ARCHITECTURAL DESIGN IN VIRTUAL ENVIRONMENTS

Exploring cognition and communication in Immersive Virtual Environments

Marc Aurel Schnabel

Dipl. Ing.

A thesis submitted in partial fulfilment of the requirement for
the Degree of Doctor of Philosophy
at The University of Hong Kong

4 June 2004
Abstract of the thesis entitled

**Architectural Design in Virtual Environments**

*Exploring cognition and communication in Immersive Virtual Environments*

submitted by

**Marc Aurel Schnabel**

for the Degree of Doctor of Philosophy
at The University of Hong Kong
in June 2004

There is a distance between the idea in the imagination of a design and its representation, communication and realisation. Architects use a variety of tools to bridge this gap. Each tool places different demands on the designer and each, through inherent characteristics and affordances, introduces reinterpretations of the design idea, thus imposing a divergence between the idea and the expression of the idea.

Design is an activity that is greatly complex, influenced by numerous factors. The process may follow rules or established proceedings and traditions. Alternatively, the designer may choose to explore freely with no need to conventions. In all instances, the medium in which the exploration takes place
will affect the act of designing to some degree. Tools are chosen, in part, to facilitate the chosen design process.

Most researches on Virtual Environments (VE) have focused on their use as presentation or simulation environments. There has been inadequate research in the use of VE for designing. It has been suggested that this tool can empower designers to express, explore and convey their imagination more easily. For these reasons the very different nature of VE may allow architects to create designs that make use of the properties of VE that other tools do not offer in that way. As yet, barely any basic research has examined the use of VE to support the acts of designing.

This thesis examines the implications of architectural design within VE. Perception and comprehension of spatial volumes within VE is examined by the comparison of representations using conventional architectural design method. A series of experiments was conducted to investigate the relative effectiveness of both immersive and non-immersive VE by looking at the creation, interpretation and communication of architectural design. The findings suggest why form comprehension and finding may be enhanced within VE activity. The thesis draws conclusions by comparing the results with conventional methods of two-dimensional depictions as they appear on paper or three-dimensional representations such as physical models.
All worldly things thou must behold and consider, deviding them into matter, forme, and reference.

(Marcus Aurelius, ca. 180, tr. 1634)
TABLE OF CONTENTS

i. Figures ..................................................................................................................... vii
ii. Photos ..................................................................................................................... ix
iii. Tables ..................................................................................................................... x
iv. Acronyms .............................................................................................................. xi
v. Acknowledgements .............................................................................................. xii
vi. Published Work .................................................................................................... xiii

Journals ..................................................................................................................... xiii
Conference Papers .................................................................................................. xiii
Software ................................................................................................................... xiv
Websites .................................................................................................................... xv
Applications adapted in the context of this thesis .............................................. xv

1. INTRODUCTION ..................................................................................................... 1
   1.1. OBJECTIVES .................................................................................................... 2
   1.2. POSTULATION ............................................................................................... 2
   1.3. METHOD ......................................................................................................... 3
   1.4. PREVIOUS AND RELATED RESEARCH ...................................................... 5
   1.5. LIMITATIONS ............................................................................................... 6
   1.6. OUTCOMES .................................................................................................. 7

2. ASPECTS OF VIRTUAL ENVIRONMENTS .......................................................... 9
   2.1. VIRTUAL ENVIRONMENTS ............................................................................. 10
       2.1.1. Desktop Virtual Environment ............................................................... 12
       2.1.2. Immersive Virtual Environment ............................................................. 12
       2.1.3. Other Virtual Environments .................................................................. 13
   2.2. ARCHITECTURAL DESIGN IN VIRTUAL ENVIRONMENTS ...................... 14
       2.2.1. Initial Design Stages ............................................................................. 18
       2.2.2. Computer Supported Collaborative Design - VDS .............................. 20
       2.3. PERFORMANCE FACTORS OF VIRTUAL ENVIRONMENTS .............. 21
           2.3.1. Psychological ..................................................................................... 22
               2.3.1.1. Spatial Knowledge ....................................................................... 22
               2.3.1.2. Cognitive Loads .......................................................................... 24
               2.3.1.3. Others ........................................................................................... 24
           2.3.2. Technical ............................................................................................. 25
               2.3.2.1. Field of View ............................................................................... 25
               2.3.2.2. Apparatus ..................................................................................... 27
               2.3.2.3. Others ........................................................................................... 27
           2.3.3. Problem/Task framing ....................................................................... 28
   2.4. MAZE ............................................................................................................... 29
   2.5. DISCUSSION ................................................................................................... 29
   2.6. SUMMARY ...................................................................................................... 31

2.7. DESIGNING WITHIN VIRTUAL ENVIRONMENTS .......................................... 33
   2.7.1. Definition of Research ............................................................................... 33
   2.7.2. Overview of Experiments .......................................................................... 34
   2.7.3. Participants of Experiments ........................................................................ 35
Figures

Figure 1: Architectural drawings ................................................................. 16
Figure 2: Rendering of Guggenheim Museum, Bilbao, Spain .................... 17
Figure 3: Field of Views .............................................................................. 26
Figure 4: Mental Unit .................................................................................. 41
Figure 5: Screenshots of database ............................................................... 44
Figure 6: Plan and model of rooftop for playground design ....................... 44
Figure 7: Screenshots of Database of VeDS ............................................... 47
Figure 8: Screenshot of the HKG model with the site of the helipad ......... 49
Figure 9: Users were involved in terms of scale, viewpoint & navigation.. 53
Figure 10: Primitives representing functions or forms ............................. 54
Figure 11: Primitives can symbolise both positive and negative representations of design elements. ............................................. 55
Figure 12: Lack of experiences or complexity of the VE created errors ...... 55
Figure 13: Plan and perspective of design with a painting by Kandinsky.... 56
Figure 14: Differences in design and operation skills ............................... 56
Figure 15: Results of the questionnaire ..................................................... 58
Figure 16: Communication Analysis ............................................................. 59
Figure 17: Communication ......................................................................... 63
Figure 18: External and internal views of the cube: front and back .......... 70
Figure 19: The 8 cuboids defining the cube .................................................. 70
Figure 20: 2D plans for the 2D condition .................................................... 73
Figure 21: Template for the maze in the 2D condition ............................... 78
Figure 22: Grid framework for the 3D condition with chat window ........... 78
Figure 23: Percentage of correctly reconstructed cuboids: 2D condition..... 81
Figure 24: Typical configurations ............................................................... 82
Figure 25: Percentage of correctly reconstructed cuboids: 3D conditions ... 83
Figure 26: Comparison of percentage of participants adopting different strategies

Figure 27: Typical 2D maze solution

Figure 28: Typical maze solutions of the VE condition

Figure 29: 2D versus DVE Maze

Figure 30: Comparison of 2D and DVE conditions in cell types

Figure 31: Comparison of DVE & IVE conditions of numbers of walls

Figure 32: Resulting mazes created by DVE participants

Figure 33: Resulting mazes created by IVE participants

Figure 34: Comparison of DVE and IVE conditions in cell types

Figure 35: Comparison of time staying inside and outside of mazes

Figure 36: Comparison of mono- and polychrome mazes in cell types

Figure 37: Comparison of 2D & DVE conditions of total text exchanges

Figure 38: Comparison of DVE and IVE conditions of chat content

Figure 39: Comparison of DVE and IVE conditions of chat content

Figure 40: Comparison of mono- and polychrome conditions of chats

Figure 41: Comparison of design activity

Figure 42: ‘Tunnel vision’ of DVE and zooming out of a MAZE result
**Photos**

Photos are taken by the author, except stated otherwise:

- **Photo 1**: Typical setting of a DVE: Screen, In-Output devices and PC ..... 12
- **Photo 2**: Display methods of Immersive Virtual Environments.......... 13
- **Photo 3**: Tracking devices ............................................................ 13
- **Photo 4**: CAVE, Workbench, Illusion-hole, 3D projection screen ........ 14
- **Photo 5**: Immersive Virtual Environments...................................... 19
- **Photo 6**: Studio Settings ................................................................ 37
- **Photo 7**: Setup of Equipment........................................................ 39
- **Photo 8**: Teamwork ....................................................................... 41
- **Photo 9**: Video Conference after VeDS ......................................... 48
- **Photo 10**: *b&k+* Housing Loft Köln Brett....................................... 71
- **Photo 11**: Wooden blocks in eight colours..................................... 71
- **Photo 12**: Reconstruction process and final volume. ...................... 72
- **Photo 13**: Desktop Virtual Environment Condition .......................... 74
- **Photo 14**: Immersive Virtual Environment Condition ......................... 74
- **Photo 15**: Student designing within the IVE condition ...................... 79
- **Photo 16**: Sample solutions of the 2D condition: rebuilt cube .......... 82
- **Photo 17**: Sample solutions of the VE condition: partly rebuilt cube .... 85
- **Photo 18**: Partly rebuilt cube with correct cuboids.......................... 84
- **Photo 19**: Scharoun’s Philharmonie, Berlin Exterior, Interior and Plan ... 107
- **Photo 20**: Photogram by Man Ray ................................................. 112
- **Photo 21**: Sketch by Asger Jorn ..................................................... 112
iii. Tables

