of evaluating the effect of spatial design on users' cognitive performance in VR, this thesis has set out to answer a series of subordinate research questions, each representing a building block with which to assemble an answer to the main research question. The following section shows the summarised responses to these questions and concludes with the answer to the main research question.

7.1.1 Subordinate Research Questions

RQ1: What architectural features enhance participants' memory when using IVE? Overall, participants performed better when using a memory palace than when trying to remember the card from the control experiment, with an increase of 32% in recall accuracy. Additionally with participants' positive feedback, these findings confirmed the assumption that the Method of Loci can be adapted to VR as an effective device to enhance users' memory. However, the comparison between the two styles of architecture used in the memory palace did not show any significant results. Using card cycle time to measure memory performance seems promising. However, a single trial per user was insufficient to provide a benchmark with which to each participant's performance. Another take away concerned the importance of finding a way to compare measurable spatial qualities between the different layouts. This exploratory experiment was also a first step to gaining a better understanding of users' experience and behaviour when using virtual reality. For a more detailed response see Chapter 3 p. 53.

Taking into account the findings and limitations of the preliminary study, using Archimemory, the next three questions served to explore in greater depth the tools needed to answer the main research questions. Many iterations and prototypes were developed to attempt answers to RQ2, RQ3, and RQ4 in Chapter 4 (A Virtual Studio Prototype). Attempts to answer RQ4 led to exploration of different potential tasks to measure participants' performance. Once the two main tasks were identified, two new subordinate questions were set. More quantifiable answers were only possible after having tested a range of hypotheses during the user study documented in Chapter 5. The condensed answers to these questions are presented below.

RQ2: How to evaluate the correlational relationship between architectural elements and spatial qualities?
The correlational relationship between architectural elements and spatial qualities was evaluated using isovists method. Four spatial qualities were explored. Two spatial qualities, *complexity* and *openness*, were selected for their direct relevance to the two architectural elements, windows and columns. This was evaluated using two isovist descriptors known as *visibility* and *visual complexity*. The spatial analysis confirms that: adding columns increases the level of complexity of the rooms; and, adding windows increases the level of openness of the rooms. Furthermore, it shows some interactions between the two. For instance, adding windows also increases the level of complexity. The visualisation of the isovist fields also gives a good representation of the spatial qualities in relation to the layout.

RQ3: How do perceived spatial qualities correlate to those measured by isovist techniques?
The evaluation of spatial qualities was performed using two different models of geometric and experienced space (Dovey, 1993). On the one hand, spatial qualities were measured using isovist; on the other hand, participants gave their experience of these same spatial qualities on a rating scale (SQR) as suggested in the experiment by Wiener and Franz (2005). Users' feedback showed an overall consensus aligning their experience to the isovist measurements. However, this method of collecting users' subjective feedback proved challenging to set up for different reasons: obtaining users' feedback from inside the VR, the type of rating scale, the type of input. Overall, it did not show the significant results anticipated, but a trend towards the confirmation that participants perceived the room with added windows as more open, and the room with the added column as more complex. This question will need further investigation to improve the SQR, maybe by using a 7-step Likert-scale, or by improving the realism of the environment, as suggested by a couple of participants.

RQ4: What tasks can be implemented to evaluate the spatial performance of an immersive virtual environment?

From a spatial cognition standpoint, the three levels of spatial abilities, figural, vista, and environmental, described by Montello, Golledge, and Org (1998) and Hegarty et al. (2006) served as the foundations for this research. To address this theory, a series of tasks were partially tested for their feasibility as well as relevance. The Mental Rotation Task (Vandenberg and Kuse, 1978) and the Perspective Taking Task (Chang et al., 2017) turned out to be complicated tasks to implement in VR. Room-scale locomotion and immersive interactions were implemented with partial success to support the Visuo-Spatial Navigation Assessment (Ventura et al., 2013).

A new design was created that merged both scales of figural and environmental spatial abilities into one navigational task; instead of collecting gems (which do not have the same value in terms of incentive), one could collect Tetris-style figures with the incentive of assembling them in a puzzle in one location. This became the Navigational Puzzle Game (NPG) described in detail in Section 5.2.2 p.123. As for the vista and users' ability to remember and manipulate a spatial object/scene in one's mind eye, this could be implemented as a post-virtual experience task, which would lean toward a more memory-related measurement, the Visuo-Spatial Memory Test (VSMT) described in Section 5.2.3 p. 128.

RQ5: What is the effect of a specific spatial quality on a participant's spatial abilities?

The Navigational Puzzle Game (NPG) was designed as an embodied cognitively demanding task, requiring participants to use their environmental and figural spatial abilities to navigate the space and resolve the three-dimensional puzzle (see Section 5.2.2, p. 123). NPG was also designed to ensure participants completed the task, as only once the task was completed would the next room be loaded.

NPG was used to measure participants' time to completion, which was then used to calculate a spatial performance efficiency P for each room with its different spatial qualities. This produced a single metric to compare the effect of spatial design on participant performance when solving the NPG. The investigation comparing each condition showed that the puzzle was completed most quickly in the rooms with fewer windows and columns, with a P of 118%. One explanation is that the closed walls reduce the visibility of the outside world, that is, reducing 'distractions', and the columns structure the space in a way that supports efficient navigation to help find the different items. The second room with columns has more windows that afford greater visibility of the second layer of columns, outside, which seems to disturb participant performance.

Overall, the NPG was well received by the participants. However, different variations would be needed to develop further spatial performance metrics. For instance, the opportunity for a user to repeat the same level more than once, or the option to choose between different levels of difficulty would be necessary to produce a more accurate benchmark.

RQ6: What is the effect of spatial qualities on a participant's memory performance?
A new task was put to the test to answer this question. The VSMT was used to measure the success rate of participants' recognition of the rooms they had experienced from images presented, once participants had exited the VR experience. When presented with 16 pairs of images, participants' responses were 78.75% correct, which aligns with the 75% threshold of correct responses usually obtained with a two-alternative forced-choice task (cf. Posner, 1980). A significant improvement on memory performance was shown when comparing the more open rooms (a higher level of *openness*) with the closed rooms. However, the difference between adding columns or not had no significant effect on memory performance.

7.1.2 Answering the Main Research Questions

Main RQ: How to evaluate the effect of spatial design on users' cognitive performance in immersive virtual environments?

In all the previous answers to the subordinate questions, at least a partial answer to the main question emerges. The literature review of spatial cognition showed a lack of consensus on the understanding of how spatial knowledge is represented in the human mind. However, a common trait exposed the dichotomy between objects and scene representation (see Section 2.4.2, p.26), also called figural and environmental spatial abilities (see Section 2.4.3, p. 34). This framework was suggested by Montello, Golledge, and Org (1998) and further studied using desktop-based virtual environments by Hegarty et al. (2006). This useful differentiation is fundamental to this research and for the design of VR applications in general.

The preliminary study, Archimemory, showed the potential of using virtual environments to enhance memory retention. It also highlighted two main challenges: the difficulty of designing a measurable cognitive task with the actual scientific understanding of such a complex process; a need to identify specific and measurable spatial qualities.

A second key theory, related to information processing, is the dual coding theory proposed by Schneider and Chein (2003). It was important to ensure the spatial perception of the environment was not the prime focus of the experiment, but as in most real-life situations, was a secondary type of information, processed automatically. Both theories of spatial abilities and dual coding theory have greatly influenced the design of the study, proposing a experimental design with a high-focus object manipulation task such as in the NPG (RQ5) and a second task based on spatial representation such as the VSMT (RQ6).

Both tasks were completed by all participants in each of the four conditions. Their performances were used to compare the benefits of the different spatial design. These rooms were objectively measured in term of spatial quality, *openness* and *visual complexity*, using an isovist method. A series of descriptors were extracted from the isovists to calculate one measurand, which represents a specific spatial quality. Details of these spatial qualities are further described in Chapter 4 (Section 4.2.3 p. 85). These objectively measured spatial qualities were also tested using an embodied approach, aiming to reconcile these mathematical measurements with participants' subjective experiences translated by the Spatial Quality Rating task (RQ3).

The answer to the main research question is therefore that the evaluation of the effect of spatial design on users' cognitive performance is possible using an embodied approach to immersive virtual environments, but that the implemented tasks encompass only a few elements of a complex field of research, such as spatial design and cognitive psychology.

Overall, even though only a partial answer to the main research question is proposed, this thesis brings to light the potential of architectural design in the development of immersive virtual environments, not only as a scientific tool but also as a method for training and learning.

7.2 Contributions to the Literature

This research transitioned from a web-based memory game to a 3DOF VR environment applying the MoL (Chapter 3), and then to an immersive virtual studio (using Room-Scale VR) to test the effect of spatial qualities on user cognitive performance (Chapter 5). This progression was influenced on the one hand by the available hardware, and on the other hand by an embodied approach to cognition. These two important factors led this work towards use of the most immersive and affordable VR systems available. Elsewhere, in the literature, the same progression occurred (Chapter 2).

Whereas previous work (using equivalent VR system, 6DOF) has often focused on solving user interaction problems in isolation, such as embodied interaction and gesture (Johnson-Glenberg, 2018), locomotion (Boletsis, 2017), or even distance estimation (Ghinea et al., 2018), this thesis contributes to the literature by providing a framework with which to design effective environments around these user-based interactions. It also demonstrates the importance of using a holistic approach in the design of VR experiences, as each of the four main elements presented in Chapter 6, Figure 6.6, user, object, environment, and metrics, can influence each other, with the main focus being on a method to measure more specifically the effects of the environment on users' performance, as detailed in Chapter 5, p. 130.

The main finding of this thesis may present an important means of orientation and reference for researchers aiming to further explore the potential of the virtual architecture framework to design effective virtual learning environments. Beyond that, it provides numerous contributions derived from the research leading up to the above conclusion, each relating to a certain aspect of the literature. To help present these, the contributions are described separately for each research topic and chapter.

7.2.1 Research into the Application of the MoL in VR

The first experiment (Archimemory, see Chapter 3) demonstrated the benefits of working with VR technology to measure participants' movements and actions as well as the potential of adapting the MoL in VR. Two other studies by Krokos, Plaisant, and Varshney (2019) and Reggente et al. (2020) have demonstrated an increase in memory retention when using the MoL in VR but from a fixed location, allowing only the rotation of the head. The Archimemory experiment (using 6DOF) permitted the participants to walk around each memory palace (using an Xbox controller), and choose their own journey to remember a sequence of playing cards.

With regards to studying the effective use of mnemonic strategies (McCabe et al., 2013), Archimemory could offer a solution to further test the potential of such a technique for undergraduates. Indeed during the testing, no participants complained about the difficulty of acquiring such a method, as it came naturally. Participants' feedback and sketches showed a high degree of retention of each layout, which could lead to further research into the effect of locomotion on spatial representation as attempted by Hegarty et al. (2006). Furthermore, the interaction system programmed to create the association playing card/image/frame as well as the general setup could be reused for further investigations in the field of spatial cognition.

Whereas previous work has often focused on a comparison of different systems to understand their respective benefits, and an evaluation of the transferability of results acquired from one environment; that is, transferring skills learned in virtual environments into the real world, such as undertaken by Xu, Murcia-Lopez, and Steed (2017) and Murcia-Lopez and Steed (2018), Archimemory focused on users' development of mental imagery in the form of spatial visualisation, by comparing the effectiveness of one type of spatial design over another, a unique approach in light of the existing literature review.

7.2.2 Research into Architecture and Cognitive Psychology Using Room-Scale VR System.

The design of the Immersive Virtual Architecture Studio (IVAS), as explored in Chapter 4 and 5, is a robust solution to deploy room-scale VR in scientific settings. The IVAS can be used as a simulation-based environment to run experiments that need to simulate real-world settings. It provides a virtual laboratory that can be used to run a wide range of experiments, from the field of behavioural psychology to cognitive neuroscience and from sociology to architecture. The method is based on an embodied approach to cognition and would allow the replicability of such studies using the same specific room-scale VR system.

Compared with previous research at the intersection between architecture and psychology, such as that carried out by Wiener and Franz (2005) and Dosen and Ostwald (2017), the methodology explored in Chapter 4 and demonstrated in Chapter 5 brings two main contributions: (a) it represents an affordable and robust solution to deploy room-scale VR in scientific settings, allowing repeatability and an equivalent level of immersion; (b) the implementation of the Spatial Quality Rating task in parallel with the isovist measurements of the same spatial qualities suggests a valid methodology to reconcile both objective and experienced space, and is supported by previous research (Dovey, 1993).

In addition, another advantage of the IVAS is its proposition as a standardised virtual room layout that fits most real-world rooms, following four principles (presented in Chapter 4). These design principles need further testing as well.

1. **Flexibility:** to make sure the same experiment can be run in both locations and eventually anywhere else, the dimension of the virtual studio had to fit the smallest of the two locations mentioned above. The smallest of the two locations was 3.2m by 3.8m. A basic layout used repeatedly in architectural analysis and space syntax in particular is the 3x3m square cell 'building block' (Hillier and Hanson, 1984) also called a 'perfect grid'.

2. **Rotation:** using a square perimeter affords the rotation of any internal layout by 90 degrees so that the sequence of rooms can be randomised without changing the layout. By rotating or mirroring the rooms, the next room will propose a layout that will appear different to the user.

3. **Trajectory:** each room has to offer the same distance to travel from the table to each item's location so that participants' time to travel are comparable.

4. **Line of Sight:** each space is composed of an interior perimeter corresponding to the physical room and delimiting participant locomotion and an exterior perimeter delimiting the participant's view. This is important, as even though confined in a limited physical space, the visible space can be increased virtually as much as necessary.

7.2.3 Research into Spatial Abilities, Navigation, and Learning

Whereas previous work in cognitive psychology used a desktop-based virtual environment or video tape to study the different scale of spatial abilities, such as that proposed by Hegarty et al. (2006) and Ventura et al. (2013), the method proposed in this thesis demonstrates advantages. The implementation of the NPG addresses both environmental and figural spatial ability in one task. The VSMT task takes into account the vista spatial ability. Moreover, the question of spatial representation of unknown environments, as studied by Slone et al. (2015) is also addressed by proposing the free navigation task before having participants engage with the NPG as described in Chapter 5 p. 126.

7.3 Limitations

In Immersive Virtual Environments, any programmed interaction can be measured accurately with the data acquired from the different input devices, such as the HMD and the controllers. Any part of the environment can also be modified at will. Such a flexible information-rich environment can rapidly weaken the ecological validity of the system. It is critical to design a controlled environment by narrowing down the scope of the experiment. The independent variable must be clearly defined. However, narrowing down the study to very specific conditions can at the same time make the overall investigation seem obscure and reductive.

As the experiment results demonstrated, different levels in spatial qualities such as *openness* and *complexity* can play a decisive role in participants' performance completing the Navigational Puzzle Game. In the case of *complexity*, for instance, the added column did not affect performance *per se*. This does not mean, however, that a certain level of complexity is not necessary to support one's navigation. This user study represents just one way to manipulate complexity. Instead of adding an array of equidistant columns, adding one or two columns at a specific location could be more beneficial. Besides adding complexity to the room, the added columns could either be measured with another spatial quality such as *order* or they could also be considered as a landmark. Many studies like Riecke (2002) have shown the importance of landmarks to facilitate one's navigation and wayfinding.