Table 1: Gesture Reference Guide ............................................................. 40
Table 2: Time Flowchart ............................................................................ 46
Table 3: Design task distribution: Landside/Airside and Static/Dynamic . 49
Table 4: Excerpt from design description by Zhang, J. and Yong, K. H... 51
Table 5: Excerpt from Chat text of Phase 2: VeDS107 and VeDS110...... 60
Table 6: Excerpt from Chat text of Phase 1: VeDS109 and VeDS112...... 60
Table 7: Excerpt from Chat text of Phase 3: VeDS107 and VeDS110...... 61
Table 8: Excerpt from Chat text of Phase 1: VeDS101 and VeDS202...... 62
Table 9: Excerpt from Chat text of Phase 2: VeDS106 and VeDS206...... 64
Table 10: Time spent on the study and reconstruction tasks............... 86
Table 11: Types of nucleuses (maze cells) by its number of walls......... 89
### Acronyms

Acronyms are used in this thesis:

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D</td>
<td>Two-dimensional</td>
</tr>
<tr>
<td>3D</td>
<td>Three-dimensional</td>
</tr>
<tr>
<td>AR</td>
<td>Augmented Reality</td>
</tr>
<tr>
<td>BUW</td>
<td>Bauhaus University Weimar, Germany</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer Aided Design</td>
</tr>
<tr>
<td>CAAD</td>
<td>Computer Aided Architectural Design</td>
</tr>
<tr>
<td>CSCD</td>
<td>Computer Supported Collaborative Design</td>
</tr>
<tr>
<td>DVE</td>
<td>Desktop Virtual Environment</td>
</tr>
<tr>
<td>HKU</td>
<td>The University of Hong Kong, P.R. China</td>
</tr>
<tr>
<td>HMD</td>
<td>Head Mounted Display(s)</td>
</tr>
<tr>
<td>FOV</td>
<td>Field of View</td>
</tr>
<tr>
<td>IVE</td>
<td>Immersive Virtual Environment(s)</td>
</tr>
<tr>
<td>IT</td>
<td>Information Technology</td>
</tr>
<tr>
<td>PC</td>
<td>Personal Computer(s)</td>
</tr>
<tr>
<td>PDA</td>
<td>Personal Digital Assistant (Handheld computer)</td>
</tr>
<tr>
<td>VE</td>
<td>Virtual Environment(s)</td>
</tr>
<tr>
<td>VDS</td>
<td>Virtual Design Studio(s)</td>
</tr>
<tr>
<td>VeDS</td>
<td>Immersive Virtual Environment Design Studio</td>
</tr>
<tr>
<td>VR</td>
<td>Virtual Reality</td>
</tr>
<tr>
<td>VRAM</td>
<td>Virtual Reality Architectural Modeller (Software)</td>
</tr>
<tr>
<td>VRML</td>
<td>Virtual Reality Meta Language (File-format)</td>
</tr>
</tbody>
</table>
v. Acknowledgements

I sincerely appreciate the time and energy everybody expended in support of this research. I acknowledge the developers and programmers of 3D MAZE Tse Hiu Ming and Hartmut Seichter, as well as the team of VRAM/G. Acknowledgements are due to the research assistants Sheung Kia Chan, Ka Po Chiu, Ivan Chu, Kevin Ho, Stephanie Lee, Tammy Liu, Emerald Wong as well as the IT-support staff under the lead of Tim Yeung and all participating students at the Departments of Architecture, The University of Hong Kong and the Bauhaus University Weimar, Germany. I am genuinely grateful to John Bradford for his advice during the first VeDS. Financial support came from the Germany/Hong Kong Joint Research Scheme (RGC/DAAD) of the University Research Committee and The University of Hong Kong. Finally yet importantly, I owe thanks to Thomas Kvan, who stood by me like a guardian angel, my friends and family who like a “sweet chariot” carried and endured me in all my non-cherubic moments.
vil. Published Work

Publications deriving directly from this research

Journals


Conference Papers


*Software*

http://www.arch.hku.hk/~marcaurel/phd/mazespec.html
Websites


Applications adapted in the context of this thesis


1. INTRODUCTION

There is a distance between the imagination of a design and its representation, communication and realisation: architects use a variety of tools to bridge this gap (Pérez Gómez and Pelletier, 1997).

Most researches on Virtual Environments (VE) within the architectural context have focused on their use as presentation or simulation environments. There has been inadequate research in the use of VE for designing. Designing within VE may minimise this divergence. As a result of this designers are empowered to express, explore and convey their imagination with fewer differences (Dobson, 1998).

Design is an activity that is greatly complex and influenced by numerous factors. The process may follow rules or established proceedings and traditions. Alternatively, the designer may choose to explore freely with no need to conventions. In all instances, the medium in which the exploration takes place
will affect the act of designing to some degree (Pérez Gómez and Pelletier, 1997). It has been suggested that for this reason, the very different nature of VE may allow architects to create designs that make use of the properties of VE that other tools do not offer (Davidson and Campbell, 1996).

This thesis examines the implications on architectural design by using immersive and non-immersive computer generated VE as the environment for design.

1.1. Objectives

The objective of this study is to identify how designers engage and communicate early design ideas when using immersive three-dimensional VE. By understanding the influence of VE on the design process, we are able to draw conclusions how the exploration of volume, void, space, shape and form in ‘gestalt’ (Arnheim, 1969) can be enriched by the use of tools in a VE.

With this understanding, we may be able to realise how VE can empower architects to bridge the gap between imagination and reinterpretation of architectural design and how VE allow architects to explore and express their ideas in a way that benefits the resulting design.

1.2. Postulation

This thesis investigates the statement: “Designing within immersive virtual environments offer settings that significantly enhance the designer’s
understanding and communication of three-dimensional architectural space”. Using VE to create and visualise ideas, the architect is challenged to deal with perception of space, solid and void, without translations to and from a two-dimensional (2D) media. From this, we expect innovative forms of design expression as well as an enhanced communication of the three-dimensional (3D) gestalt. This thesis postulates that immersive and non-immersive VE enhance conception, perception and understanding of spatial volumes in comparison with representations using conventional architectural design media. We also examine the relative effectiveness of these conditions in enabling the translation to a tangible representation through a series of design experiments. By exploring issues of quality, accuracy, communication and understanding, this thesis studies the impact VE have on the design of architectural forms and space.

1.3. Method

Within a framework of a qualitative study, we set up a series of experiments in which designers worked in VE and Immersive Virtual Environment (IVE) that engaged them in a range of tasks: conception, perception, navigation, transcription of forms, and remote communication between design partners. We explored initial design schemes, their textual descriptions and issues of collaborations within IVE. Related and comparable to the investigation by Yip (2001) that compared outcomes, collaboration and communication of architectural design using either textual description or 2D media, this thesis compares those issues comparing VE with 2D techniques.
We started with a Joint Design Studio as the initial series of experiments. An architectural design studio is the most common form of architectural design conception, communication and collaboration in both educational and professional environments. It used IVE as a tool of design as well as the platform of communication between remote partners. Here, we investigated frameworks and factors influencing how architectural students create and communicate their proposals in an design studio, which we called *Immersive Virtual Environment Design Studio* (VeDS). Further we explored how this new approach of design studio enables new forms of design expressions. The outcomes of this studio suggest that architectural design is perceived, communicated and created very differently than in non-immersive studio settings.

Based on these findings we saw the need to explore how designers arrive at different outcomes within a VE in more details. Within a laboratory setting, we conducted another series of qualitative experiments that analysed an abstract cubic structure. Similarly to the investigations of Mizell et al. (1999), who also used an abstract structure (in their case a rod-wire sculpture) without any intrinsic meaning in order to minimise the influence of unrelated factors, we employed abstract forms in two sets of experiments. One being a collaborative design task of a 3D maze and the other being a cubic structure based on predefined interlocking volumes and spaces.

From the results of those experimental design studios, we were able to draw conclusions. We compared the resulting outcomes of the experiments with conventional methods of design that involves 2D depictions as they appear on paper or 3D representations such as physical models.
1.4. Previous and Related Research

Architectural design within VE has been widely used as a method of design simulation and presentation. Educational and professional settings employ VE successfully to study, communicate and present architectural design. The rapid development of digital tools during the past decades had profound impacts on the architectural education and the way how architects create, converse or appreciate 3D spatial environments (Koutamanis, 1999). Numerous publications illustrate the impact digital media had on design studios and propose solutions for the multi-media design studios and how to make use of VE (Maver, 2002). Dave (1995) investigated distributed design studio, Wenz and Hirschberg (1997) studied collaborative design within remote collaboration, while Hirschberg et al. (1999) analyzed pattern of communication within digital design studios. VE often became a presentation tool only to assess design alternatives and final design solutions (Achten et al., 1999). Yet, they did not look into the comprehension and conception of design within VE.

One particular form of design studio emerged in the early nineties that investigated various possibilities digital media and VE can offer to the learning and the exploring of architectural design. These so called Virtual Design Studios (VDS) defined virtuality as acting while physically distant or as acting by employing digital tools (Maher et al., 2000). Yet virtual did not refer to an Immersive VE. Instead, VE were established by the choice of design (Achten, 2001), way of communication (Schmitt, 1997) or digital tools (Kurmann, 1995, Regenbrecht et al., 2000, de Vries and Achten, 2002). Yet a significant potential of research remained unexplored. Within the context of a VDS, a real immersion
into a VE could be used for design interaction. I was involved in various VDS at The University of Hong Kong since 1997 (VDS, 1993-2002, Donath et al., 1999, Hirschberg et al., 1999, Kolarevic and Ng, 1999). It became apparent to me that the next logical step to develop the VDS is a joint design studio that combines true immersion and VE. Mitchell (1995) also refers to the need for an ongoing evolution of the VDS towards a fully integrated studio where the borderlines between realms are dismantled. In the same way, Chen et al. (1998) suggest that human-human interactions could take place within computer systems of a new type of virtual studios, instead of through or external to them, as it happened in some VDS.

1.5. Limitations

Numerous factors influence architectural design. It is impossible to isolate all individual sources to establish a direct chain of cause-and-effect. Yet, significant formal decisions are made in the initial stage of design. For example, basic decisions of form, volume, space, and their relationships to each other are sketched out and established for further review, development or refinement. In order to limit and focus the scope of our research, we only investigated these early design stages. However, the design process is not linear and not limited to a particular method. Consequently, we can only interpret and abstract the outcomes of this qualitative research relating to the design methods we employed in our experiments. A further development of the various designs in other media may result in diverse outcomes to the findings of the initial design stage.
The results of this research depend profoundly on the available technologies and the technical equipment and setup used in our experiments. Furthermore, our participants and their individual skills, methods and understandings of architectural design inevitably influence the outcome of this study, especially in the context of a creative design process. Yet, this thesis tries to establish general trends and connections within the specified framework of a qualitative research that allow an interpretation independent of influencing factors.

1.6. Outcomes

This research has demonstrated that VE minimises the distance between the imagination of a design and its representation within an architectural design process. VE support an enhanced understanding of 3D space. Within certain phases of the design-process, such as the initial form finding or the definition of volume, void and solid, VE have an advantage in exploring and expressing an architectural design proposal.

The results of the VeDS show that IVE produce different architectural expressions and exploration of form and gestalt from those explored with 2D tools. The design proposals illustrate that the 3D space is explored and used extensively in order to create innovative schemes. They prove that designers can successfully use the medium to create and communicate architectural structures within a normal studio setting. The process of collaboration and design is enhanced and the communication between designers is more focused on the subject itself.
The findings of the laboratory experiments confirm that participants in the VE realm have a greater understanding of the 3D space, develop a more profound communication of idea and outcome as well as have a deeper involvement with the design itself. The outcomes confirm however, that conventional design tools are still the prevailing design medium that designers are used to work with.

We have demonstrated that design tools employing VE have significant contributions to the design process by enhancing perception and understanding of 3D form, volumes and space. This is true not only for purposes of presentation or simulation, but also for the different stages of the design process itself. From the results, we also have identified that a direct translation of information from VE into other real media is potentially problematic. However, similar to the conclusions of Yip (2001) re-representation and translation into other realms actually contribute to the quality of the whole design process.

This thesis sustains findings that the medium of design and its use influence the outcomes significantly. This corresponds to conclusions drawn in related studies, such as those of Mizell et al. (1995), or Gao and Kvan (2004).

To summarise, VE offer architects possibilities that are not present in other environments, and therefore contribute to the design process significantly. Designing within VE augments effectively the imagination and depiction of architectural design schemes.
2. ASPECTS OF VIRTUAL ENVIRONMENTS

According to Kvan (1994), new opportunities arise for architectural design. Schmitt and Chen (1991) state that it is not sensible to assume that any given design process may be supported by only one tool, conventional or computer-aided. Yet Computer Aided Design (CAD) can assist the interaction among the design process, its methods, and employed tools. As Milgram et al. (1994) describe it, the conventional media of design, the technologies of Computer Aided Architectural Design (CAAD) and tools of VE increasingly overlap each other. The influences of these realms and their opportunities to aid designers however are not sufficiently studied. Of particular interest to this thesis is the extent to which the application of VE within architectural design may affect the quality and with that the outcome of design itself. When computers first became available to support architectural design, conventional methods were ahead of the use and implementation of the technology and efforts to integrate them had to be
discovered (Cross, 1977, Mitchell, 1977). As so often happens when technology is introduced, we have to understand the implications of the technology and the opportunities offered, especially the opportunities to change the ways we design (Hammer, 1990). In rushing to implement technology, we replicate current practice without considering the foundations on which we are making decisions (Hollan and Stornetta, 1993). Likewise, we recognise that VE can offer modes of practice that not only differ from the current ones, but also do not need to simulate the conventional methods.

This chapter will look into these issues, discuss the research done in this field, and conclude with the definition of our research within the context of architectural VE.

2.1. Virtual Environments

According to Stuart (1996), VE can be defined as artificial interactive computer generated environments which have been developed using computer software and presented to the user in such a way that the perceived result appears and feels like a real environment. In such systems, users can interact through a human-computer interface and the system will give the users an impression that they are inside the environment that can be either the representation of real or imagined agents, objects and processes.

VE can be immersive, which means that rather than looking at a typical computer screen, the display creates the impression that the users are inside the environment generated by the computer. Multimodal interfaces improve the
“immersiveness” of the users’ interactions. Users can wear special gloves, suits, earphones or headsets, all of which receive input signals and give feedback to users through several sensory modalities. In such a way, some of our senses such as sight, sound and touch are controlled by the computer (Steuer, 1992). Psychologists are still debating on the meaning of immersion (Travis et al., 1994), yet we use the above mentioned explanations as a working definition for this thesis.

In a design application, VE offers real-time viewing that facilitate designers to evaluate their decisions immediately (Dobson, 1998). The ease of evaluating the design could enhance the quality of design. VE are influencing the way that spaces are designed and changing our experience of the built environment. Their applications are based on a range of technologies, built for entertainment, academic research, military, and advanced manufacturing purposes. However, VE are still greatly evolving and with this evolution their descriptions are continuously re-defined (Benedikt, 1991, Lawson, 1994, Milgram et al., 1994, Coyne, 1995, Vince, 1998).

Several types of VE are used within CAAD. The experiments of this thesis employed two major categories. In one the users are experiencing a VE by sitting in front of monitors, while in the other, users immerses themselves into a VE. The following sections will explain the two types in detail.
2.1.1. Desktop Virtual Environment

VE system displayed on monitors is typically categorised as Desktop Virtual Environment (DVE). DVE has evolved from animated CAD (Buckingham Shum et al., 1997). The user interacts with the environment and objects generated by personal computer (PC) through input devices such as mouse, keyboard or joystick. At the same time, the computer will give feedback through several media such as vision from screen, auditory from speakers or touch sensation from tangible feedback interfaces (Photo 1).

![Photo 1: Typical setting of a DVE: Screen, In-Output devices and PC](image)

2.1.2. Immersive Virtual Environment

Immersive Virtual Environments (IVE) are displayed by using other forms of displays than DVE. Rather than using monitors, IVE use displays that allow users a more or less exclusive view of VE. This can be achieved for example with Head Mounted Displays (HMD) or large screens that almost fill the viewer's entire field of vision (for example CAVE) (Photo 2).
 Movements of the user’s head or body parts are tracked with position tracking devices (Photo 3) and simulated on the display or screen, providing an optical illusion of being immersed into the displayed scene.

2.1.3. *Other Virtual Environments*

There are many other forms of VE: from drawn or painted 2D to physically modelled 3D. There are immersive and non-immersive VE using electronic means as projections, to name a few: CAVE, Workbench, Illusion-hole and stereoscopic projection-methods. Mazuryk and Gervautz (1996) summarise
comprehensively applications and technologies of VE. Photo 4 below illustrates some of those technologies.

**Photo 4: CAVE, Workbench, Illusion-hole, 3D projection screen** (VR Media Lab, Aalborg Universitet, Denmark and BUW, Germany)

### 2.2. Architectural Design in Virtual Environments

The question of describing architectural design itself is central to any debate about the use of VE to support architectural design. There are many definitions of design. Lawson (1980, 1994) for example defines architectural design as an act of creation, while Dorst (1996) tries to address more general definition of design related to any action within an artistic intention. Others have considered the difference between design in physical worlds and design in VE (Bridges and Charitos, 1997). This thesis will not identify a singular definition of design, yet provide a background of different interpretations. These allow establishing a framework as basis for this thesis.

In practice, an architect draws upon a wide variety of media to express his or her ideas. Within the course of a project, different representations are used at different times to explore different issues (Lawson, 1994, p. 90). An architect can
produce drawings using any kind of medium, such as all sorts of paper, pencils, ink and paint. Drawings may be soft edged or hard lined, fuzzy or precise. Physical models are created using almost any material, such as cardboard, clay, plastic and metal. These models can represent an abstract form or the real material and appearance. As these representations gather, architects begin to identify constraints, opportunities, and references that might be important to come up with a solution. An architect articulates sketches of space in two or three dimensions, using representations such as perspectives, plans, elevations and sections, or models to understand and communicate the design. Obviously, there are significant differences between manual drawings, sketches, paintings, etc. and images and models produced using CAD systems. Since the introduction of CAAD by Sutherland’s Sketchpad (Sutherland, 1963), extensive research has been undertaken to explore various possibilities and potentials of different media and realms (Goldschmidt, 1991, Schön and Wiggins, 1992, 1994, Robbins, 1994, Goel, 1995, Lawson and Loke, 1997, Suwa and Tversky, 1997, Verstijnen et al., 1998). It is obvious, however, to see and understand the fundamental differences of the two realms by looking at the drawings shown in Figure 1. They illustrate the diverse nature and expressions of the drawing techniques.
Nevertheless in all descriptions of the design development, we find in common the activities of cogitation, expression/modelling and communication/testing (Broadbent, 1988). Without engaging in discussion about computer-mediated cogitation or speculating on what the results of VE supported design may be, it is obvious that the tool used is affecting the process and outcome of a design. The impact of the medium of representation on the content has been the subject of many studies. Marshall McLuhan (1964) proclaimed that ‘the medium is the message’. In the same way 2D drawings had a significant impact on architectural design in the 15th century, hence it is logical to assume that digital media, especially IVE, have a considerable impact on architects’ ability to conceive, understand and communicate spatial environments. Before we consider ways in which VE designs can be carried out, however, it is useful to consider the process of architectural design and to gain an understanding of the processes along the way.