The results of the VSMT also showed a significant improvement in recall linked to the higher level of openness. Indeed, participants remembered best the rooms with the most windows affording them an increased range of visibility. However, this same quality made them slower in performing the NPG. A series of precise questions could have brought more insight to understand what was more memorable about the room with more windows: was it the architectural elements visible outside, or maybe the quality of the texture mapped onto these different elements?

7.3.1 Chapter 3 - Archimemory

In Chapter 3, the comparatively small sample size of the preliminary study, Archimemory, led to some inexplicable results, suggesting that this potential sampling error could lower the impact of the findings of this part of the study, and that these should be regarded as trends rather than definitive effects. In addition, only two broadly defined architectural styles were used to compare their effect on recall performances; this experiment would have benefited from the knowledge acquired in the following chapter, mainly the measurement of the spatial qualities using isovists.

The association between photos (from various themes) and playing cards, was in itself a difficult mechanism to measure. The time taken by each participant can vary widely with the type of associations at play. An increase in the number of trials per participant would have produced a potential benchmark with which to compare recall performance in recall more accurately. The inclusion of gaze-tracking data could have been helpful to understand users' behaviour in more detail, but this extends beyond the scope of this chapter. Finally, the study in Chapter 3 was conducted with participants in a stationary position. Therefore, the findings potentially lack generalisability, which suggests further research is required to extend their validity.

7.3.2 Chapter 5 - IVAS

The Spatial Analysis

One shortcoming of the method used to run the spatial analysis was the lack of absolute value for each spatial quality. Indeed, the value represented a percentage of *openness* or *visual complexity* relative to the specific layouts. The problem became evident where two different layouts/rooms had the same values. However, the visualisation of the isovist field depicted the situation, showing clearly the differences. This demonstrates that for such complex measurements involving two or even three dimensions, a visual representation can be as important as more abstract values. Nevertheless, it also shows the limit of the investigation in the spatial analysis. Further work is needed to develop a classification of measurement for each spatial quality in relation to a variety of architectural elements.

The Spatial Quality Rating Task

With regards to the counterpart subjective measure of the same spatial qualities, here follows a list of shortcomings of the current setting:

- A five-point Likert scale is too narrow, and the neutral position does not help. Perhaps a six-point scale would be more appropriate.
- Participants need to rate against some reference space that they have to visit first. In the present configuration, they were indeed rating the rooms in comparison to the first encountered room.
- The variations in enclosure and complexity were limited, which made it difficult to rate subtle variations from the user's standpoint.
- Increasing the number of trials for each participant so a benchmark can be established.
- Having a virtual poll inside the VR space would be beneficial as it would maintain the feeling of presence in that space, an invisible, external interlocutor asking the questions.

The Navigational Puzzle Game

The main shortcoming of the NPG was an unresolved bug in the code. Consequently, participants were not able to throw the blocks away. If they tried to do so, the blocks would go to the right instead of falling, which made it unrealistic. This was an incidental problem however, as there was no requirement to throw the blocks away to complete the task and it was not of major concern. Another issue, which is common in VR, is the way dynamic blocks interact with each other. They were jumpy at times, which made it difficult for some participants to manipulate them to complete the puzzle on the table. The solution was to ensure they did not come into contact by introducing them vertically in the correct rotation. Many software solutions have been developed since to resolve these problems. That apart, here follows a list of further suggestions made along the user-testing sessions to improve the application.

- The starting key should be of a different shape and material
- Table extension to manage more easily the Tetris-shape items
- Have a version for younger users with a lower table
- Create more variations of the jigsaw puzzle

The Visuo-Spatial Memory Test

The main concern for this task was related to the presence of the colourful blocks in the images utilised in the test. These probably influenced the way in which participants recognised the different rooms. It was difficult to evaluate if they were paying attention to the spatial features, such as columns and windows, or to the objects left in the space. This brings back the dichotomy between scene and object discussed throughout this thesis. One way to resolve these issues would have been to save all the images without any blocks in the space. Another way would have been to include gaze-tracking data to better analyse participants' recognition processes.

7.4 Future Work

This section provides a set of suggestions stemming from questions and opportunities identified throughout this research. Each suggestion is associated with one of the three future stages of development as part of my wider research interests, of which this thesis is only the first step. Indeed the full potential of this research will have to be developed in stages as each stage ideally requires different skill sets involving experts from a range of fields.

1. Virtual Architecture Framework
2. Virtual Architecture Assets Library
3. Generative Virtual Architecture Software
4. Interactive Virtual Architecture Model

7.4.1 Virtual Architecture Framework

In summary, the first stage, explained here, was to find a methodology to evaluate the effect of architectural design on human cognitive performances in VR. The second stage consisted of using this methodology to further test each architectural element (see Section A p.187) in a variety of arrangements, as well as testing different spatial qualities (see Section 4.2.3 p. 85) to build a library of parametric assets. These assets would be categorised following a range of spatial performance efficiency P in relation to each cognitive task. These could then be attached to "generative design" software to automate the creation of layouts and 3D models to be tested by users, ideally online to increase accessibility.

Finally, with the vast amount of data collected from the online participation, the last stage would consist of developing a predictive model of user engagement based on their movement patterns. Such a refined model could then be used to propose a spatial design that is not only adapted to the task at hand, but also to the specificity of learners' modes of engagement.

7.4.2 Virtual Architecture Assets Library

Integrating more Tasks

The Archimemory experiment described in Chapter 3 (p. 53) was also designed to evaluate the benefits of using one style of architecture over another. In light of the findings in chapter 5 and the Virtual Architecture Framework, the memory task could well be implemented following the IVAS protocol with a higher level of immersion, to further test the effect of spatial qualities on memory recall.

Adding Spatial Qualities and Refined Variables

One of the main contributions of this thesis is the Virtual Architecture Framework. This framework needs to be developed further by carrying out more user studies, and evaluation of other VR experiences. A follow-up study should take into account different spatial qualities such as *spaciousness* and *order* maintaining use of columns, walls and windows. The next step would be to complete a classification of the effect between Spatial Qualities and Architectural Elements. Then, going even further, the study could include the architectural features and the architectural properties proposed by Alexander (2005). In addition, the integration of advanced 3D isovists would be beneficial to study the effect from a more spatial standpoint (Varoudis and Psarra, 2014).

Development of Online Version

A room-scale VR system required people to come to a specific location to participate in the experience. Today, readily available, cheaper and non-tethered VR headsets are commercially available on the market, and represent an opportunity to gather more data from thousands of people using this hardware from home. A full version of IVAS online is planned in 2020 as an open-source project. The effort of Mozilla Hubs to develop an open-source web-based VR platform represents a fantastic opportunity to create an online version of the experiment.[1]

7.4.3 Generative Virtual Architecture Software

The workflow explained in chapter 4 (see Section 4.3.2, p. 96) was based on the existing plug-in Grasshopper, bundled with Rhino. The development of the previous stage with a library of assets would only make sense if there was software designed for an architect or designer to use these assets in an efficient manner in the pursuit of effective designs.

7.4.4 Interactive Virtual Architecture Model

This stage is user-based and aimed at refining the understanding of user modes of engagement within the spatial environment. The first step is to identify patterns in participants' movement that correlate with a specific mode of engagement and then to generate a reusable dataset. These identified movement patterns and dataset will then be used to inform the design and the experience of the VE. The process is divided into four phases. In a first phase, participants would be required to complete a Wechsler

[1] Read more about the Mozilla Hubs Cloud Project here `https://hubs.mozilla.com/cloud`

Intelligence Scale for Children [2]. The relationship between players' body movements in games and their engagement is referred to in the study by Bianchi-Berthouze (2016), in which she defines a series of modes of engagement that would serve as a foundation for the research.

A comparison between different environments would be used to encourage users to move around and complete the NPG and the VSMT. Head and hand positions over time data will be collected. The movement data collected through the VEs will be used to develop a method to recognise and classify movement patterns associated with the identified mode of engagement from phase 1. The process is divided into two stages using different types of machine learning algorithms inspired by Böck (2018) and shown in Figure 7.1. The development of this method is based on the implementation of InteractML in Unity (Diaz, Perry, and Fiebrink, 2019).

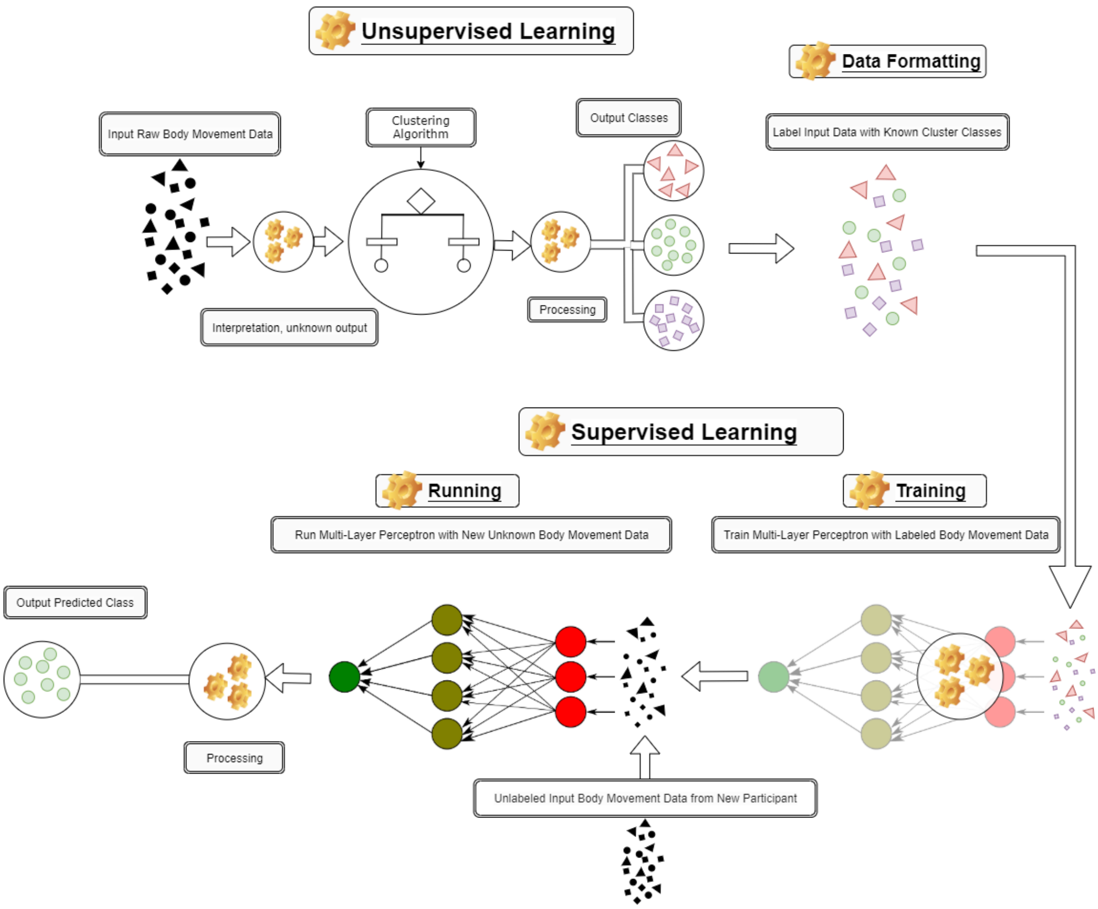


FIGURE 7.1: **Calibration Method Machine Learning stack.** This visualisation of a potential workflow was conceived in collaboration with C. Diaz for the application submitted to Innovate UK, smart Grant, January 2020

[2]The Wechsler Intelligence Scale for Children Fifth Edition (WISC®-V) is an intelligence test that measures a child's intellectual ability in five cognitive domains that impact performance: Verbal Comprehension, Visual-Spatial, Fluid Reasoning, Working Memory, Processing Speed. It can be accessed online at `https://www.pearsonclinical.co.uk/q-interactive/q-interactive.aspx`

The objective of this stage is to create a virtual calibration method, which could be used at the beginning of a virtual experience to rapidly capture participants' specific mode of engagement. Based on that evaluation, the experience can be personalised to enhance participants' engagement with the content, and by doing so, improve their learning performances.[3]

7.5 Closing Remarks

If the computer is to be the extension of our senses, it is essential that its operation supports users' spatial abilities, minimising effort and maximising efficiency. This can be achieved by the design of immersive virtual environment in accordance with these desirable norms, with due consideration of anatomical constraints. Therefore, this thesis has tackled the problem of designing effective virtual environments from various angles: evaluating objective spatial qualities, taking into account users' subjective experience, presenting a room-scale VR optimised for embodied cognition, proposing a batch of cognitive tasks covering memory and spatial abilities, and finally, a series of performance metrics. Each of these contributions as a whole forms a methodology to support the design of effective virtual environments, making VR more suited to support the growing trend in immersive learning.

While the presented methods for enhancing this human-machine dialogue may have been applied to the current state of technological development, the concepts behind them may continue into the future, even one in which VR technology advances further and moves to a set of eXtended Reality (XR), in which our physical surroundings are superimposed with a digital layer of 'Augmented Realities'.

For example, with the next generation of VR HMD (or VR goggles, or VR glasses) touted as 'wireless and wearable', with affordances to switch between realities, then the contributions of this thesis could be transferred as follows:

- The insights into spatial performance and generative design could be integrated into a VR application. At the moment the spatial analysis occurs in software distinct from that used to generate the VR experience; 3D models are generated with yet another application. The integration of all these components would afford designers the ability to generate and test in real-time spatial design within the VR application. The architect and the user finally merge into one entity as do the geometric and the experienced space.[4]
- The rooms used in IVAS were custom-built 3D models imported in Unity and manually aligned with the actual physical environment, a basic mixed reality. AR

[3] This section describes a feasibility study that has obtained a overall score of 78% to Innovate UK Smart Grant in March 2020

[4] Companies such as Constructive lab `http://constructivelabs.com/` or Tvori `https://tvori.co/` are working on these new types of immersive design tools.

headsets, such as the Hololens from Microsoft already embed the capability of scanning the surroundings and building a 3D model that can then be used to map a digital layer onto it. In May 2020, Oculus Quest released the 'Playspace Scan' feature to detect objects, which gets in the way. Soon, the next generation of HMD will integrate all such advanced features allowing a detailed 3D model of the surroundings to be created 'on-the-fly'. The integration of the VAF into such a technology could afford the user an optimisation of their physical space, virtually adapting the spatial performance to specific tasks requirements.

- Using the VAF to design effective VR training simulation for enterprise has vast potential. VR is already used to 'on-board' new employees, carrying out staff inductions, guide experience and knowledge transfer to new recruits (Osborne and Watson, 2020). VR can be set up as self-access, so that employees can train in their own time. The key is to set up the right metrics so that an employee can gain insights by being assessed in real-time.[5]

Whatever developments occur, future research is likely to continue to focus on improving the interaction between humans and computers. Spatial computing promises to bring a more immersive experience in the way humans navigate their digital landscape, giving them the choice to integrate it into the physical world or to create their own bespoke virtual environments. My hope is that this work can inspire architects and designers alike to actively take part in the creation of this new style of virtual architecture.

[5] I worked on such a solution between November 2018 and Mai 2019. A demo can be find online at `https://vimeo.com/391474801`

Appendix A

Archimemory Preliminary Experiment

Architectural Elements Over the centuries, many more architectural elements have been added to the architect's tool box. Architectural elements are the components used to design houses, public buildings, and any other type of architectural structure. Here is a list in alphabetic order, of the main architectural elements and their definitions (Curl, 2006).