Research has recently begun to look in detail at the architectural design process within VE. One area in which we have no detailed insight is the role of VE on the quality of the outcome within a design process. As we consider applying
computer tools to the course of design, we need to keep the multiple representations of conventional and computer-aided media in mind. When thinking about using VE for architectural design, it is necessary to remind ourselves that the tool for creating architectural design does influence the outcome or process. Yet a tool, by its definition being an aid, shall be used for supporting the design process. By the same token, we must not fall into the trap of replicating non computer methods without considering the ways in which work can be restructured, the dangers of which have been identified in other disciplines by Zuboff (1988). For example, Figure 2 shows a CAAD rendering of a manual sketch. The replication however, fails to take into account different line-weights and ‘feelings’ that a pencil sketch can present. Yet the rendering can communicate different properties of the design that a sketch can never produce.

At this point we have to look closer where VE can be employed usefully in the development of architectural design and where real and VE will lead to different communication and understanding of the design process. Two areas are obvious. The point of embarkation or initial stage of design, which determines the very
basic outlines of the whole process, is one field. Decisions made at the very beginning of a development will have implications up to the final outcome. Another area, where VE are already used, is the collaborative design studio that makes use of virtual realm. Yet VE was never used as the medium of design.

These two areas will be discussed in the following sections.

2.2.1. Initial Design Stages

VE play an increasing role in architectural design especially during early design activities (Bertol and Foell, 1997). Equipment and software to engage in VE become easily available and particularly affordable. However, not sufficient attention has been paid to the results and possibilities of architectural design within VE (Stuart, 1996). Lessons learnt from academic contexts have been employed in various commercial settings within the creative industries (for example ACS, 2001). A few corporations and architectural companies make use of global locations, sharing of resources and work force. This collaboration goes beyond video-conferencing or file-sharing and includes shared design sessions and expertise consultation (Burry et al., 2001).

The overall dimensions of an architect’s final ‘product’ as well as constraints of resources make it usually inevitable that architects communicate and express their intentions with the help of models. Architects can use a variety of tools to translate their designs. In recent years, computer generated VE are increasingly used as a device of communication and presentation of design intentions (Leach, 2002). VE are employed successfully to study, communicate and present
architectural design (Bertol and Foell, 1997). However, according to Maze (2002), VE are seldom used in initial design stages for creation, development, form finding and collaboration of architectural design. Nowadays VE are integrated in many consumer products, such as games, communication devices and simulations. In contrast, IVE that enable users 3D interactions with space and volume have not been used widely in the design process. Only some visionary illustrations, such as movies, games or ambitious experiments, like aeronautics, employ IVE in the design process as pictured in Photo 5.

Photo 5: Immersive Virtual Environments

Left: IVE Designers (VR Media Lab, Aalborg Universitet, Denmark)

Middle: VR-Game Centre (The Game Emperor, USA)

Right: CAE-flight simulator (CAE Inc., Québec, Canada)

Kvan (1999) elaborates the benefits of communication and re-representation of design within different media. However, he reports that descriptions contribute more to the initial design communication than any other media. On the other side it is reported extensively that IVE offer new opportunities and solutions to architectural design problems (Bridges and Charitos, 1997, Goebel et al., 1998, Vince, 1998). Yet the literature does not clarify just how well 3D forms within IVE are understood and it is suggested that basic research is needed to demonstrate the benefits to the quality of architectural design in initial design
stages. We set therefore up a series of experiments to explore some basic questions of how designers perceive models in IVE.

2.2.2. Computer Supported Collaborative Design - Virtual Design Studio

As Kvan (1999) postulates, Computer Supported Collaborative Design (CSCD) can enhance the exploration of ideas and their communication. However, multimedia support can actually reduce the interaction and exploration of design. Kalay (1998) describes the difficult situation of architectural ventures that employ CSCD methods. Integrated projects are undertaken by severely fragmented teams, leading to decreased performance of both processes and products. Yet, due to the complexity of the project, these processes have to be used. Virtual Design Studios (VDS, 1993-2002) have been widely used in the last decade as an environment for architectural design teaching. A variety of publications explain and propose solutions for these multi-media CSCD studios within a quasi VE (Saad and Maher, 1996). While most VDS have been successful (Hirschberg and Wenz, 2000), various issues have been reported, e.g. lack of communication and collaboration (Kvan, 2000a); technology overhead (Kruijff, 1998); and potential contributions to design outcomes (Wojtowicz and Butelski, 1998). In all these design studios, virtuality has been defined as acting while physically distant (Maher et al., 2000). Virtual has not yet referred to an IVE per se. Instead, VE were established by the choice of design and communication media: computers, CAAD programs (2D and 2.5D), VRML, emails and chat channels, electronic file transfers (ftp), video conferences, projection screens, webpages and automated databases (Donath et al., 1999).
Immersion has not been used for design interaction, although shared immersive virtual spaces have been employed for design reviews (Davidson and Campbell, 1996). The next logical step to develop the VDS is, therefore, to establish joint design sessions where users can collaboratively create, interpret and communicate design ideas within an IVE and to examine if this context offers any new opportunities or solutions to problems encountered. Mitchell (1995) argues that there is a need for an ongoing evolution of the VDS towards a fully integrated studio where the borderlines between realms are dismantled. Before engaging in a full VeDS, however, we saw a need to examine the nature of an immersive space in a simple design task. We engaged students in a task where students can explore and familiarise themselves with IVE. Their experiences gained were then translated and applied to the VeDS.

2.3. Performance Factors of Virtual Environments

There are varieties of factors that influence the users’ performance while working in VE, from psychological to technical and design related issues. These factors then affect the behaviour, perception, knowledge and response of the user and therefore ultimately the design itself. It is vital to keep these factors in mind when interpreting the results of the experiments.

In this section of the thesis, I will describe these of the key factors because they are significant to the outcome of the experiments. Within these, not all factors can be studied individually and exclusively. Therefore, some crossovers and influence of other aspects have to be acknowledged. However, in order to keep
the focus of this thesis it is not necessary to study all possible influencing factors and excluding issues. Yet a basic knowledge and trend can be distilled from the main factors, which are stated below.

2.3.1. Psychological

This section will describe the main psychological factors that influence the use and performance of design within VE.

2.3.1.1. Spatial Knowledge

In every environment, a single perspective is not sufficient. Users need to explore the environment to acquire spatial knowledge and develop a cognitive map to understand the model (Weatherford, 1985). A VE has to give adequate and enough cues to help users build up spatial knowledge successfully (Thorndyke and Hayes-Roth, 1982).

Spatial knowledge is manipulated, retrieved and detected in the form of memory, called spatial representation (McNamara et al., 1989). Users navigating inside VE will form a representation of the environment in their mind to help them navigate and orientate. This is similar to our real world experiences. Subsequently users engaged in an architectural task within VE, form and imagine a spatial representation in their mind and then refer to it by acting within the representation of the VE. Waller and Miller (1998) analyse the effectiveness of a simple VE exercise system. Participants learnt how to solve a spatial puzzle in different media. They observed that people who used the VE system spent more
time training, but performed significantly better in solving the puzzle than people using other media.

The literature reveals that individuals can build up accurate knowledge about their and other’s navigation by moving through VE (Witmer et al., 1996, Ruddle et al., 1997). Another spatial knowledge is the sense of orientation. The awareness of the space around us results in knowledge about the configuration of the environment (Hunt and Waller, 1999).

There are other cues to aid orientation, such as visual cues, like depth cues and perspective cues, gravitational cues. With a HMD, equipped users can determine a vertical orientation, and other cues addressing the various senses of individuals experiencing VE. Robertson et al. (1997) have shown that an increase in the sense of orientation with more orientation cues, resulting in better execution of navigation tasks.

Interestingly Mizell et al. (1999) find that it is not crucial for individuals to experience stereoscopic vision while viewing VE to enhance their spatial knowledge and performance, though Ager and Sinclair (1995) point out the undisputed advantages of 3D representation through StereoCAD. Being aware of these issues, we have to employ monoscopic viewing within our experiments due to the limitations of technical availability.

To facilitate the complex process of architectural design within VE, it is crucial to understand the capabilities of cognitive loads individuals can cope with. Subsequently the issue will be discussed in the following section.
2.3.1.2. Cognitive Loads

Cognitive Load Theory, as defined by Sweller (1999) states that optimum learning occurs in humans when the load on working memory is kept to a minimum to best facilitate the changes in long term memory. Sweller finds that, for a better task performance, it is necessary to minimise the cognitive loads of the users.