- Arch: a curved structure capable of spanning a space while supporting significant weight.
- Ceiling: the upper interior surface of a room.
- Column: a structural element that transmits, through compression, the weight of the structure above to other structural elements below.
- Door: a movable structure used to close off an entrance, typically consisting of a panel that swings on hinges or that slides or rotates.
- Fireplace: an open recess in a wall of a room, at the base of a chimney, etc, for a fire; hearth.
- Floor: the surface of a room on which one stands.
- Lighting and fixtures: something attached as a permanent appendage, apparatus, or appliance
- Roof (dome, flat, inclines): the exterior surface and its supporting structures on the top of a building.
- Staircase: a flight or series of flights of steps and a supporting structure connecting separate levels.
- Wall: an upright structure of masonry, wood, plaster, or other building material serving to enclose, divide, or protect an area, especially a vertical construction forming an inner partition or exterior siding of a building.

- Window: aperture in a wall to allow light and air to enter a building. It is often framed and spanned with glass mounted to permit opening and closing.

Building upon architectural elements, architects developed the architectural language further by designing features such as, but not limited to: cornice, cresting, entablature, facade, frieze, latticework, mansard roof, parapet, spandrel, turret. Although these more complicated objects are not considered in the context of the present research, they are part of the architectural language with their functions and meaning, and constitute a resource for further investigation.

The Memory Card and Recall Board - Code in Javascript Part 1

```
var shuffledCards = [];
var row1Cards = [];
var assignedCards = [];
var maxCards = 9;
var currCard = 0;

$(document).ready(function()
{
    // shuffle
    shuffledCards = shuffle(cards);
    shuffledCards = shuffledCards.slice(0, maxCards);
    // console.log(shuffledCards);
    // add event for text 2 game button:
    $('#convertString').click(function()
    {
        getCardsFromTextField();
        $('#part_2').fadeIn('normal');
        makePart2();
         // alert("done");
    })

     $('#convertString').on('click',function(e){
        e.preventDefault();
        $('.clearit').val("");
    });

    // add events part 1
    $('.shownext, #backCard').click(function(e)
    {
        if(currCard < maxCards)
```

```
        {
            '.frontCard'). shuffledCards
        }
        else
        {
            //finish part 1:
            currCard = 0;

            //remove click function
             $('.shownext, #backCard').unbind("click");

            //show button
            $('#nextStep').fadeIn('fast').click(function()
            {
                $('#part_1').fadeOut('normal', function()
                {
                    $('#part_2').fadeIn('normal');
                    makePart2();
                }
            )
            });
        }
        return false;
    })
})
```

The Memory Card and Recall Board - Code in Javascript Part 2

```
function makePart2()
    //place row 1 and create row 2
    //duplicate for "independent" array
    for(var i=0; i< shuffledCards.length; i++)
    //console.log(row1Cards);
    //sort
    row1Cards.sort(function(a, b)
    //build 2 rows...
    for(var i=0; i < row1Cards.length; i++)
    //drag
    $(".imgToDrag").draggable();
    //drop
    //set val and style
```

```
    //put into array
    //check if all are full

function evaluate()
{
   // alert("Done!");
    //compare images from div to position in Array
    for(var i=0; i < maxCards; i++)
    //show me the money!
    $('#results').toggle();
}

function sendOff()
{
    $.ajax(
    {
        type: "POST",
        url: "save_xp01.php",
        data:
        card01: Number(assignedCards[0] == shuffledCards[0].cardname),
        success:function(data){}
    })
        .done(function( msg ) {
        $('#results').append( "Thank you.");
            console.log(msg);
    });
}
```

Screen Browsing mode - Extract from the CSharp script running in Unity

```
F: Set of pictures for association Purposes
C: Set of 52 deck of cards
U: The user who is interacting with the system

screenActive : It will check whether any frames is activated or not
currScreen : Load the Current Screen
allScreens : All Screens
isAccosiated : Is the screen associated with the card?
inBrowsingArea: Is the user in browsing area (BA)?
isScreenVisible: Is the given screen visible to user inside BA?
numScreen: Total Number of Screens
```

```
currCardIdx: Index of the Current Playing Card
activeScreenIdx: Index of the Active Screen.
lastActiveScreenIdx: Index of the last active screen
numEntered: An array indices where user has entered
numCardAssociated: Total number of cards associated
maxCards: Maximum number of cards
minDist: A tolerance for minimum distance between user
and screen to make browsing mode active
maxDist: A tolerance for maximum distance between user
and screen to make browsing mode active
screens: Arraylist holding all screens and its status
cards: ArrayList holding all cards
pictures: ArrayList holding all pictures
picCardScreenAssoc: Arraylist holding card-picture-frame association
cardAssignedIndex: List of indices of cards already assigned
pictureAssignedIndex: List of indices of pictures already assigned
cardDisp: Where the playing card will be display
userNum: Create a number for each user output files
userPos: Current position of the User
guiColor: GUI color, to control alpha of playing cards
cardsAssignedTxt: will say that all cards associated

loadScreens():
Initializing all Screen as Inactive:
foreach (Transform kidlette in allScreens.transform)
{
screenNo f;
f.name = kidlette.name;
f.pos = kidlette.transform.position;
f.status = false;
f.cardAssoc = false;
screens.Add(f);
}

Update is called once per frame:
if(numCardAssociated<maxCards)
userPos =   //User's Current Position
//Check and modify the value of screenActive

UpdateScreenActive()
If any of the screen is activated by user movement, update the variable
```

```
If "all" the screens are deactivated, make this variable false.
activeScreenIdx = -1;
for(int i=0; i<screens.Count; i++)
{
screenNo f = (screenNo)(screens[i]);
f.status = true;
screens[i] = f;
activeScreenIdx = i;

if(activeScreenIdx!=lastActiveScreenIdx)
numEntered[i]++;
lastActiveScreenIdx = activeScreenIdx;
}
else
{
screenNo f = (screenNo)(screens[i]);
f.status = false;
screens[i] = f;
}
```

		Palladio = 1 Curvy = 2				
	Participants	ArchType	Quesiton 1 : features	Question 2 : association		Why
1	3	1				
2	6	2				
3	7	2				
4	9	1				
5	11	2				
6	12	1				
7	17	2	Green/red			
8	19	1	Green Sofa, blue carpet, plants			
9	21	2				
10	26	2		Motorbike	10 diamond	red
				Michael Jackson	King diamond	king of pop
				Obama	8 spade	connections
11	28	1	Plant	BigBen	8 club	8 O'clock
			Blue Rugs	Swan	7 heart	heart - love
				Cyclist	2 heart	2 of them
12	31	2	ligth spot, bricks, table	Lady bird	5 diamond	4 legs+1 head red
				Motocycle	10 spade	first that came up
				beach	2 diamond	
13	34	1	plant, soafa, table, brick	5 Skydivers	5 spades	
				Golden Eagle	King spade	
				Michael Jackson	Jack diamond	
14	37	1	rugs, red, sofa	3 daulphins	3 spades	
				Jimmy hendrix	1 spade	
				Madonna	Queen club	
15	40	1		woman fire	Queen club	
				motorbike	5 heart	
				snake	Jack Club	black and white
16	42	2		galaxy	7 spade	special number
				eagle	king spade	royal
				Sidney opera	8 club	architecture
17	44	1	red coach		6 heart	symmetrical
				sea	9 heart	fav number
				Liberty	king of heart	
18	47	2		motorbike	Ace Club	champion
				Madonna	Queen club	
				Timelap snowbaord	8 club	numbers of element

TABLE A.1: Participants Qualitative Answers

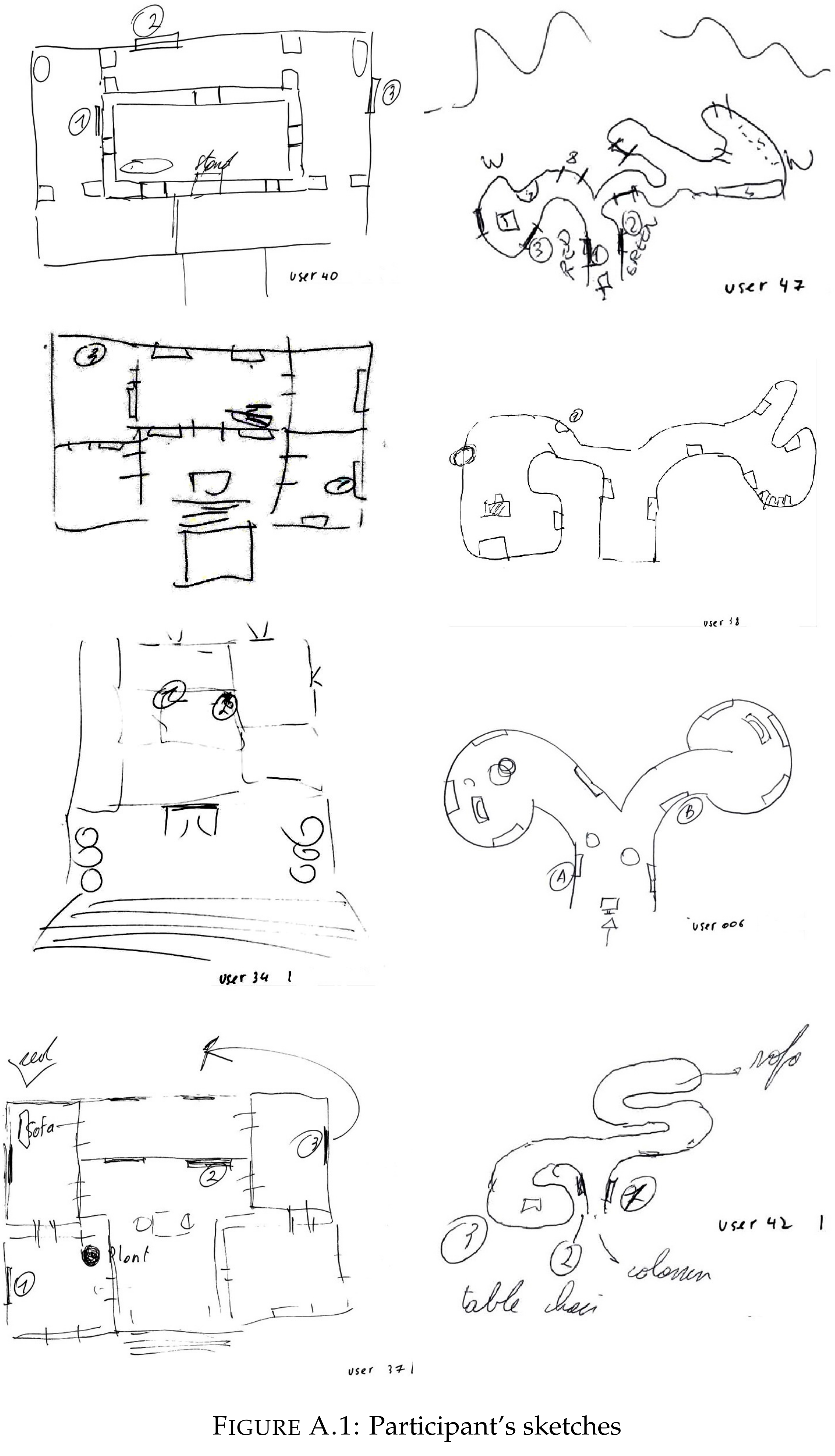


FIGURE A.1: Participant's sketches

	Participants	When	ArchType	Number of Cards	Time to associate
			Palladio = 1		
			Curvy = 2		
1	3	13/11/2014	1	9	04:00
2	6	14/11/2014	2	3	07:00
3	7	06/11/2014	2	6	04:00
4	9	06/11/2014	1	9	07:00
5	11	06/11/2014	2	5	08:00
6	12	06/11/2014	1	1	09:00
7	17	06/11/2014	2	7	06:00
8	19	06/11/2014	1	4	08:00
9	21	06/11/2014	2	0	09:00
10	26	27/11/2014	2	9	05:00
11	28	28/11/2014	1	3	08:00
12	31	28/11/2014	2	9	05:00
13	34	28/11/2014	1	9	03:00
14	37	05/12/2014	1	4	05:00
15	40	05/12/2014	1	6	05:00
16	42	16/12/2014	2	2	05:00
17	44	16/12/2014	1	7	05:00
18	47	16/12/2014	2	9	05:00
			Mean	5.67	06:00