VE are able to provide a large volume of information concurrently. Dillon and Marian (1988) report that if users are not able to focus and handle information, the application induces cognitive overload, thus reducing task performance. Cognitive load can also be increased by difficulty in device control, insufficient cues in VE and disturbance from the surroundings, or mismatch of real life experiences with those in VE. Therefore, it is essential to keep a balance between offering all possible cues within VE and overloading the user with information, which ultimately inhibits the performance within VE (Ataman, 1999). Considering these issues, we tried in our experiments to eliminate factors that could distract or result in a cognitive overload. The VE-system did not offer complex navigation or interface-structures, the displayed or created elements were reduced to simple primitives and the task did not require complex design-strategies.

2.3.1.3. Others

There are many other psychological factors, such as gender, age, level of experience, physical, emotional, social and cultural differences, to name just a
few. I have to acknowledge that I will not look further into these factors in order to focus the scope of this thesis. Being aware of that, we recruited participants from a fairly homogeneous group of students for all experiments (see Section 2.7.3.) trusting by doing so that differences are distributed equally over all experiments. In the context of this thesis, the outcomes of the experiments have to consider the specific settings and differences on the results of the above-mentioned factors have to be studied separately.

2.3.2. Technical

This section will describe some technical factors that influence the use and performance of design within VE.

2.3.2.1. Field of View

The human Field of View (FOV) spans approximately 200 degrees horizontally, taking into account of both eyes, and 135 degrees vertically. Figure 3 illustrates the human FOV. The FOV within VE cannot directly be compared with real environments. Virtual Reality (VR) systems replace that FOV with a simulated one, by a display and a computer graphics system. In VE, to the extent that the technology affords it, we can enhance the feeling of presence within this realm to a limited extent by taking into account the characteristics of humans’ visual perception and FOV (Kalawsky, 1993).
The FOV within VE is limited and determined by display devices. By using a HMD, the impression of the FOV can be enlarged since the free head movement allows users an unlimited surround view. Additionally, it allows easy multi-viewpoints and multi-user perspectives of a VE. This is an important factor in collaborative environments as engaged in our experiments.

A key design variable for a HMD is the FOV size. A narrow FOV has been shown to degrade performance in visual search and spatial awareness tasks; it causes longer task completion times, disrupted eye- and head-movement coordination, and misperception of size and space. Yet a overly wide FOV may also degrade performance, causing VR sickness due to vection and visual vestibular mismatch (Arthur, 2000).

PC monitors have a very limited FOV of less than 20 degrees. Evidently a decreasing FOV causes a decline in spatial awareness and an increase in visual searches (Arthur et al., 1997). It therefore matters to the outcome of experiments to distinguish between a DVE, which employs PC monitors with a narrow FOV, and an IVE that uses HMD with a wide FOV. We have to keep this in mind when interpreting the results of the different experimental settings presented in this thesis.
2.3.2.2. Apparatus

Wong (2000) reports that the weight of HMD play a significant role in the degrading users’ performance within IVE. His findings describe that HMD are useful for short-time tasks. We ensured our tasks were not protracted.

Wiring and user-friendliness of the equipment as well as computing time of the generated VE play a significant role in the performance of the designer. Due to the given constraints, the experiment could not eliminate them. However, the setup of the experiments took into consideration these issues and minimised the impact of those by adequate training of the equipment as well as external assistance and support to the designer to reduce the impact of those factors. To reduce computing time and the lag between action and reaction, we focused on the necessary elements and cues within the VE. We used a monoscopic polychromatic VE with some spatial, navigational and orientational hints. Earlier tests revealed that our set up could provide the participants with an adequate impression of VE and IVE.

2.3.2.3. Others

Numerous technical issues influence the performance of the designer within VE. Tools for VE are constantly evolving. Equipment becomes more sophisticated, user-friendly and lighter. Influences of the real world can be reduced further and a deeper immersion of the inhabitants of VE can be achieved. We used current and available technology and apparatus in the experiments of this thesis, as
described in more details within the setup of the experiments of the following next chapters.

2.3.3. Problem/Task framing

The framing of the design problem itself has a great impact on the design progress and its outcome. Issues, such as the formulation of the task itself, the skills and experience of the designer, the method and guidelines, limitations of space, money and regulations have an extensive influence on the design process. Several studies have examined how the framing, moving and reflecting of a problem or design task influences the outcome (Schön, 1984, Gao and Kvan, 2004). Design, however, is not linear and may not follow conventions. Designing is the process of problem solving, in which design problems are classified into well defined, ill-defined and wicked (Schön, 1985). It can evolve freely and is therefore not predictable. Therefore, in most cases the design outcome cannot be evaluated as right or wrong, better or worse. Yet, evaluation criteria have to be objective and not favour particular design outcomes. Nevertheless, in many architectural design problems constraints and opportunities are similar to each other as well as unique to each environment, media and design. This thesis pays special attention to the formulation of the problems and their tasks of the various experiments. Taking the above-mentioned matters into account, we formulated problems that do not seek favour one realm and hinder the other.

The following section will describe an abstract problem that tries to eliminate influencing variables and is solvable in all realms.
2.4. Maze

The design of a maze is a representative design problem, one that focuses its attention on issues of form, spatial memory and spatial description. Mazes have been used to explore design and cognition tasks by others (Mallot, 2000). Although a maze is a very basic entity with clear and simple rules, it is a considerable challenge for both designers and users. This offers the possibility to study and compare designs on an abstract level without being biased to personal preferences of design, layout or gestalt. The design and exploration of mazes has been regarded as a fascinating topic throughout history of architectural design (Berer and Rinvolucri, 1981). Several studies have compared specific differences of mazes experienced in VE or reality (Waller et al., 1999). Traditionally, however, mazes are 2D stretching out in length and depth with ‘walls’ defining or separating the paths. Since architects deal with complex 3D structures, a maze that also expands into different levels to become a real 3D structure is more appropriate in the exploration of spatial assemblies within the architectural design context. Therefore, we have chosen the creation and communication of 3D maze-like structures as a design problem of our experiments.

2.5. Discussion

It is widely claimed that VE offer architects the potential of a greater overall 3D understanding of space and volumes (Anders, 1999). Within VE, they can experience freely various viewpoints and at the same time maintain a feeling of presence within the models thus enhancing the exploration of space, volume and
location. Digital 3D models are generated with the intention of conveying overall design intentions similar to physical models, constructed to improve the perception of designs developed by drawings (Schmitt, 1999). As a result, VE provide an immediate feedback to users, which is not possible within CAD or traditional design media. Architects can therefore work three-dimensionally since they can experience every object inside VE through movement and interaction within a 3D spatial environment. This possibility offers a different ‘conversation’ with the design that otherwise is not obvious or possible. Additionally, spatial interaction can be addressed in a manner akin to the real world. The design process becomes more immediate, in some aspects, with the tools available enhancing the translation of the architects’ and users’ mental intention into spatial objects and 3D design decisions (Davidson and Campbell, 1996). The experiences seem valuable despite of the shortcoming and overhead of the technology used and the abstract realism of IVE.

An abundance of CAAD systems have been developed since Sutherland (1963) introduces Sketchpad. Yet most of these systems fall short as tools for design but excel as tools for drafting, production and rendering. CAD has reformed the drafting process, enabling fast entry and alteration of designs, but much to the expenses of the creative expressions of the designs. As Dorsey and McMillan (1998) argue, often the artistic and intellectual challenges of an architectural design have already been resolved before the architect sits down in front of a computer. It is important that future CAAD systems consider design as a continuous process and communication tool (Schmitt et al., 1996). We believe that there is a largely untapped potential for VE as a tool in the early phases of the design process. In this way, we argue CAAD can empower architects through
its design qualities and aid them beyond its drafting and production capabilities. VE then may play a greater role aiding and amplifying the creative process. VE can assist and influence positively this engagement (Do and Gross, 1998). In the first stages of a design process, the architect does not need a very sophisticated and complex tool that offers an abundance of settings or varieties of photorealistic depictions (Campbell and Wells, 1994b). Analogous to pencil sketches on piece of paper, a tool that allows an exploration of basic compositions and creative phrasing of the design elements (Regenbrecht et al., 2000). A tool that is as simple and as abstract, that allows ambiguity and focus on essential elements, as paper and pencil can support successfully an architect’s endeavour to sketch out his or her design ideas three-dimensionally within a virtual space.

2.6. Summary

We can conclude that VE may have considerable influences on the design processes, their outcomes and the mode 3D gestalts are communicated. Yet Gero (1999b) asks “Where's the Research?”, referring to the lack of research or design development in virtuality:

“There is surprisingly little research on the effects of designing virtually on either process or product. Again the issues are whether the designing process changes and whether the resulting design is materially different.”

VE are a design media that can play a complementary role in the design process by aiding in overcoming some of the limitations of traditional media. Marshall
(1992) claims that only synchronisation between designer, idea and tool leads to a successful result. Moore and Allen (1981) postulate that traditional media fail to represent 3D space since a 2D media cannot reveal architectural volumes, form and void to its full extent. If VE are treated not only as drafting technology but also as an environment of design comprehension, architectural design can bring forward a new centre that provides the architect with extended dimensions in design.