TABLE A.2: Participants raw scores

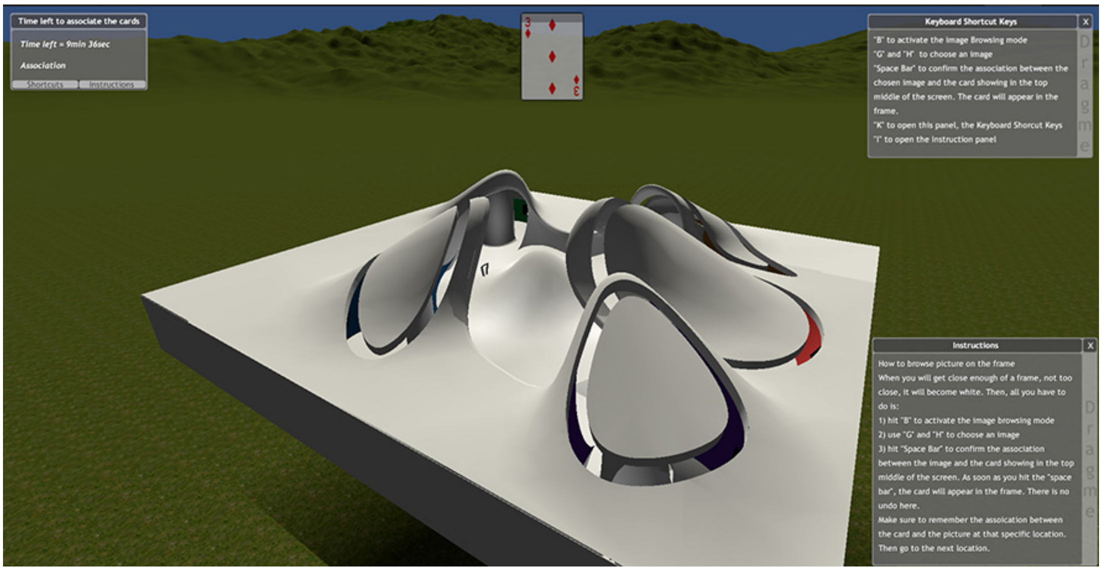


FIGURE A.2: ArchiMemory - Organic Room Exterior

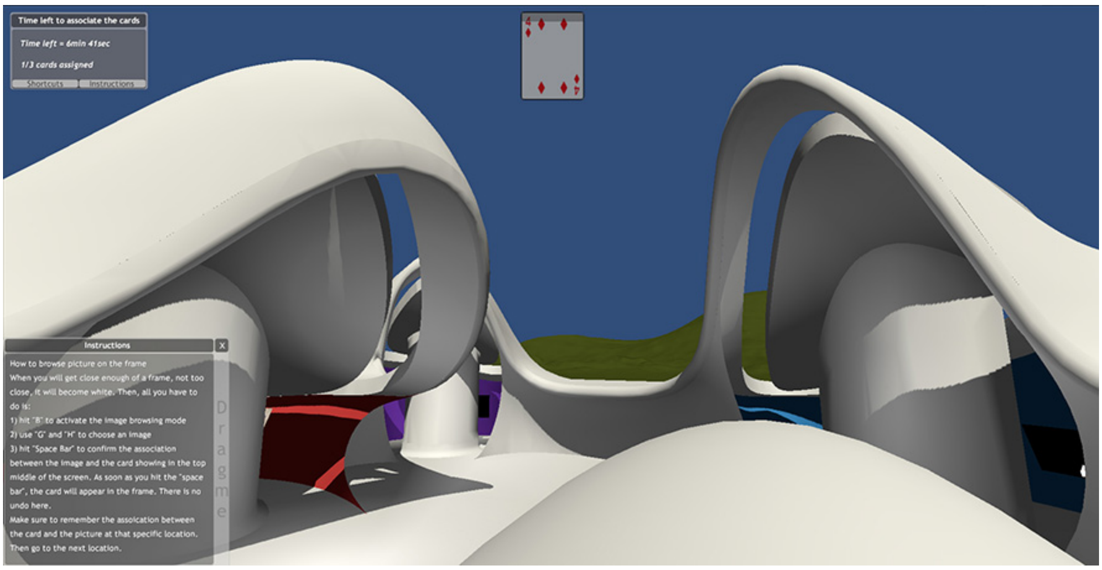


FIGURE A.3: ArchiMemory - Organic Room View 1

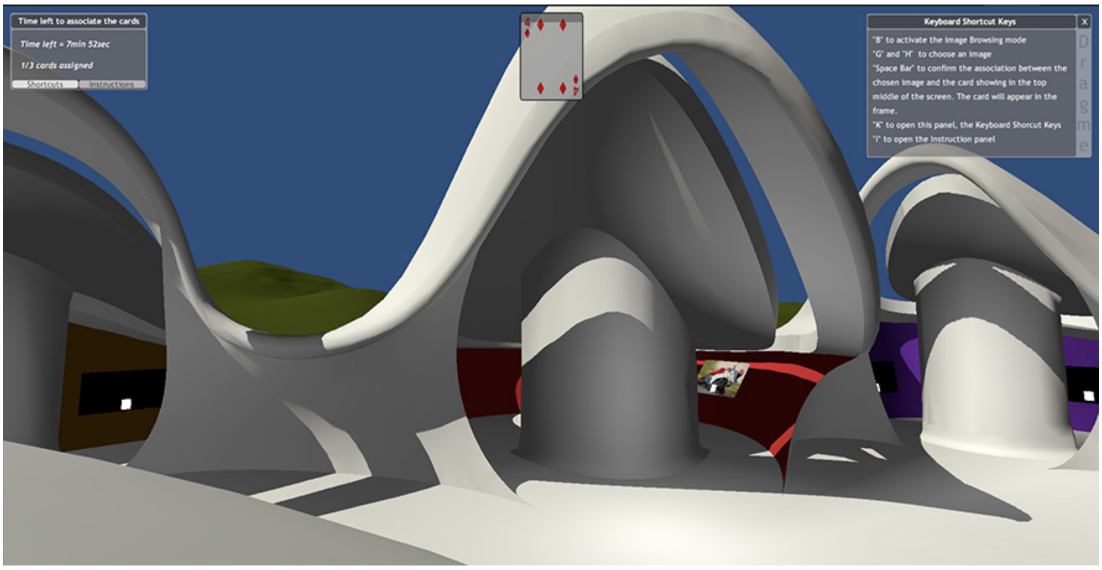


FIGURE A.4: ArchiMemory - Organic Room View 2

Appendix B

Archimemory: International Conference on Spatial Cognition 2015

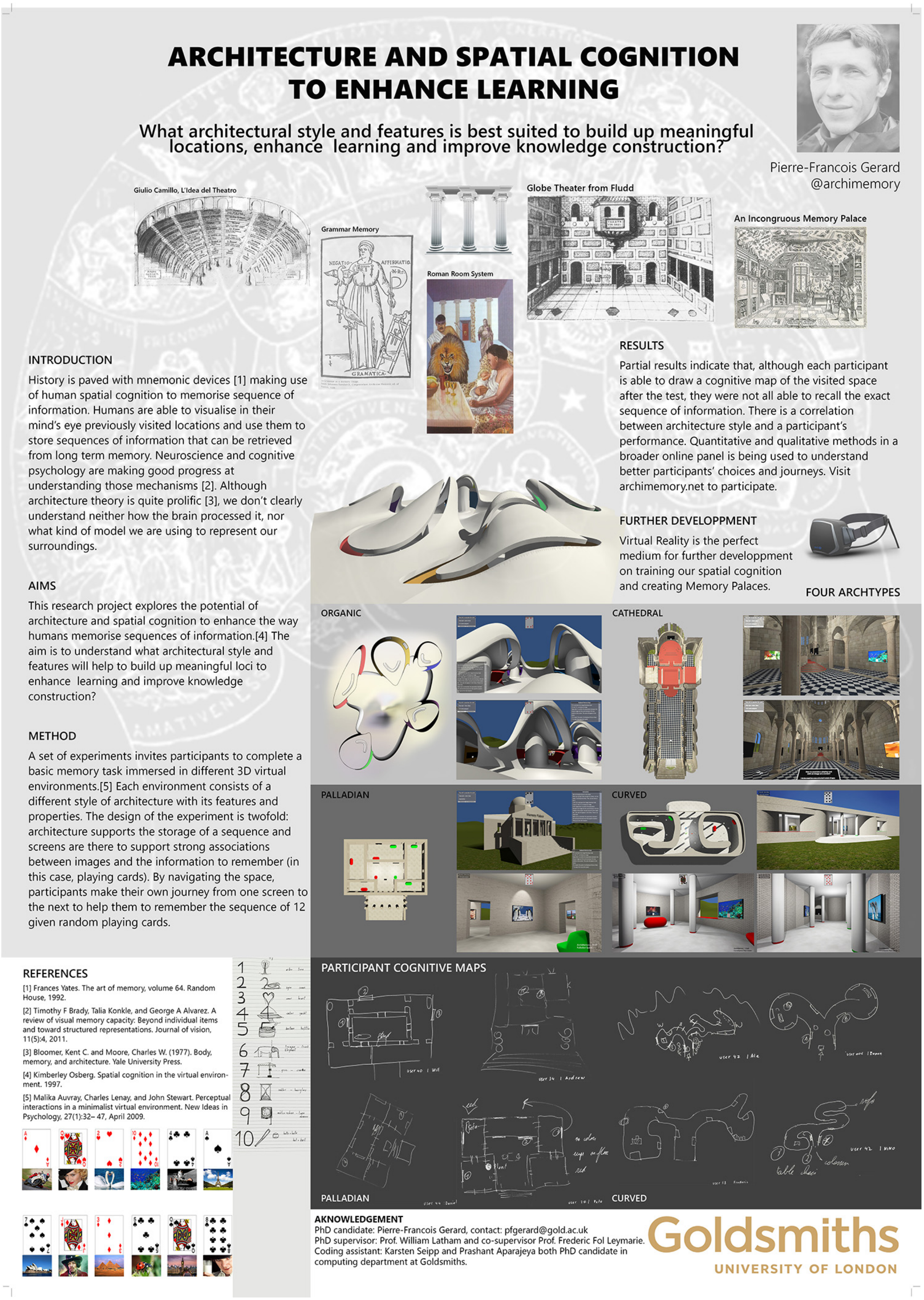


FIGURE B.1: Poster presented at the International Conference on Spatial Cognition 2015 - Roma

Report on International Conference on Spatial Cognition in Roma
From 6th to 11th September 2015
Pierre-Francois Gerard

It felt good to leave the already cold London weather early this September and land in Roma's Mediterranean climate for a whole week of International Conference on Spatial Cognition. What a city, what a history! My day time was packed with talks and lectures giving each a different take on situated cognition, my nights were dedicated to apply all those theories along hours of walking and navigating this old city filled with memories.

The conference venue was an interesting building to start with. Situated in an old neighborhood at the East of Termini Station, part of Sapienza - Università di Roma, the faculty of psychology was barely recognisable from the street. However, once you got inside, the space was quite remarkable. There was this wide and long mildly inclined ramp punctuated by little steps distributing students and conference's participants alike to the four levels of rooms and auditorium. At the back, there was a large court yard to share thoughts and eat lunch in the sunlight.

<u>Keynotes Speakers - Scientific Method</u>

The main keynotes were given on the top floor. Arrived only on Tuesday afternoon, I missed Monday keynote lecture with Kevin O'Regan: *"Constructing space: A theoretical basis for how naive artificial or biological agents can construct spatial notions"* . A couple of early friendship informed me that O'Regan is a quite prolific author, this presentation wasn't that great. There is plenty to catch up online anyway. On Tuesday was Vittorio Gallese important Keynote on "*Embodied Simulation and the Space around us."* He explained the main concept of inter- and extra-personal space used by a lot of author that week.

The first keynote I attended was quite enlightening on the scientific methodology developed by psychologists. Yan Bao, associate professor from Peking University, explained step by step what is "attention" and how does it work through human's eyes. To do so, she scientifically answered one very specific question by doing one very specific experiment. From there, a new question arise that lead to the next experiment that will bring a new answer and suggest the following question, and so forth. She presented a cascade of 12 studies based on a cuing task mainly to demonstrate the effect of *"Inhibition of Return"*; the ecological significance of this mechanism being that it is favouring novelty and curiosity.

The next keynote, "*Inter-subjective relations in lived space and instituted space"* was given by Shaun Gallagher, an interesting fellow American philosopher. He is actually working with astronauts, trying to understand their feelings in space travel using Virtual Reality. Where it really pumped me up was when he started to talk about how architecture shapes our experience and how we can modulate the way we are experiencing things by modifying our environment. He also coined a powerful concept which is the "*affordance landscape"*. I will follow him closely.

FIGURE B.2: Report of the ICSC 2015 - Roma

ABSTRACT SUBMISSION FORM

– INDEPENDENT CONTRIBUTIONS (TALKS OR POSTERS) –

Please complete this form and submit it to icsc.rome@gmail.com with the subject "Abstract submission". [1]

Author(s) and affiliation(s): Pierre-Francois Gerard, William Latham and Frederic Fol Leymarie, department of Computing, Goldsmiths University of London

Title: "Architecture and Spatial Cognition to Enhance Learning."

Abstract (max. 250 words): [2]

Background:
History is paved with mnemonic devices that make use of human spatial cognition to memorise sequence of information. Humans are able to visualise in their mind's eye previously visited spaces and use them to store sequences of information that can be retrieved later. Neuroscience and cognitive psychology are making good progress at understanding those mechanisms. How does architecture influence this ability? What features will help to build meaningful spaces for learning?

Aims:
Based on the Method of Loci, this research explores the potential of architecture to enhance the way humans memorise sequences of information.

Method:
A set of experiments invites participants to complete a basic memory task immersed in different 3D virtual environments. Each environment consists of a different style of architecture with its features and properties. The design of the experiment is twofold: the architecture supports the storage of a sequence and the framed pictures support the creation of strong associations between locations, images and the information to remember.

Results: [3]
Partial results indicate that, although each participant is able to draw a cognitive map of the visited space after the test, they were not all able to restitute the exact sequence of information. There is a correlation between architecture style and a participant's performance which will be explained in detail in our presentation. Quantitative and qualitative methods in a broader online panel will be used to understand better participants' choices and path the next couple of month.

Conclusions: [4]

Which type of presentation do you prefer?	**Talk (x)**	**Poster (x)**
Will you contribute a Short Paper? [5]	**Yes (x)**	**No ( )**

[1] **Your abstract submission cannot be processed unless you have answered all parts.**
[2] **Abstracts that are longer than 250 words or that are not organized in the suggested way will be returned.**
[3] **If you have not yet obtained results, you should state the expected results.**
[4] **If applicable.**
[5] **Short papers will be published with DOI in a supplement of *Cognitive Processing – International Quarterly of Cognitive Science* (http://www.springer.com/journal/10339).**

FIGURE B.3: Abstract Submitted to ICSC 2015 - Roma

Appendix C

Creative Machine Exhibition Demo

Creative Machine exhibition - 6th November

"The Memory Palace"

Pierre-Francois Gerard
PhD student, Computing Dep.
Goldsmiths University of London

Biography

Pierre-Francois Gerard is currently PhD Student in Computing Department at Goldsmiths University of London. He is exploring the relation between space, memory and technology to enhance learning. With a background in Architecture (MA Brussels) and Information and Communication Technology (MA Valenciennes) , he specialized as a 3D visualizer. For more than 10 years of professional practice with international architects and designers from Brussels, London and Shangai, he realized the potential of 3D visualisation techniques (stills, animations, real-time walkthrough,...) as a creative force not only in the design process but as a primary communication tool. Through the lens of cognitive science and developing technologies, Pierre-François's current interests lie in exploring how architectural visualisation can be used in order to build customised "*memory palace*" to enhance knowledge construction.

Short description of the Artwork

Research in spatial cognition shows us that human beings have developed very powerful ways to remember and organise their memories over the millennia. For instance, who didn't experienced to remember something (retrieving phase) more efficiently when placed in the original learning environment (encoding phase). This happens because we are encoding unconsciously a lot of information about our surroundings. Taking advantage of these powerful memory systems, we have developed a variety of mnemonic devices. One particular technique is called the "Method of Loci". Spatial characteristics of this method provide very strong cues for both organisation and encoding processes. Visual imagery is used as a trigger to transform information analogically and place them along user's path. What makes this method so efficient is the number of links that are traced between multi-modal mechanism used for encoding and the abstraction used through metaphorical concepts.

FIGURE C.1: Creative Machine Exhibition

Participation Information and Research Agreement

Goldsmiths, University of London

Researcher contact: Pierre-Francois Gerard, email: pfgerard@gold.ac.uk

Aims of the study

This research project aims to investigate how human spatial cognition can enhanced the way we memorise information. Through the use of 3D virtual environment and different association principles, these experiments are exploring how a person can improve the way he/she learns and remembers new sequence of information.

Logistics of the study

The study will involve questionnaires, discussions (individually or in a group, online or offline), workshops and software tests. Discussions and workshops will be filmed, and software test data will be recorded.

Research agreement

I, the undersigned, agree to take part in the aforementioned research project. I understand that I am free to terminate my involvement in the research project at any time but understand that by doing so I will invalidate any of the data provided by my involvement. I agree to participate in completing questionnaires, participate in workshops, software tests, and
engage in a documented discussion (offline and online) where the results are published anonymously. I am aware that the filmed and photographic material may be used for further documentation on different platforms (printed, digital) in an academic context (presentation at conferences or scientific papers), and not for commercial purposes. I am also aware that other materials I may produce during the project (for example, sketches or prototypes) may be used in the same context. I also acknowledge that, when testing software related to the research, data relative to my interactions with the software will be collected anonymously.
I declare to agree with the use of this data in the mentioned context.

Printed name: _

Gender: M / F Date of birth: ____/____/___ Place of birth: _ _ _ _ _ _ _ _ _

Email: _

Signature of participant:_ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ Date: __ / __ / ____

Signature of researcher: _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _

FIGURE C.2: Research Agreement for Participant

Ethical Approval Form (EAF1)

CONFIDENTIAL

GOLDSMITHS COLLEGE University of London

Research Ethics Committee

NAME OF APPLICANT .....Pierre-Francois Gerard

DEPARTMENT ……Computing

This form should be completed in typescript and returned to the Secretary of the Research Ethics Committee, for any research project, teaching procedure or routine investigation involving human participants or animals to be undertaken in the College or by or upon Goldsmiths College staff outside the College.