Currently VE are employed successfully to study, communicate and present architectural design. Davidson and Campbell (1996) demonstrate with the GreenSpace that share IVE can be used for design reviews. However, VE are seldom used for creation, development, form finding and collaboration of architectural design.

VDS in the past were an attempt to collaborate virtually in order to create architecture. Yet these studios do not employ the full potential of this idea. Therefore, the next step is to establish a platform where designers can collaboratively create, interpret and communicate design ideas within a VE.

This introduces a new way of designing and therefore fits well within existing paradigms (Mitchell, 1994). Wiener (1954) predicts the future merging of location and culture. Referring how physical and virtual architecture is an expression of cultural understanding. Both have their own properties, but both deal with the same matter. This will result in new understanding of architectural design and vice versa, this understanding influences the definition of architectural design.
2.7. Designing Within Virtual Environments

This section presents an outline of the experiments designed in order to test the above stated postulation (see Section 1.2.). Both studio and laboratory experiments are formulated with the purpose of investigating a designer’s conception, perception and communication of 3D space within VE. We are looking for clues that are directly related to issues of quality, understanding, communicating and rebuilding of designed or experienced architectural compositions, and through these, evidence indicated that VE affect design outcomes.

The results of the experiments present us the opportunity to compare perception and understanding of spatial volumes in immersive and non-immersive VE with representation of conventional media.

2.7.1. Definition of Research

The objective of our research is to identify how designers perceive architectural space within VE by looking at the creation, interpretation and communication of architectural design. In order to investigate the relative effectiveness of immersive and non-immersive VE, we conducted a series of experiments. With this, we want to understand if form comprehension and form finding is enhanced within VE activity.

Therefore, we set up two clusters of experiments, one being a particular scenario, a design studio that enabled students to design within a VE that imbeds
immersive tools into a broad context of CSCD, the other being an abstract problem, a controlled and isolated study that looked into particular aspects of design within VE.

Both groups of experiments engaged students in typical architectural design contexts. The findings of both clusters are then compared. This enables us to interpret the outcomes beyond an experimental setting. We were then able to draw conclusions that are relevant to the praxis of the architectural design profession.

2.7.2. Overview of Experiments

Placed within the above context, two clusters of experiments within VE were set up to gain understanding of how designers perceive and create form and space within IVE.

Firstly, the Studio Experiments, called ‘Virtual Environment Design Studio’, look into conditions of architectural design, collaboration, communication, understanding and re-representation within a setting of a VE design studio. It simulates a normal design process within the architectural profession by its nature.

Secondly, the Laboratory Experiments, called ‘Cube’ and ‘Maze’, look at those issues of the Studio Experiment isolated in an exclusive manner within different settings of immersive and non immersive VE.
In both cases, we explored factors influencing designers during the design process and investigated the relationship of 3D space within VE versus the physical realm. The resulting outcomes of the experiments were tested against conventional methods of designing and representations. The two clusters of experiments and their results are described in details separately in the following two chapters (see 3. Virtual Environment Design Studio and 4. Laboratory Experiments).

2.7.3. Participants of Experiments

As already mentioned above, the participants of the experiments have an influence on the outcome. For all experiments, we engaged students of both genders of diploma and master’s programmes at the departments of architecture of The University of Hong Kong (HKU) and the Bauhaus University Weimar (BUW), Germany. The students were introduced to the various tools and equipment as well as their potential possibilities preceding to all experiments. Each student has extensive experience using digital media, CAAD and architectural design tools and at least four years of architectural design training inside and outside of the academic context. This qualifies the participants as experts, which is important to validate the outcomes. All students participated voluntarily and they did not receive any grade or major incentives for their participation. Finally, each of the students took part in only one of the experiments to which they were assigned randomly.
3. **VIRTUAL ENVIRONMENT DESIGN STUDIO**

This chapter will describe the cluster of experiments we undertook in studio conditions and report their outcomes. With these experiments, we aim to identify how designers create, collaborate and communicate design ideas within VE akin to a real studio experience. This investigation applies experiences and knowledge gained from normal architectural and virtual design studios to an IVE framework.

The design studio is the established context for architectural learning. Collaborative learning and designing have been demonstrated to support effective learning in architectural design (Kvan et al., 1999). It is therefore crucial to test our postulation in the broad context of a design studio. As a result, we explored in more detail how a VDS, that is truly virtual and designers are immersed into a VE, affect the process and outcome of design (Photo 6).
By using VE to envision ideas, the architect is challenged to deal with perception of solid and void, navigation and function, without translations to and from a 2D media (Campbell, 1996). The goal of our study is to identify to which extent perception and understanding of spatial volumes are different in immersive and non-immersive VE and how designers use and communicate design ideas by using VE in comparison with 2D representations. We focused on the creation and communication of a specific 3D design task as a mean for generation of ideas and spatial expression. We explored factors that influence designers during the design process and the role VE play for designers within a 3D environment. We assumed that IVE are an important factor so that participants may design richer structures with the help of VE. Finally, we investigated design intentions, their translation, realisation, textual descriptions and collaborations within VE. All this becomes in particular apparent in the initial design stages of design. Comparable to brainstorming and concept finding activities, we did not require participants to produce elaborated final designs. Still the basic forms and arrangements of the design are determined and gestalt and function are established. Hence, we were able to examine this phase of the design process.
3.1. Platform and Apparatus

We sought tasks that engaged designers at different levels of complexity within VE. Thus, we decided upon two tasks: the design of a playground for children and the design of a commercial helicopter landing station in an urban setting. These tasks required users to work in three dimensions at all times. Yet they could be abstracted to reduced representational problems. The VE interface did intentionally not to allow a detailed modelling and users could therefore only establish initial layout of solid and voids in order to generate their design proposals. Based on Kvan’s (2000a) earlier experiments, a playground is a simple architectonic exercise and meaningful results can be produced easily. The helipad is a more typical architectural design and building task with multiple functional needs (sight lines, access, form, etc.), yet also very much a 3D question (fight path, urban context, etc.). Both tasks included navigation and perception challenges. We conducted them under the same experimental settings with remote communication between design partners. A controlled observation permits transcription of design allowing comparison of the various results. While the playground task was carried out under experimental conditions, the helipad design project was carried out as an immersive Virtual Design Studio (VeDS).

VeDS (2001) aimed beyond the initial idea of a VDS by introducing new dimensions to the participants. Firstly, we wanted to see if a virtual studio could be run in an immersive environment. Secondly, we wanted to see if the use of immersive VR design systems shifted design and its communication to a different mode or level. It has been suggested, for example, participants in a VE might express and communicate their intentions, ideas and designs not only in a
different but also in an improved manner (Dorta and LaLande, 1998). We hypothesised that the VeDS would have a positive impact on the development of design, its communication and understanding.

In the experiments, we used immersive VR equipment, as shown in Photo 7, two Pentium III computers, connected to broadband internet connections, with 17 inch PC monitors, Kaiser Proview 60 Head Mounted Display and a Polhemus Fastrak magnetic tracking device and a Polhemus Stylus.

![Photo 7: Setup of Equipment](image)

**Left:** Student using HMD with tracking-device and holding a Stylus  
**Right:** PC with communication software and mirror image from the HMD

We modified the Virtual Reality Architectural Modeller (VRAM) software, which was developed by Regenbrecht et al. (2000), and added new input features based on gestures, called VRAM/G (Seichter, 2001). Comparable to the input for handheld computers or PDA devices, users gestured with the stylus and their movements were tracked by the tracking device and, via one computer, translated by VRAM/G into basic 3D primitives. Table 1 shows the reference guide of gestures that the software recognises and translates into relevant primitives. A set of object libraries allows variations of a set of primitives.
A second PC was used as communication channel, using ICQ-software, an internet browser (Internet Explorer), a web-based database as well as other presentation software (AutoDesk 3DStudio VIZ and Adobe Photoshop).

As in a moderated discussion session where the microphone is passed to speakers, the Stylus was virtually passed between the teams on each remote side and the resultant design sketches were produced within the IVE in the course of the alternating sessions described below (see also Table 2, page 46). To support the design process more fully, text communication was also provided (Wong and Kvan, 1999). In order to capture the design intent, we used a modified ‘think aloud’ methodology by establishing a design team of two participants at each end: one team member wears the HMD designing actively with the Stylus and the second team member takes notes and chats with the remote team via chat-lines.
conveying design intent and action. The remote team has the same pairing of one team member wearing the HMD and the other communicating via the text-channels. By this way, we created a ‘mental unit’, in which two designers form one ‘design unit’ (Figure 4).

Figure 4: ‘Mental Unit’: each side teams up in pairs to form one design unit

The units were able to perform multiple and complex tasks synchronously without being cognitive overloaded by the assignments. The designer using the HMD was free of all complex communication actions that could hinder the smooth flow of the act of design. While the other team member was only writing and corresponding with the remote team, a record of all communication was automatically generated. In this way, the text records provided a protocol to be analysed later (Photo 8).

Photo 8: Teamwork

While one student (middle) was designing within VE, the other (left) watched the action and communicated with the remote participants (right).
In addition to participating in earlier VDS, HKU and BUW have independently conducted research within VE. These experiences proved crucial to the success of the VeDS, a process that may be plagued by technical and operational complications. Experiences with VDS and IVE are essential to anticipate and solve problems that arise in the studio. Issues such as collaboration and coordination, technical matters of hardware, bandwidth, file transfers and communication, social differences of understanding, group dynamics, emotional engagements and time differences have to be tackled, as well as tuning of equipment, ensuring equal opportunities for all participants and availability of facilities. Although in the past our goal has been to engage in heterogeneous environments, with each participant using whatever equipment they wish, the problems of VE collaboration precluded such freedom. In this experiment, both universities employed the same configurations and used the same immersive VR equipment. Additionally all participants of these experiments received thorough instructions on the use of the equipment prior to the experiments. They familiarised themselves with the functions and aspects of IVE and VRAM/G.

The design tasks were specified in order to present the students with assignments that are appropriate in scale, content and effort to the medium available. Factors taken into account included technical constraints (tracker range, room size, etc.), the scale of model and points of view (gravity, bird’s eye view, etc.). Special care was taken neither to favour nor to hinder the designers in creativity and translation of idea and result.

Each step during the process was recorded and data collected. Partly during and after the experiments all participants had to create digital presentations
describing their design strategy, intention and outcome. Additionally the students filled out a questionnaire, in which we enquired about the participant's individual IT and VE background and their experience of these tasks.

3.2. Playground

The first task, based on a study by Kvan et al. (1999), is to design a playground for a toddler’s school that is located on a rooftop of a high-rise building. This is a common scenario for the Hong Kong urban environment, in which multipurpose buildings have to be designed due to land shortage. This first design challenge was used to help students gain familiarity with the equipment as well as the different representation of design within VE. It is our intention that students free their minds from traditional design procedures and explore the media in addition to their ideas. The primitives generated by the software allow a playful approach to design; setting the playground as a design challenge supports that purpose.

3.2.1. Experiment

Each student was assigned randomly to a partner for collaboration. One team member designed within the IVE, while the other member watched the partner’s actions on a computer screen. With this setup, the team was trained to collaborate as one design unit (Figure 4). While one student of a team was actively engaged within IVE creating and placing the forms into the design, the other took part from ‘outside’, communicating with, advising and commenting to the partner while placing screenshots and text notes into the database. This method enabled
the teams to design and comprehensively record the progress at the same time (Figure 5). These data were used for analysis after the experiment.

3.2.2. Task

The task was to design a playground located on a rooftop above a toddler’s school for fifty pupils of four to five years old. The available area of 178m$^2$ is assumed to be safely surrounded by a fence or wall. The rooftop can be accessed via three sets of stairs; however, only one set was to be used while the others are for emergency access only (Figure 6).
The student teams had to concern themselves with the choice and placement of design elements within the roof area. The playground design had to respond to the educational and social needs of children as well as safety and enjoyment. The students had to collaboratively create an idea for the playground as a recreational play space and produce a modelled record of the idea within one hour. Similar to a normal design process, the students could use any symbol to represent objects in the model but they had to ensure that any abstract form remains interpretable by others.

3.3. Immersive Virtual Environment Design Studio - VeDS

The second experiment springs from, and builds upon, a series of VDS in which HKU and BUW participated in earlier years (VDS, 1993-2002, Bradford et al., 1994, Donath et al., 1999, Kolarevic et al., 2000, Kvan et al., 2000a). In our VeDS, teams on the two sides worked together on the same design task and finished their project within a single day. The design ideas, proposals and modifications were exchanged with the remote partner in short and frequent intervals, reminding us of a Ping-Pong match. Each side had the authority (not ownership) over parts of the design. Coordination became necessary in order not to obstruct the team partner's activity. This setup simulates a typical scenario where architects and specialists contribute to an overall scheme in sequential and parallel activities that form typical collaborative work (Wojtowicz and Butelski, 1998, Kvan, 2000b).
3.3.1. Ping-Pong

Each university had access to only one set of VR equipment; thus, only two teams at each side could work at the same time. The intent was to engage students in rapid design exploration akin to brainstorming in order that sessions were completed in one continuous cycle. HMD use is limited in its effectiveness (Wong, 2000) so each phase (called Ping or Pong) was set to 30 minutes during which the students had control of the model. This was followed by file-exchange and fine-tuning/adjustment of equipment (Table 2).

![Table 2: Time Flowchart]

As mentioned above, for each pair, one team member designed using the IVE equipment while the other took notes and annotated the design in collaboration with the team partner. Then they wrapped up their design, cleaned the model of unwanted elements and placed the model and the chat text into the database. This system was modelled on a modified version of a database by Wenz and Hirschberg (1997) as well as Hirschberg, et al. (1999). In database allowed the students to prepared a short presentation explaining design intentions and achievements of that phase (Figure 7).
The remote team then took over the model and continued the design work. After
alternating four times, the exchange concluded with a final phase where the work
was refined for presentation within the database. This phasing allowed some
buffer for potential problems in file transfer or temporary bandwidth constraints.

Using this sequence, a complete cycle of VeDS was finished within four hours
and could be repeated daily over one week in order to accommodate all teams.

With this method, 18 groups in total took part in the studio. After the last teams
had completed their work, a final critique supported by an internet-based
videoconference was arranged in which all teams came together presenting their
work to each other, instructors and external examiners in order to discuss the
different outcomes and the new approach to design (Photo 9).
3.3.2. Helipad

The task should be defined that exploits the capability of VE, in which the contribution of VE can be significant. This task was one in which users must fully navigate a 3D (not 2.5D) space. Thus, the task of the VeDS was a small landing ground for helicopters in the central area of the city of Hong Kong. Not only was the Hong Kong Government searching for a design of a new helipad at the proposed site, the task also fit into the constraints and opportunities of VE. In this assignment, the designer can work in a virtual model of Hong Kong from the viewpoint of the pilot flying to and from the site or of the passenger waiting at the helipad to embark (Figure 8).
The assignment for teams was split in two parts, one for each team: either the land- or the airside of the helipad. Additionally, each part of the task had one static and formal, as well as one dynamic and path-focused. Both of which had to be addressed in the design proposal (Table 3). The teams gained authority of a design area and at the same time had to negotiate with the remote team, who worked on another area of the same site. Both teams had to collaborate in order to reach a solution while they also had enough freedom to explore their own design aspirations.

Table 3: Design task distribution: Landside/Airside and Static/Dynamic

<table>
<thead>
<tr>
<th>Team</th>
<th>Authority</th>
<th>Programme</th>
<th>Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Landside</td>
<td>Check-in/Waiting enclosure for passengers</td>
<td>static</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Driveway/Parking</td>
<td>dynamic</td>
</tr>
<tr>
<td>B</td>
<td>Airside</td>
<td>Control tower for Air controllers and tourists</td>
<td>static</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Apron/Flying</td>
<td>dynamic</td>
</tr>
</tbody>
</table>
3.4. Results of Studio Experiments

This cluster of experiments shows that students using IVE engage actively in exploring space and volume in an inclusive manner. We validated that it is possible to successfully design, communicate and collaborate in IVE using an architectural design studio setting. Students communicated their spatial ideas using 3D objects that are accessible and interpretable by others in close relationship with the original design intent. This can either be very lively and similar to a sketch as in the case of the Playground experiment or as complex as a full design studio akin to the VeDS. Although it was possible that the teams would concede to the technical complexity of the system and the difficulty of working together, the teams did engage in collaborative work, building up, step by step, on the work of the efforts of team partners and preceding steps.

The intention was to use IVE as a tool to create and communicate an initial design proposal that is the beginning of a whole and longer design process. The experiments served as a primary base for further explorations and developments of the design. The results are therefore only slices of the more extensive developments and not wholly elaborated and finished schemes. The results are to be understood as early depictions of the participants' ideas and they act as a visual tool for their communication.

3.4.1. Playground

Since this task functioned more as an introductory agent for students to familiarise themselves with issues of IVE, we could not ensure the validity of the
data to full extent and we would not analyse the collected results in great detail. However, the outcomes offer us a valuable indication of how students react using the system and IVE to design and communicate architectural schemes for the first time. Students collaborated on their design successfully. Students working with IVE received constructive support from his or her team partner, who was able to watch the action on a computer screen that mirrored the image of the HMD. Since the student outside the IVE could successfully follow and understand the actions of his or her team partner, communication, creation, evaluation and presentation of the design could be carried out concurrently. The two students formed therefore successfully an ‘enlarged brain’ or one design unit. Students used the primitives available in the software as playful entities to sketch and express their design intentions in an abstract yet meaningful way. Spatial relationships between requirements of the talks and the desired design proposals could be created (Table 4).

Table 4: Excerpt from design description by Zhang, J. and Yong, K. H. (VeDS108)

"We conceive the playground as a place where children have the freedom to pursue their dreams, away from the harsh realities of the adult world. … The design began with a series of enlarging cones symbolizing the physical and mental growth and development of a child. … Along this series of cones, other volumes begin to emerge, some floating in the air. It is as if the mind of a child is free to wander… However, often the realities of the world take over, sweeping through the thoughts of the child… It reaches a point where the child begins to understand the nature of life, and tries to balance both dream and reality…"

The result of this experiment did not reveal any major problems. Participants stated after the experiment that they were enthusiastic about using an IVE system for a bigger design task. This confirmed the feasibility of conducting a larger
studio using this technology for a longer period of time. As a result, we went ahead with the VeDS without any significant modifications to the system or procedures. A complete documentation of the Playground with its digital models, renderings and annotations by the students and can be viewed online at: http://courses.arch.hku.hk/vds/veds01/local.