1. **Title of proposed project:**

ArchiMemory XP

2. **Brief outline of the project, including its purpose:**

This project use software based experiment to explore how the user can enhanced his memory by using his spatial cognition. Based on the Method of Loci mnemotechnic, a set of experiments using playing cards, images and space will be developed. The basic set up proposes 3 different environments. Each present differents architectural characteristics. It is design to understand what spatial characteristics enhanced the way the user is remembering.

3. **Proposed starting date:**

6th november 2014

4. **If external grant funding is being secured, does the research need ethical approval prior to the initiation of that funding?**

No external grant

5. **Has the project been approved by an Ethics Committee external to the College? If so please specify.**
   (NB for projects so approved, applicants may if they wish submit a copy of that application, but should sign the back of the form and return it as specified above)

no

1

FIGURE C.3: Ethical Approval Form

Pierre-Francois Gerard
PhD student Computing Department
Goldsmiths University of London
pfgerard@gold.ac.uk

ArchiMemory :
Spatial Memory for knowledge construction
(400 words)

Department of Computing
Keywords : architecture, spatial cognition, mnemonic, knowledge construction, wayfinding, cognitive map, virtual reality

History is paved with mnemonic devices that makes use of our spatial ability to remember and navigate our surrounding effortlessly. How does architecture influence this ability? What characteristics will help to build meaningful virtual spaces that will enhance the way people learn, memorise and retrieve information?

Research in spatial cognition shows that human beings have developed very powerful ways to remember and organise their memories. For instance, who didn't experience remembering something (retrieving phase) more efficiently when placed in the original learning environment (encoding phase). This happens because we are encoding unconsciously a lot of information about our surroundings. Taking advantage of these powerful memory systems, we have developed many mnemonic devices over the millennia. One particular technique is called the "Method of Loci". Spatial characteristics of this method provide very strong cues for both organisation and encoding processes. Visual imagery is used as a trigger to transform information analogically and place them along user's path. What makes this method so efficient is the number of links that are traced between multi-modal mechanisms used for encoding and the abstraction used through metaphorical concepts.

Looking at the game industry growth and the average number of hours people are immersed in virtual worlds, we can easily imagine how to use gameplay principles to enhance learning experience and to design an application that would train a user to build up such kind of memory palace. Once trained, a user will be able to use his "ArchiMemory" to organise acquired information internally. He will then be more efficient at retrieving, associating and building new knowledge.

This research project is exploring that question by testing human participant in a simple memory task immersed in different 3D virtual environments. The main idea is to present an environment that promotes the principle of association running our cognitive brain by spatially structuring the way we encode and retrieve information.

We compare 3 differents conditions where each environment consist of a different type of architecture with their features and properties. The "space" is there to support the sequence of information to remember. Frames, hanging on the wall in specific locations, will help the participant to support the creation of strong associative memories between locations, images and the information to remember.

Partial results indicate that, although each participant was able, to draw a cognitive map of the visited space after the test, they were not all able to restitute the exact sequence of information. There is a correlation between certain architecture's characteristics and participant's performance. Participants deployed different methods and mnemonics to deal with the task. Conclusions would be premature as experiments are still running.

FIGURE C.4: Spatial Memory for Knowledge Construction - Abstract InLab Conference

Appendix D

IVAS - Room Design

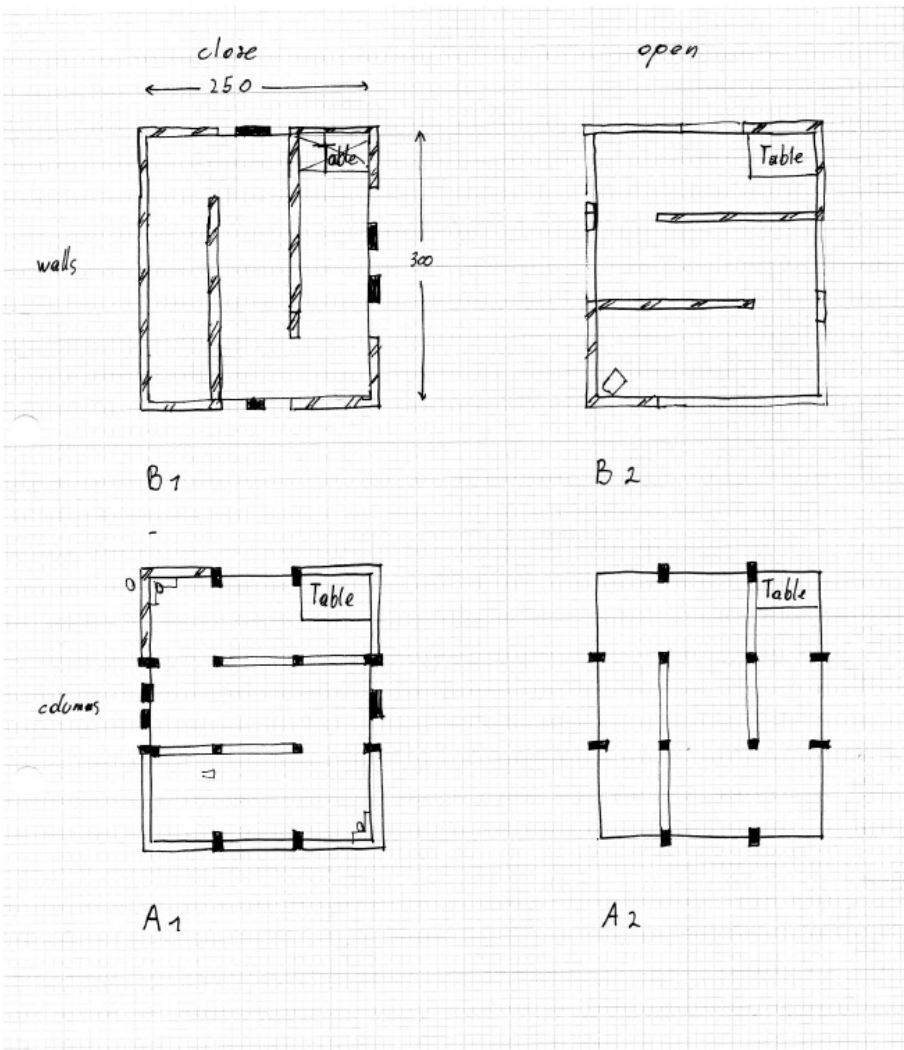


FIGURE D.1: Layout option based on rectangle with narrow corridors

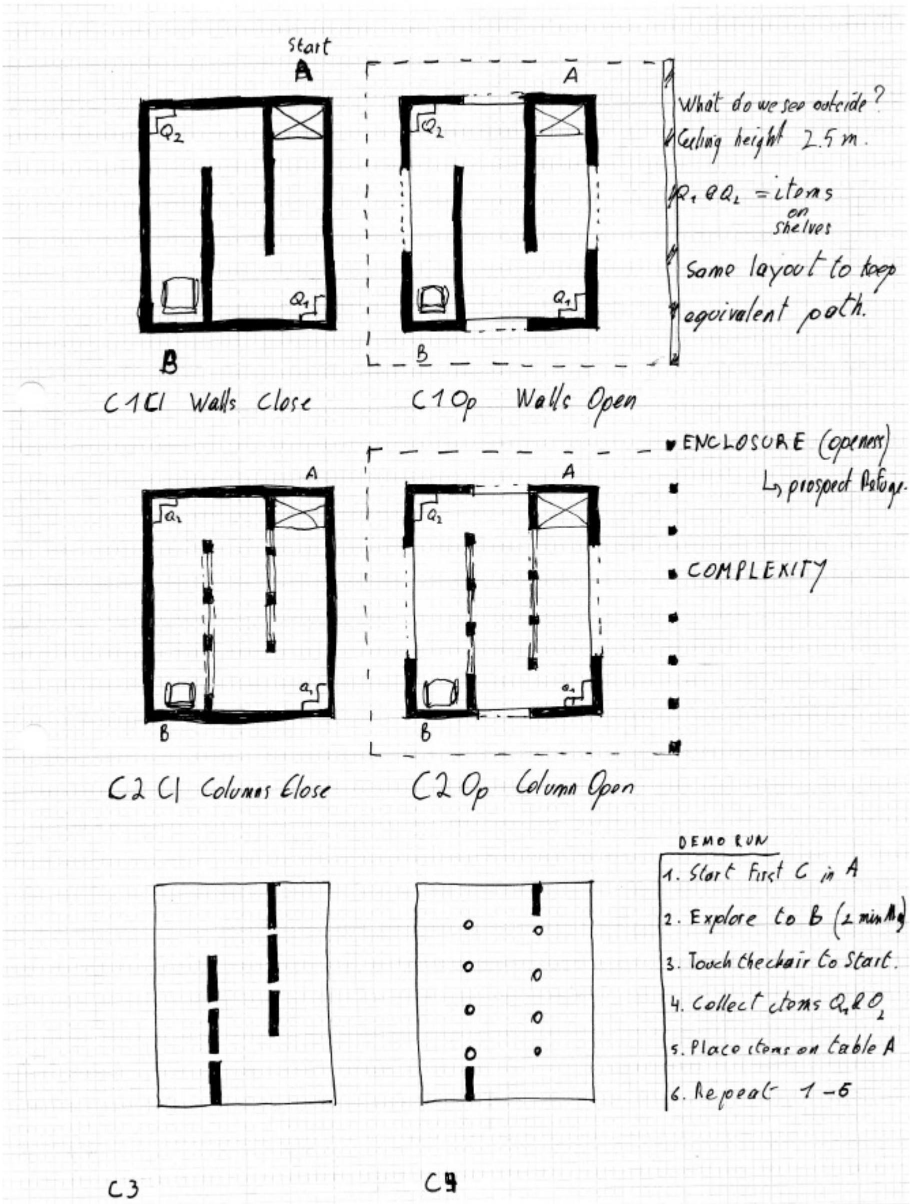


FIGURE D.2: Layout option based on rectangle with narrow corridors. Figuring out where to place the Puzzle Table

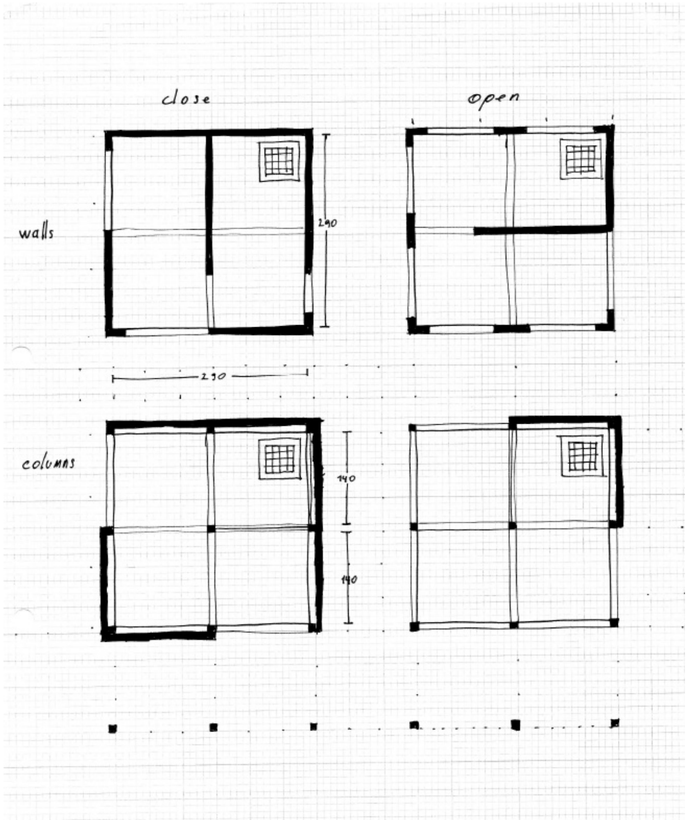


FIGURE D.3: Layout option based on square and equidistant walls

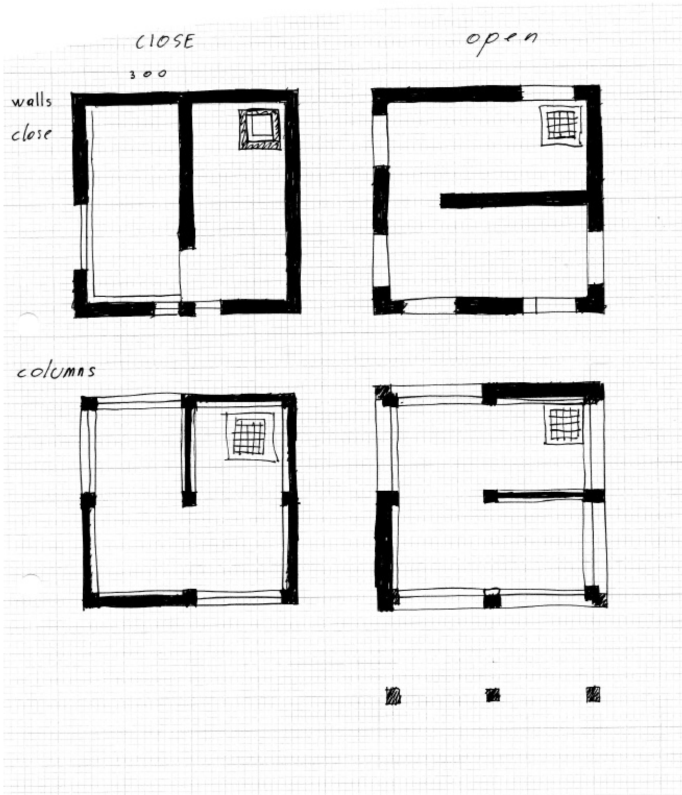
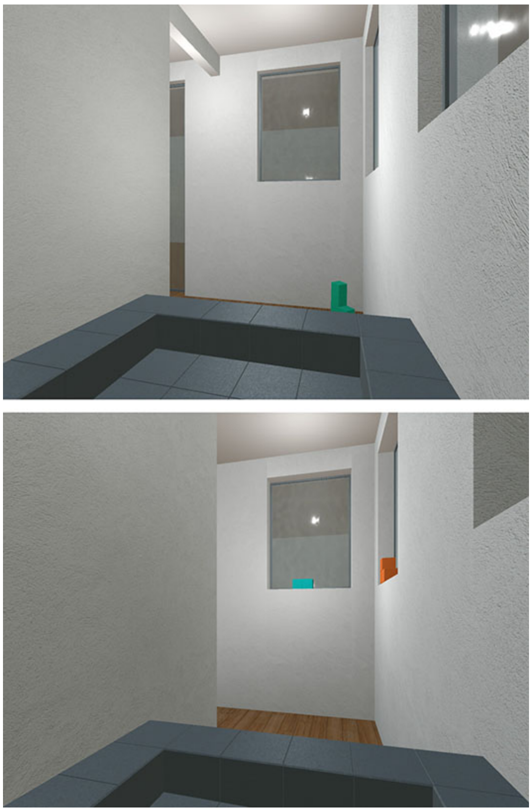
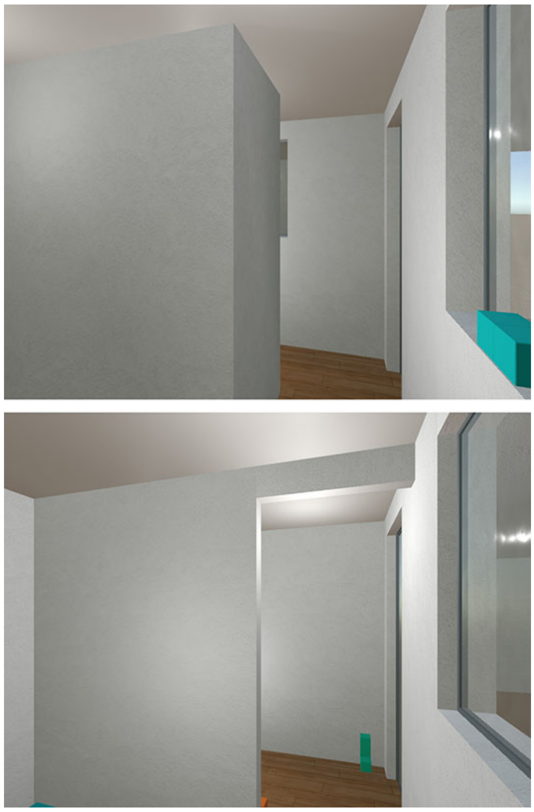


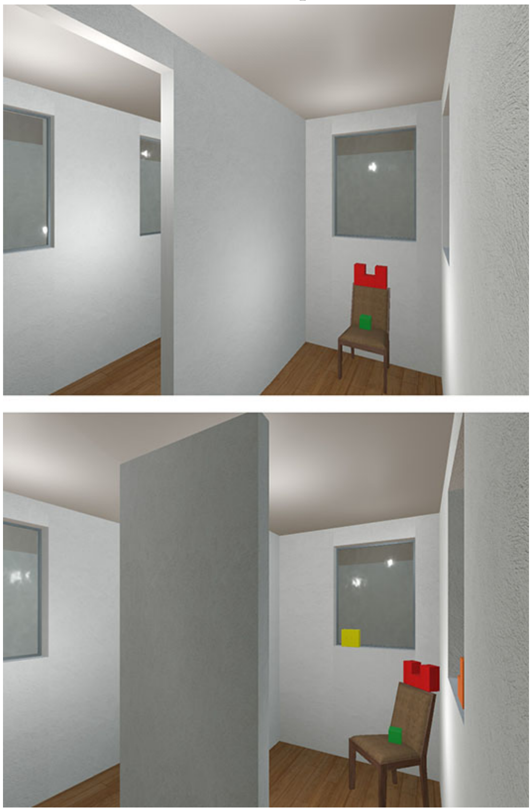
FIGURE D.4: Layout options based on square with different openings



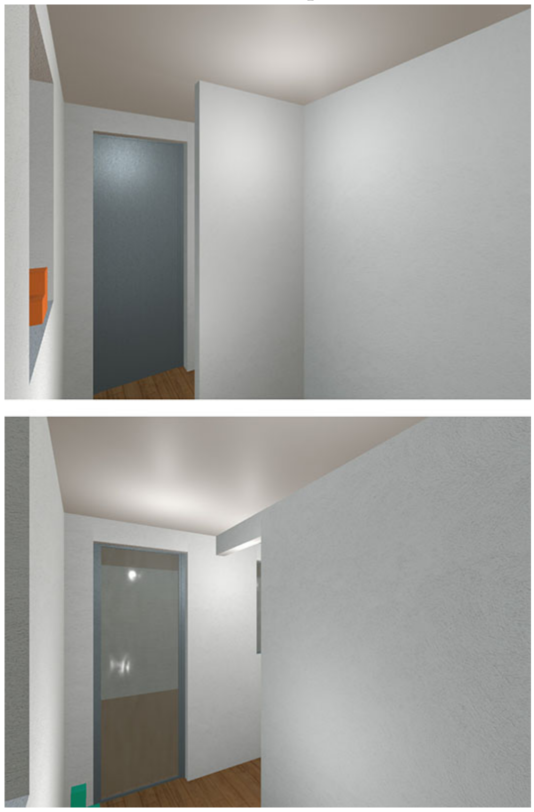
(A) PTT 4AB pair 01



(B) PTT 4AB pair 02

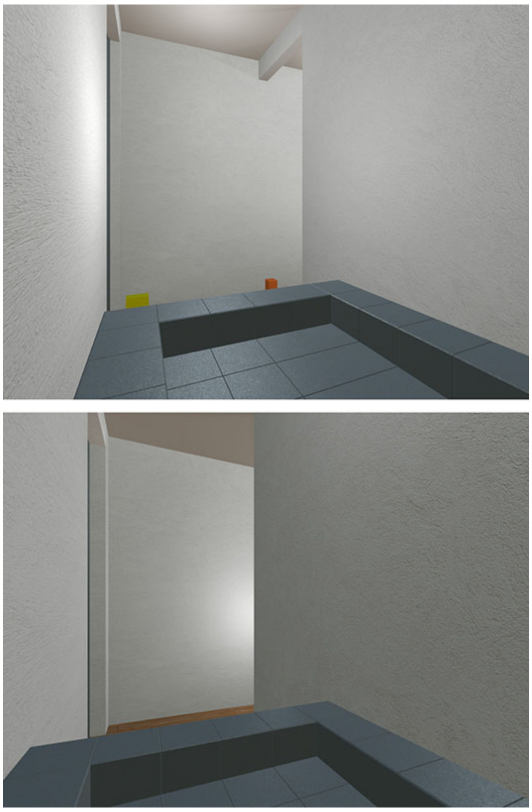


(C) PTT 4AB pair 03



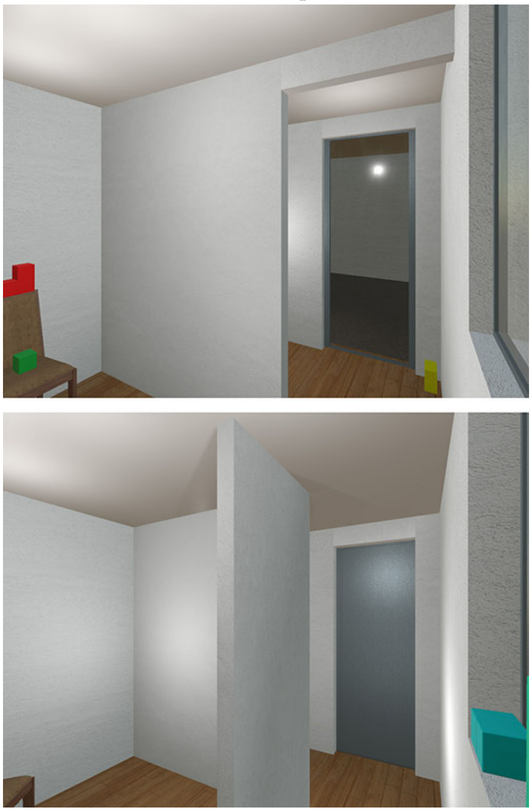
(D) PTT 4AB pair 04

FIGURE D.5: Perspective Taking Task - Interior Views 01

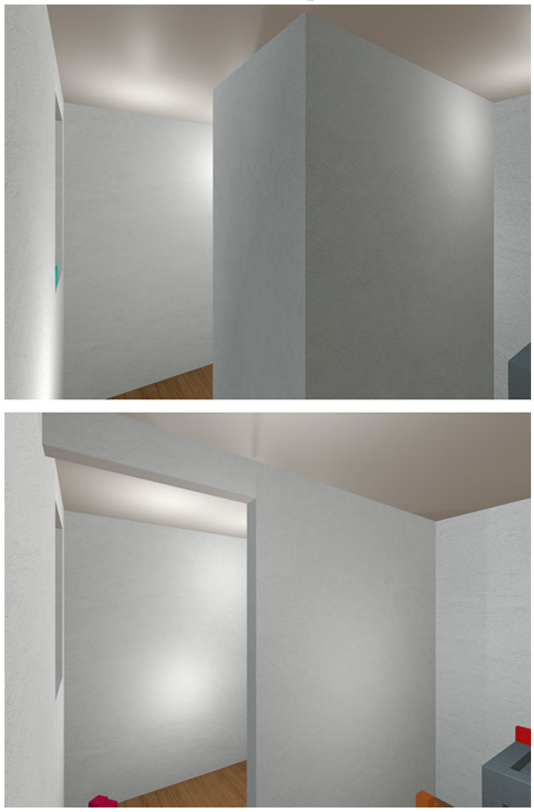


(A) PTT 4AB pair 05

(B) PTT 4AB pair 06

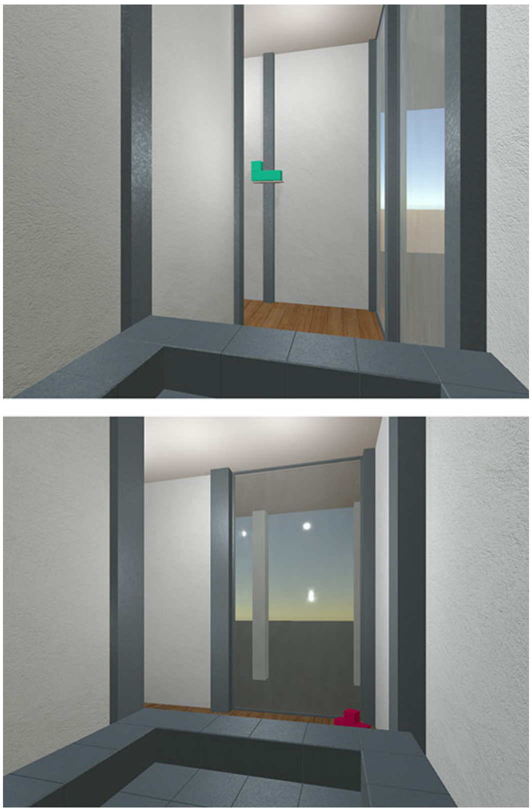


(C) PTT 4AB pair 07

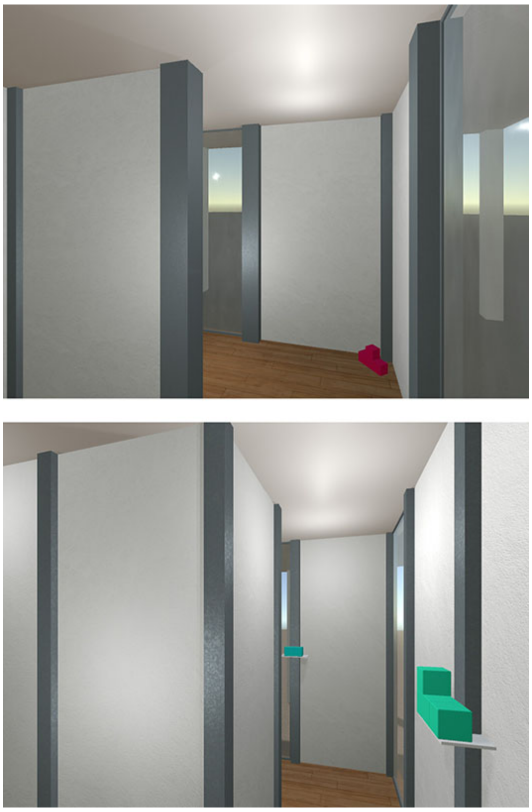


(D) PTT 4AB pair 08

FIGURE D.6: Perspective Taking Task - Interior Views 02

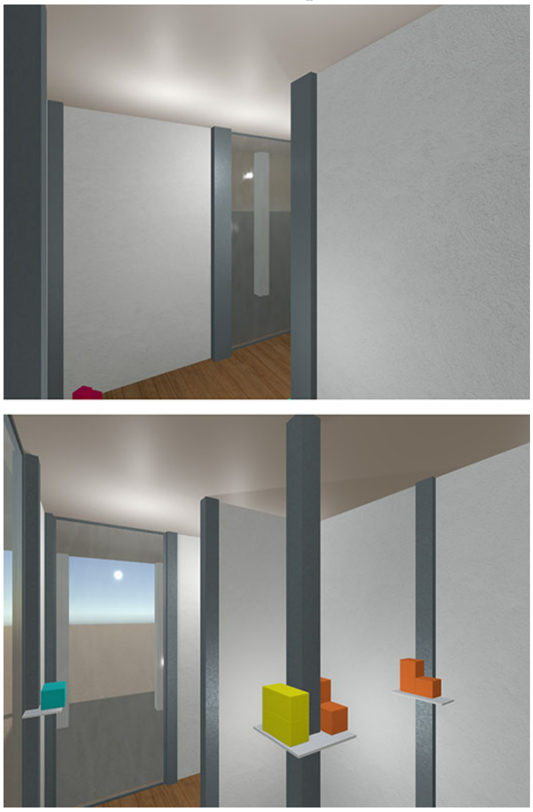


(A) PTT 4AB pair 09



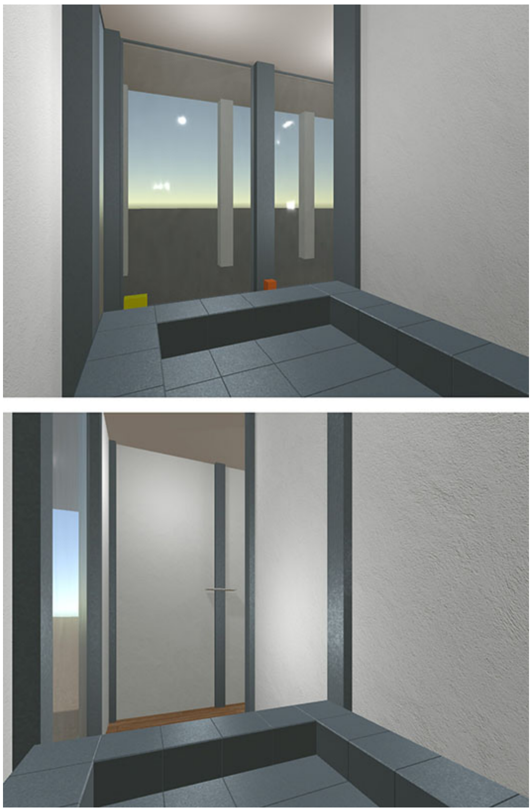
(B) PTT 4AB pair 10

(C) PTT 4AB pair 11

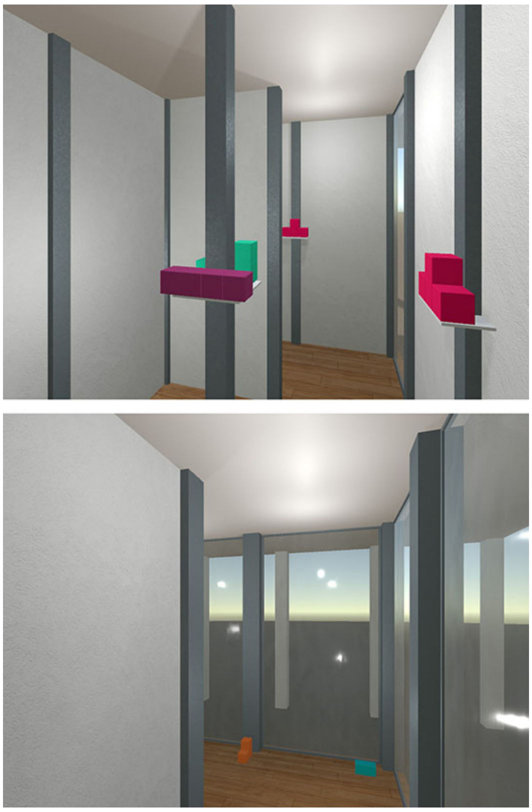


(D) PTT 4AB pair 12

FIGURE D.7: Perspective Taking Task - Interior Views 03

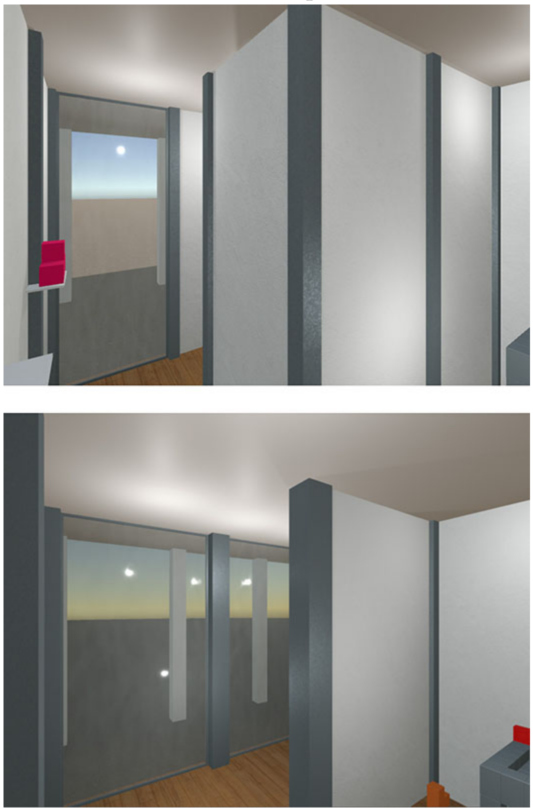


(A) PTT 4AB pair 13



(B) PTT 4AB pair 14

(C) PTT 4AB pair 15



(D) PTT 4AB pair 16

FIGURE D.8: Perspective Taking Task - Interior Views 04

Appendix E

IVAS - Data Collection

IVAS eXPeriment.

IVAS stands for Immersive Virtual Architecture Studio. This research project aims to investigate how different architectural elements affect people cognitive and spatial performance when in Virtual Reality. The main set consists of a room scale VR experience (with HTC Vive) where you will have to solve a few jigsaw puzzles in different virtual environments.

Your participation in today's experiment is greatly appreciated.

*Required

1. **Email address** *

____

Instructions

Follows the step by step for the experiment:

FIGURE E.1: Consent Form and Questionnaire - page 1/4

0/ Fill in the Consent Form

1/ Tutorial: once the HMD (Head Mounted Display) is set, you wil have the time to learn how to move in VR and interact with the Tetris like shapes by completing the jigsaw puzzle. (Use trigger button to grab objects.)

2/ Transition: When the puzzle is solved you will find yourselves in a transition area. Please stay on the wooden floor close to the table. The next scene will load automatically after a few seconds.

3/ Scene 1 of 4 : take the time to explore and look around, then find the green cube. It acts as a start button when inserted in the red hole next to it. When that red shape becomes green as well, your task starts: gather all the items and complete the jigsaw puzzle.

4/ Transition - Questions: Once the puzzle is solved, you will be in the transition area for 40 seconds during which I will ask you a couple of questions on how you felt about the space. You will have to reply on a scale from 1 to 5.

5/ Repeat the two previous points 4 times for the 4 different rooms.

6/ After the last room, place the controlers back on the table and take the HMD off.

7/ Fill in the rest of the questionnaire here under

8/ Do the Perspective Taking Task with the researcher.

9/ Well done and thank you for your participation.

Consent form

Please read carefully all of the following questions and tick the 'I agree with this statement' box if you agree. If you do not agree with any statement in this form, you will not provide informed consent and should not proceed with this experiment.

2. **I have read and understood the instructions and understand the aims of this research and what will be required of me during the experiment.** *

   Tick all that apply.

   ☐ I agree with this statement

FIGURE E.2: Consent Form and Questionnaire - page 2/4

3. **I consent to collection and processing of personal information during this study and understand that this information will be kept with strict confidentiality under the Data Protection Act 1998. (no data that can be used to identify me will be stored or assessed by the experimenter.)** *
   Tick all that apply.
   - [ ] I agree with this statement.

4. **The study will involve using Virtual Reality software and hardware, questionnaires and perspective taking task. Software test data (position and gaze tracking) will be recorded.** *
   Tick all that apply.
   - [ ] I agree with this statement.

5. **The use of a Virtual Reality (VR) with a Head-Mounted Display (HMD) can cause some temporary vision and balance problems. Any discomfort that could appear during the experiment will disappear shortly after getting out of the HMD.** *
   Tick all that apply.
   - [ ] I agree with this statement.

6. **I am free to terminate my involvement in the research project at any time but understand that by doing so I will invalidate any of the data provided by my involvement.** *
   Tick all that apply.
   - [ ] I agree with this statement.

The VR experiment.

Thank you for filling in this form, lets get you into VR now. Don't click the next button yet!

Questionnaire

Please reply to all the following questions

7. **Your age:** *
   Mark only one oval.
   - ( ) Below 11
   - ( ) 11-20
   - ( ) 21-30
   - ( ) 31-40
   - ( ) 41-50
   - ( ) 51-60
   - ( ) 61-70
   - ( ) Over 70

8. **Your sex:** *
   Mark only one oval.
   - ( ) Female
   - ( ) Male
   - ( ) Prefer not to say
   - ( ) Other: ____________________

FIGURE E.3: Consent Form and Questionnaire - page 3/4

About your experience with Virtual Reality

9. **How much experience do you have playing video games?** *
Mark only one oval.

	1	2	3	4	5	
No experience	◯	◯	◯	◯	◯	Playing everyday

10. **How many time have you experienced Virtual Reality?** *
Mark only one oval.

◯ Never
◯ Once or twice
◯ Many times
◯ Every week
◯ Every day

11. **How much immersive would you scale your experience?** *
Mark only one oval.

	1	2	3	4	5	
Not immersive	◯	◯	◯	◯	◯	Fully immersive

12. **Could you describe in a short paragraph how did you feel when you were experiencing the IVAS today?** *

13. **Here is a good place for any questions, comments or suggestions you might have.**

Powered by
Google Forms

FIGURE E.4: Consent Form and Questionnaire - page 4/4

Table E.1 Free Exploration - Randomize Rooms - Time/Room in seconds

Users	Scene1	Time1	Scene2	Time2	Scene3	Time3	Scene4	Time4
User150	IVAS_9B2	26.75	IVAS_9A1	24.50	IVAS_9B1	12.25	IVAS_9A2	11.50
User151	IVAS_9A1	10.75	IVAS_9B1	7.00	IVAS_9B2	16.25	IVAS_9A2	10.75
User153	IVAS_9A1	15.00	IVAS_9B1	35.00	IVAS_9A2	21.00	IVAS_9B2	11.75
User161	IVAS_9B1	43.75	IVAS_9B2	67.50	IVAS_9A2	26.75	IVAS_9A1	25.25
User170	IVAS_9A2	31.75	IVAS_9B2	19.75	IVAS_9A1	26.00	IVAS_9B1	26.00
User171	IVAS_9B1	30.25	IVAS_9B2	12.50	IVAS_9A1	4.00	IVAS_9A2	14.50
User172	IVAS_9A1	32.75	IVAS_9A2	32.25	IVAS_9B1	27.00	IVAS_9B2	25.00
User174	IVAS_9B2	34.25	IVAS_9A2	20.50	IVAS_9A1	22.75	IVAS_9B1	21.50
User175	IVAS_9A2	30.25	IVAS_9A1	10.50	IVAS_9B2	10.25	IVAS_9B1	21.25
User178	IVAS_9A1	51.25	IVAS_9B1	33.75	IVAS_9B2	35.00	IVAS_9A2	22.25
User179	IVAS_9B2	32.75	IVAS_9A2	40.25	IVAS_9B1	27.25	IVAS_9A1	51.25
User182	IVAS_9A1	21.50	IVAS_9B2	15.50	IVAS_9A2	14.50	IVAS_9B1	15.25
User185	IVAS_9A1	6.25	IVAS_9A2	13.75	IVAS_9B2	21.00	IVAS_9B1	19.25
User186	IVAS_9A1	41.75	IVAS_9A2	23.00	IVAS_9B2	21.25	IVAS_9B1	24.25
User187	IVAS_9B2	27.50	IVAS_9A2	19.50	IVAS_9B1	12.50	IVAS_9A1	12.00
User191	IVAS_9B1	24.75	IVAS_9A1	39.00	IVAS_9B2	19.00	IVAS_9A2	18.50
User194	IVAS_9A1	37.00	IVAS_9B2	19.00	IVAS_9A2	22.50	IVAS_9B1	10.00
User195	IVAS_9A1	25.50	IVAS_9B1	31.25	IVAS_9B2	23.50	IVAS_9A2	22.00
User196	IVAS_9A1	38.75	IVAS_9B2	16.50	IVAS_9A2	16.75	IVAS_9B1	18.50
User197	IVAS_9A1	51.00	IVAS_9A2	88.50	IVAS_9B1	22.25	IVAS_9B2	21.75
User198	IVAS_9B2	48.75	IVAS_9A2	124.75	IVAS_9B1	36.50	IVAS_9A1	31.00
User202	IVAS_9A2	33.00	IVAS_9B2	16.25	IVAS_9B1	17.00	IVAS_9A1	21.75

Table E.1 continued from previous page

Users	**Scene1**	**Time1**	**Scene2**	**Time2**	**Scene3**	**Time3**	**Scene4**	**Time4**
User205	IVAS_9A1	30.75	IVAS_9B2	30.50	IVAS_9A2	19.25	IVAS_9B1	21.50
User206	IVAS_9B1	24.50	IVAS_9A2	37.25	IVAS_9B2	16.50	IVAS_9A1	32.50
User207	IVAS_9B1	38.25	IVAS_9A1	52.75	IVAS_9B2	28.75	IVAS_9A2	23.75
User208	IVAS_9B2	23.75	IVAS_9A1	30.00	IVAS_9A2	19.00	IVAS_9B1	19.00
User209	IVAS_9A1	10.25	IVAS_9A2	28.75	IVAS_9B2	19.25	IVAS_9B1	17.75
User210	IVAS_9A2	23.25	IVAS_9A1	27.25	IVAS_9B2	15.50	IVAS_9B1	12.25
User211	IVAS_9B2	36.00	IVAS_9A2	35.00	IVAS_9B1	19.25	IVAS_9A1	21.00
User212	IVAS_9B2	22.75	IVAS_9A2	45.50	IVAS_9B1	40.50	IVAS_9A1	33.25
User213	IVAS_9B1	22.25	IVAS_9A1	46.50	IVAS_9A2	21.75	IVAS_9B2	14.00
User214	IVAS_9A1	25.25	IVAS_9B1	12.50	IVAS_9A2	23.00	IVAS_9B2	17.25
User215	IVAS_9B1	44.25	IVAS_9A2	54.25	IVAS_9A1	29.00	IVAS_9B2	20.25
User216	IVAS_9B2	34.00	IVAS_9A2	54.25	IVAS_9A1	22.75	IVAS_9B1	8.25
User217	IVAS_9A2	27.75	IVAS_9A1	32.75	IVAS_9B2	15.00	IVAS_9B1	25.75
Total Time		1058.25		1197.75		744.75		721.75
Average		**30.24**		**34.22**		**21.28**		**20.62**
Median		30.25		30.50		21.00		21.00
Mode		30.25		35.00		19.25		21.50
St Dev		10.85		23.38		7.37		8.20

TABLE E.2: Free Exploration - Time/Room in seconds

Users	Rooms			
	A1	A2	B1	B2
User150	24.50	11.50	12.25	26.75
User151	10.75	10.75	7.00	16.25
User153	15.00	21.00	35.00	11.75
User161	25.25	26.75	43.75	67.50
User170	26.00	31.75	26.00	19.75
User171	4.00	14.50	30.25	12.50
User172	32.75	32.25	27.00	25.00
User174	22.75	20.50	21.50	34.25
User175	10.50	30.25	21.25	10.25
User178	51.25	22.25	33.75	35.00
User179	51.25	40.25	27.25	32.75
User182	21.50	14.50	15.25	15.50
User185	6.25	13.75	19.25	21.00
User186	41.75	23.00	24.25	21.25
User187	12.00	19.50	12.50	27.50
User191	39.00	18.50	24.75	19.00
User194	37.00	22.50	10.00	19.00
User195	25.50	22.00	31.25	23.50
User196	38.75	16.75	18.50	16.50
User197	51.00	88.50	22.25	21.75
User198	31.00	124.75	36.50	48.75
User202	21.75	33.00	17.00	16.25
User205	30.75	19.25	21.50	30.50
User206	32.50	37.25	24.50	16.50
User207	52.75	23.75	38.25	28.75
User208	30.00	19.00	19.00	23.75
User209	10.25	28.75	17.75	19.25
User210	27.25	23.25	12.25	15.50
User211	21.00	35.00	19.25	36.00
User212	33.25	45.50	40.50	22.75
User213	46.50	21.75	22.25	14.00
User214	25.25	23.00	12.50	17.25
User215	29.00	54.25	44.25	20.25
User216	22.75	54.25	8.25	34.00
User217	32.75	27.75	25.75	15.00
Sum	993.50	1071.25	822.50	835.25
Average	28.39	30.61	23.50	23.86
Median	27.25	23.00	22.25	21.00
Mode	25.25	14.50	12.25	16.25
Std Dev	13.06	22.19	9.89	11.30

Table E.3 Navigational Puzzle Game - Randomize rooms - Time/room in Seconds

Users	Scene1	Time1	Scene2	Time2	Scene3	Time3	Scene4	Time4
User150	IVAS_9B2	26.75	IVAS_9A1	24.50	IVAS_9B1	12.25	IVAS_9A2	11.50
User151	IVAS_9A1	10.75	IVAS_9B1	7.00	IVAS_9B2	16.25	IVAS_9A2	10.75
User153	IVAS_9A1	15.00	IVAS_9B1	35.00	IVAS_9A2	21.00	IVAS_9B2	11.75
User161	IVAS_9B1	43.75	IVAS_9B2	67.50	IVAS_9A2	26.75	IVAS_9A1	25.25
User170	IVAS_9A2	31.75	IVAS_9B2	19.75	IVAS_9A1	26.00	IVAS_9B1	26.00
User171	IVAS_9B1	30.25	IVAS_9B2	12.50	IVAS_9A1	4.00	IVAS_9A2	14.50
User172	IVAS_9A1	32.75	IVAS_9A2	32.25	IVAS_9B1	27.00	IVAS_9B2	25.00
User174	IVAS_9B2	34.25	IVAS_9A2	20.50	IVAS_9A1	22.75	IVAS_9B1	21.50
User175	IVAS_9A2	30.25	IVAS_9A1	10.50	IVAS_9B2	10.25	IVAS_9B1	21.25
User178	IVAS_9A1	51.25	IVAS_9B1	33.75	IVAS_9B2	35.00	IVAS_9A2	22.25
User179	IVAS_9B2	32.75	IVAS_9A2	40.25	IVAS_9B1	27.25	IVAS_9A1	51.25
User182	IVAS_9A1	21.50	IVAS_9B2	15.50	IVAS_9A2	14.50	IVAS_9B1	15.25
User185	IVAS_9A1	6.25	IVAS_9A2	13.75	IVAS_9B2	21.00	IVAS_9B1	19.25
User186	IVAS_9A1	41.75	IVAS_9A2	23.00	IVAS_9B2	21.25	IVAS_9B1	24.25
User187	IVAS_9B2	27.50	IVAS_9A2	19.50	IVAS_9B1	12.50	IVAS_9A1	12.00
User191	IVAS_9B1	24.75	IVAS_9A1	39.00	IVAS_9B2	19.00	IVAS_9A2	18.50
User194	IVAS_9A1	37.00	IVAS_9B2	19.00	IVAS_9A2	22.50	IVAS_9B1	10.00
User195	IVAS_9A1	25.50	IVAS_9B1	31.25	IVAS_9B2	23.50	IVAS_9A2	22.00
User196	IVAS_9A1	38.75	IVAS_9B2	16.50	IVAS_9A2	16.75	IVAS_9B1	18.50
User197	IVAS_9A1	51.00	IVAS_9A2	88.50	IVAS_9B1	22.25	IVAS_9B2	21.75
User198	IVAS_9B2	48.75	IVAS_9A2	124.75	IVAS_9B1	36.50	IVAS_9A1	31.00
User202	IVAS_9A2	33.00	IVAS_9B2	16.25	IVAS_9B1	17.00	IVAS_9A1	21.75

Table E.3 continued from previous page

Users	Scene1	Time1	Scene2	Time2	Scene3	Time3	Scene4	Time4
User205	IVAS_9A1	30.75	IVAS_9B2	30.50	IVAS_9A2	19.25	IVAS_9B1	21.50
User206	IVAS_9B1	24.50	IVAS_9A2	37.25	IVAS_9B2	16.50	IVAS_9A1	32.50
User207	IVAS_9B1	38.25	IVAS_9A1	52.75	IVAS_9B2	28.75	IVAS_9A2	23.75
User208	IVAS_9B2	23.75	IVAS_9A1	30.00	IVAS_9A2	19.00	IVAS_9B1	19.00
User209	IVAS_9A1	10.25	IVAS_9A2	28.75	IVAS_9B2	19.25	IVAS_9B1	17.75
User210	IVAS_9A2	23.25	IVAS_9A1	27.25	IVAS_9B2	15.50	IVAS_9B1	12.25
User211	IVAS_9B2	36.00	IVAS_9A2	35.00	IVAS_9B1	19.25	IVAS_9A1	21.00
User212	IVAS_9B2	22.75	IVAS_9A2	45.50	IVAS_9B1	40.50	IVAS_9A1	33.25
User213	IVAS_9B1	22.25	IVAS_9A1	46.50	IVAS_9A2	21.75	IVAS_9B2	14.00
User214	IVAS_9A1	25.25	IVAS_9B1	12.50	IVAS_9A2	23.00	IVAS_9B2	17.25
User215	IVAS_9B1	44.25	IVAS_9A2	54.25	IVAS_9A1	29.00	IVAS_9B2	20.25
User216	IVAS_9B2	34.00	IVAS_9A2	54.25	IVAS_9A1	22.75	IVAS_9B1	8.25
User217	IVAS_9A2	27.75	IVAS_9A1	32.75	IVAS_9B2	15.00	IVAS_9B1	25.75
Total Time		1058.25		1197.75		744.75		721.75
Average		30.24		34.22		21.28		20.62
Median		30.25		30.50		21.00		21.00
Mode		30.25		35.00		19.25		21.50
St Dev		10.85		23.38		7.37		8.20

TABLE E.4: Navigational Puzzle Game - Time/room in Seconds

Users	Rooms			
	A1	A2	B1	B2
User150	47.75	85.50	59.00	100.50
User151	105.50	60.25	56.50	47.00
User153	45.50	88.25	49.25	66.75
User161	39.25	51.25	65.50	56.50
User170	27.25	96.25	45.75	50.25
User171	43.75	61.50	96.25	65.25
User172	70.25	79.75	48.75	50.00
User174	26.50	48.75	112.25	77.50
User175	57.50	75.75	53.75	48.25
User178	50.75	57.75	63.50	55.00
User179	52.75	62.75	51.75	48.25
User182	27.75	50.75	45.25	49.50
User185	43.50	69.50	47.00	68.75
User186	42.00	52.25	56.25	49.25
User187	25.75	52.50	35.25	52.50
User191	47.25	79.00	85.75	73.75
User194	104.00	78.00	86.75	94.25
User195	83.50	174.00	123.25	139.50
User196	39.25	124.25	110.00	48.25
User197	63.75	62.00	70.50	73.00
User198	39.00	66.00	61.00	75.00
User202	58.00	145.50	63.25	89.25
User205	66.00	52.25	88.75	93.00
User206	52.25	44.25	49.50	36.25
User207	39.50	50.75	105.50	34.25
User208	114.75	74.25	52.75	160.25
User209	100.25	43.75	40.25	42.25
User210	41.75	60.75	36.25	32.25
User211	50.00	95.50	55.75	103.50
User212	34.25	53.50	52.50	55.50
User213	33.00	46.75	51.25	42.75
User214	106.75	71.25	104.25	47.25
User215	55.75	60.00	97.25	45.50
User216	27.00	52.50	55.00	69.75
User217	45.25	69.50	55.50	51.75
Sum	1907.00	2496.50	2331.00	2292.50
Avg	54.49	71.33	66.60	65.50
Median	47.25	62.00	56.25	55.00
Mode	39.25	50.75	#N/A	48.25
Std Deviation	25.04	28.28	24.07	28.32

TABLE E.5: Spatial Quality Rating - Enclosure and Complexity

	Rooms	A1		A2		B1		B2	
	User	Close	Comp	Close	Comp	Close	Comp	Close	Comp
1	150	3	2	3	3	3	2	5	2
2	151	4	3	2	2	1	2	2	2
3	153	4	4	3	4	3	2	2	2
4	161	3	1	3	1	4	1	4	1
5	170	3	4	4	3	4	3	4	4
6	171	2	3	2	3	4	2	3	3
7	172	4	3	2	3	3	2	4	2
8	174	2	3	3	3	3	2	4	2
9	175	3	3	4	3	2	3	3	3
10	178	5	2	3	3	4	2	2	3
11	179	1	3	2	4	4	1	4	3
12	182	2	2	2	2	3	2	4	3
13	185	3	3	2	2	3	2	3	2
14	186	2	3	2	2	5	2	4	1
15	187	2	3	4	3	2	2	2	1
16	191	3	1	3	2	3	2	2	4
17	194	4	1	1	2	1	1	1	1
18	195	3	1	3	4	2	4	5	2
19	196	5	2	4	4	4	4	3	3
20	197	2	3	3	3	3	4	3	4
21	198	3	3	3	1	2	3	3	1
22	202	2	1	2	1	4	2	3	1
23	205	3	3	4	2	2	3	4	2
24	206	3	3	3	1	3	1	3	1
25	207	2	3	3	4	3	2	3	4
26	208	1	3	1	4	2	3	2	2
27	209	3	2	3	4	3	3	4	2
28	210	3	1	4	1	3	1	3	1
29	211	2	3	1	3	4	2	2	2
30	212	3	2	3	2	4	1	4	1
31	213	2	2	2	2	3	2	2	2
32	214	3	2	2	2	4	1	3	2
33	215	2	2	2	2	3	3	3	2
34	216	3	3	3	1	3	3	3	1
35	217	4	3	4	2	4	3	3	3
Sum		99	86	95	88	108	78	109	75
Average		2.83	2.46	2.71	2.51	3.09	2.23	3.11	2.14
Median		3	3	3	2	3	2	3	2
Mode		3	3	3	2	3	2	3	2
Std Dev.		0.95	0.85	0.89	1.01	0.92	0.88	0.93	0.97

TABLE E.6: Spatial Quality Rating - Complexity for each room

Complexity	1 = Simple	5 = Complex	
A1	A2	B1	B2
2	3	2	2
3	2	2	2
4	4	2	2
1	1	1	1
4	3	3	4
3	3	2	3
3	3	2	2
3	3	2	2
3	3	3	3
2	3	2	3
3	4	1	3
2	2	2	3
3	2	2	2
3	2	2	1
3	3	2	1
1	2	2	4
1	2	1	1
1	4	4	2
2	4	4	3
3	3	4	4
3	1	3	1
1	1	2	1
3	2	3	2
3	1	1	1
3	4	2	4
3	4	3	2
2	4	3	2
1	1	1	1
3	3	2	2
2	2	1	1
2	2	2	2
2	2	1	2
2	2	3	2
3	1	3	1
3	2	3	3

TABLE E.7: Spatial Quality Rating - Enclosure for each room

Enclosure	1 = Open	5 = close	
A1	A2	B1	B2
3	3	3	5
4	2	1	2
4	3	3	2
3	3	4	4
3	4	4	4
2	2	4	3
4	2	3	4
2	3	3	4
3	4	2	3
5	3	4	2
1	2	4	4
2	2	3	4
3	2	3	3
2	2	5	4
2	4	2	2
3	3	3	2
4	1	1	1
3	3	2	5
5	4	4	3
2	3	3	3
3	3	2	3
2	2	4	3
3	4	2	4
3	3	3	3
2	3	3	3
1	1	2	2
3	3	3	4
3	4	3	3
2	1	4	2
3	3	4	4
2	2	3	2
3	2	4	3
2	2	3	3
3	3	3	3
4	4	4	3

TABLE E.8: Frequency of SQR for Openness and Complexity

	A1-ComplexClose		A2-ComplexOpen		B1-SimpleClose		B2-SimpleOpen	
Rat.	Open	Comp	Open	Comp	Open	Comp	Open	Comp
1	2	6	3	6	2	7	1	10
2	11	9	11	12	6	16	8	14
3	15	18	14	10	15	9	14	7
4	5	2	7	7	11	3	10	4
5	2	0	0	0	1	0	2	0

TABLE E.9: Pairwise Comparisons NPG Completion Time Random Sequence

(I)	(J)	Mean Diff. (I-J)	Std. Error	Sig.b	95% Confid. Interval Diff.	
					Lo. Bound	Up. Bound
1	2	-16.843*	5.790	.038	-33.063	-.622
	3	-12.114	5.376	.185	-27.175	2.947
	4	-11.014	5.066	.221	-25.208	3.180
2	1	16.843*	5.790	.038	.622	33.063
	3	4.729	5.135	1.000	-9.656	19.113
	4	5.829	4.749	1.000	-7.477	19.134
3	1	12.114	5.376	.185	-2.947	27.175
	2	-4.729	5.135	1.000	-19.113	9.656
	4	1.100	5.487	1.000	-14.271	16.471
4	1	11.014	5.066	.221	-3.180	25.208
	2	-5.829	4.749	1.000	-19.134	7.477
	3	-1.100	5.487	1.000	-16.471	14.271

Based on estimated marginal means
* The mean difference is significant at the .05 level.
b Adjustment for multiple comparisons: Bonferroni.

TABLE E.10: Navigational Puzzle Game - Box Plot Statistics

	ComplexClose	**ComplexOpen**	**SimpleClose**	**SimpleOpen**
Upper whisker	83.50	96.25	123.25	103.50
3rd quartile	60.88	78.50	86.25	74.38
Median	47.25	62.00	56.25	55.00
1st quartile	39.25	52.38	50.38	48.25
Lower whisker	25.75	43.75	35.25	32.25
N	35	35	35	35
Mean	54.49	71.33	66.60	65.50
Std. Dev.	25.04	28.28	24.07	28.32

Table E.11 Visuospatial Memory Test - Raw Data

		Pair images																Per scene				Tot.
	User	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	A1	A2	B1	B2	
1	150	1	1	1	1	1	1	1	0	0	0	1	1	0	1	1	1	2	3	3	4	12
2	151	0	1	1	1	1	1	0	1	1	0	1	1	1	0	1	1	3	3	3	3	12
3	153	1	1	1	1	1	0	1	1	1	1	0	1	1	1	1	1	3	4	3	4	14
4	161	0	0	1	1	1	0	1	0	1	0	0	1	1	0	1	0	2	2	2	2	8
5	170	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	1	4	3	3	4	14
6	171	0	0	0	0	0	0	1	1	0	0	0	1	1	1	0	1	1	3	2	0	6
7	172	1	1	1	1	1	0	1	1	1	1	1	0	0	0	0	1	3	1	3	4	11
8	174	1	1	1	1	1	0	1	0	0	1	1	0	1	0	0	1	2	2	2	4	10
9	175	1	1	1	1	1	1	0	1	1	1	0	0	0	1	1	0	2	2	3	4	11
10	178	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	4	4	4	4	16
11	179	1	1	1	0	1	0	0	0	1	1	1	1	1	1	1	1	4	4	1	3	12
12	182	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	4	3	4	4	15
13	185	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	4	4	4	13
14	186	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	4	4	4	4	16
15	187	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	4	4	2	4	14
16	191	0	0	1	1	1	0	1	0	1	1	1	1	1	1	1	1	4	4	2	2	12
17	194	1	1	1	1	1	0	0	1	1	1	1	1	1	0	0	1	4	2	2	4	12
18	195	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	4	4	3	4	15
19	196	1	1	1	1	1	0	0	0	1	0	0	1	0	0	0	1	2	1	1	4	8
20	197	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	4	4	4	3	15
21	198	1	1	0	1	1	1	1	1	1	1	0	1	1	0	1	1	3	3	4	3	13

Table E.11 continued from previous page

		Pair images																Per scene				Tot.
22	202	1	1	1	0	0	0	1	1	0	1	1	1	1	1	1	1	3	4	2	3	12
23	205	1	0	1	1	1	1	1	1	1	0	0	1	1	0	1	1	2	3	4	3	12
24	206	1	1	1	1	1	0	1	1	0	1	0	0	1	1	1	0	1	3	3	4	11
25	207	1	1	1	1	1	1	1	1	0	1	1	0	1	1	1	1	2	4	4	4	14
26	208	1	1	1	0	1	0	0	0	1	1	1	1	1	0	1	1	4	3	1	3	11
27	209	1	1	1	0	1	1	1	1	1	1	1	0	1	1	1	1	3	4	4	3	14
28	210	1	1	0	0	1	0	1	0	1	0	1	1	1	1	1	1	3	4	2	2	11
29	211	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	4	4	4	4	16
30	212	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	4	4	3	4	15
31	213	1	1	1	0	1	0	0	1	1	1	1	0	1	1	1	1	3	4	2	3	12
32	214	1	1	1	0	1	1	1	1	1	1	1	1	0	1	1	1	4	3	4	3	14
33	215	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	4	4	2	4	14
34	216	1	1	1	1	1	0	1	0	1	1	0	1	0	1	1	1	3	3	2	4	12
35	217	1	1	0	1	1	1	1	1	1	1	0	1	1	1	1	1	3	4	4	3	14
																		107	115	100	119	441

TABLE E.12: VSMT - Number of correct images per user per room (max.= 4)

A1	A2	B1	B2
2	3	3	4
3	3	3	3
3	4	3	4
2	2	2	2
4	3	3	4
1	3	2	0
3	1	3	4
2	2	2	4
2	2	3	4
4	4	4	4
4	4	1	3
4	3	4	4
1	4	4	4
4	4	4	4
4	4	2	4
4	4	2	2
4	2	2	4
4	4	3	4
2	1	1	4
4	4	4	3
3	3	4	3
3	4	2	3
2	3	4	3
1	3	3	4
2	4	4	4
4	3	1	3
3	4	4	3
3	4	2	2
4	4	4	4
4	4	3	4
3	4	2	3
4	3	4	3
4	4	2	4
3	3	2	4
3	4	4	3

TABLE E.13: Visuo-spatial Memory Test - Descriptive Statistics

Desc. Stat.	
Mean	12.6
Standard Error	0.391506
Median	12
Mode	12
Standard Deviation	2.316183
Sample Variance	5.364706
Kurtosis	0.906878
Skewness	-0.82062
Range	10
Minimum	6
Maximum	16
Sum	441
Count	35
Confidence Level(95.0%)	0.795637

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