3.4.2. **VeDS**

All teams have succeeded in designing a helipad and thus completed their tasks. The VeDS allowed a variety of design outcomes since every design studio has its own characteristic and every design-team their own approaches. Consequently, the results can be analysed in various ways. In this thesis, we explored the essence of the progress, form and communication of the students’ works as described below. General speaking, the outcomes of the VeDS confirm that collaboration and designing within IVE lead to successful and valid architectural design schemes.

3.4.2.1. **Progress and Form**

A review of the graphic results and digital models shows that students used the 3D design space actively. Volumes were created to represent design elements at all cases within the available 3D design space. Typically, a design created in a 2D space would have placed elements in plan with some raised in section/elevation to create 3D spaces. In both experiments (Playground and Helipad), however, the students started 'drawing' the design elements at all points above the ground plane. Observation during the creation processes of the designs
showed that participants did not use a 'bottom-to-top' (floor by floor), an 'inside-out' (function defines form) or 'outside-in' (form defines function) approach to their design. Mostly, students used an integrated design method by making use of all approaches almost at the same time. Being virtually inside the model, they sculpted their proposals, employing the flexibility of viewpoints offered in VE. They explored the spatial impact of their design proposals in relation to existing forms and activities from outside and inside the model (Figure 9). They changed their viewpoint constantly from a general macro- or overview to a micro view of details in order to check spatial relationships and design proportion of the various elements of their design.

![Figure 9: Users were involved in terms of scale, viewpoint and navigation VE, offered to explore ideas and their spatial impacts on the overall design (Playground, VeDS104).](image)

Although the input systems were crude and clumsy, users rapidly learnt to represent their design intent by using the available representational volumes: cubes, cylinders, cones and spheres. The objective of the assignment was to establish initial relationships of form, space, solid and void, in order to establish the overall gestalt of the design, while a detailed planning was not required (Figure 10).
The software offered a variety of library elements (see Table 1). Nevertheless, the teams predominantly made only use of the most basic set of library elements. Despite this constraint, these primitives offered students a significant range of design expression. This matches the simplicity of the software, its interface and its operation that did not require any complex menus or operational overheads or special setups. Similar to conventional design media, such as paper and pen, initial ideas were sketched freely into the space. Equivalent to a 2D medium, the various shapes symbolised both positive and negative representations of form and space or symbolised just reference points or other graphical elements. Viewers of the models, however, were able to understand this ambiguity of this 3D sketching. Yet the three-dimensionality of the primitives and the ability to change viewpoints and scale allowed the students to explore the space in a way that a sketch cannot offer (Figure 11).
In some cases, because of the lack of experience, problems with the hard- or software or the complexity of VE, errors occurred, but often they were transformed into meaningful solutions, a design behaviour which is observed in other traditional 2D design environments as well (Schön and Wiggins, 1992). For example, instead of deleting unwanted elements, some teams chose to keep those elements and integrate them into their design. These ‘errors’ were then actively repeated to generate the desired outcome (Figure 12).

Other instances demonstrated that students were inspired by their 3D models and translated their spatial compositions back to an idea or image of which their design reminded them. For example, the 3D gestalt of one team’s work was
related to a painting by Wassily Kandinsky (Figure 13). This method is comparable to the works of Man Ray and Ager Jorn (see Photo 21).

Each VDS merges the diverse backgrounds and skills of participants, their education, knowledge and understanding of architectural design. Subsequently these differences are expressed in the design. Since each team had authority over its own area, the VeDS allowed a distinct development of each team’s design and if desired by the teams a clear distinction between the two design areas. In the course of the studio, it was necessary for students to agree on common readings as well as a shared definitions of each team’s working space, their borders and common elements and parts as well as working and design strategies. As illustrated in Figure 14 one team worked with a variety of colours and forms while the other restricted themselves to grey cubes and walls. Yet an influence of the other team onto their own design can be recognised.

Figure 13: Plan and perspective of design with a painting by Kandinsky as mental inspiration (image added later by student, Playground, VeDS106)

Figure 14: Differences in design and operation skills as well as architectural language can be observed. (Helipad, VeD106, Phase 2-4)
Participants noted in the chat line communications that the resultant designs surprised them in their ingenuity and presentation. Constrained to their own preconceptions, they realised that working with the tool within IVE was not only easier than initially anticipated, but also have created outcomes that were superior to those their own skills enabled them within other design media. It appears that IVE allowed students to experience their ideas in ways that are different from non-immersive environments. They reported in the questionnaires that the interaction of idea and creation was direct, that each stroke had an immediate impact on the design. They could not only understand easily the intentions of the other teams but also were inspired by the ease and freedom the tool and the environment offered them. For the students, it seemed that they communicated directly with their model and being part of it, instead of being a only distant designer. The students stated that this kind of design method has led to new forms and new arrangements. Nevertheless, for all students it is a novelty to design within IVE. Architectural design studios have not developed much further from conventional design methods despite the available technologies and innovative topics. Students are therefore not used to designing three-dimensionally and interactively, as it is possible with IVE (Figure 15).
Did VE allow you to define the layout of your design?

- 15% Quite some
- 26% Radically
- 31% Slightly
- 23% Little
- 5% No change

Did VE help represent your ideas?

- 42% Quite some
- 16% Radically
- 21% Slightly
- 21% Little
- 0% No change

Did VE stimulate the creation of new ideas?

- 36% Quite some
- 11% Radically
- 16% Slightly
- 37% Little
- 0% No change

**Figure 15:** Results of the questionnaire

**Top:** Over on third strongly agreed that VE aided the representation of design-ideas.

**Middle:** To nearly one forth VE supported the representation of design absolutely.

**Bottom:** More than 50% said VE stimulates positively.

Following the VeDS, the students expanded their designs based on their initial schemes by using other conventional media and tools. Yet, the further progress of the designs restrained recognisable the initial gestalt that was developed within the VeDS.
3.4.2.2. Communication

The experiments proved that the teams communicated confidently as anticipated, by means of the set up, of which two participants formed one communication unit to correspond with the remote team. Earlier VDS (Donath et al., 1999, Kolarevic et al., 2000) reported of communication difficulties with the remote teams. However, we did not encounter such problems. The teams intensively discussed issues of design, concepts and form. Due to the nature of the task and application, the groups had to formulate their intentions and discuss them with their remote partners in order to develop their scheme further. In addition, participants developed a personal interest in sharing their experience and creation with their colleagues and other teams. We analysed the chat dialogs using the same protocol analysis and coding schema as Kvan et al. (1997). The outcomes are illustrated in Figure 16.

![Communication Analysis](image)

**Figure 16:** Communication Analysis

- **Left:** Total percentage (mean) of all phases of the VeDS
- **Right:** Percentage (mean) of individual phases of the VeDS

In the analysis of the chat protocols, we expected a high number of navigation/orientation discussions, as well as explanations of meaning of elements placed in the scheme. Surprisingly, contrary to our assumptions, the chat texts showed only a few lines of such conversations (Table 5).
Table 5: Excerpt from Chat text of Phase 2: VeDS107 and VeDS110

<table>
<thead>
<tr>
<th>User</th>
<th>Time</th>
<th>Message</th>
</tr>
</thead>
<tbody>
<tr>
<td>pakling@hk</td>
<td>23/2/2001 3:21 PM</td>
<td>we are creating the steps leading to the sky helipads....(using cubes)</td>
</tr>
<tr>
<td></td>
<td>23/2/2001 3:26 PM</td>
<td>Maybe think cylinders would be appropriate.....</td>
</tr>
<tr>
<td>hoiman</td>
<td>23/2/2001 3:26 PM</td>
<td>good! hum u can see...there is a cylinder beside the planed platform... we think they are the back office for the helipad...</td>
</tr>
<tr>
<td>pakling@hk</td>
<td>23/2/2001 3:27 PM</td>
<td>we may create cubes and spheres.....</td>
</tr>
</tbody>
</table>

This suggests that participants could not only orientate themselves easily within VE, but they were also able to abstract and extract the design intent of the remote partner without much difficulty. Neither the tool nor the environment was an issue to talk about because both of them have blended into the design process harmoniously (Table 6).

Table 6: Excerpt from Chat text of Phase 1: VeDS109 and VeDS112

<table>
<thead>
<tr>
<th>User</th>
<th>Time</th>
<th>Message</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angel</td>
<td>2/24/2001 2:03 PM</td>
<td>The spheres are the sign to guide the people to the entrance. All the building located near the new wings of exhibition center. The cubes are the solid spaces may be buildings. The cones are the tent for people to take a rest before they get on board. All the elements in small size are the signs. The small spheres are the sign for going forward. The small size cubes are tell people turn left.</td>
</tr>
<tr>
<td>Tom</td>
<td>2/24/2001 2:04 PM</td>
<td>that sounds good... cool</td>
</tr>
<tr>
<td></td>
<td>2/24/2001 2:11 PM</td>
<td>what's the form of the checking counter?</td>
</tr>
<tr>
<td>Angel</td>
<td>2/24/2001 2:12 PM</td>
<td>many big cylinders......</td>
</tr>
<tr>
<td>Tom</td>
<td>2/24/2001 2:42 PM</td>
<td>the cubes are the control tower</td>
</tr>
<tr>
<td></td>
<td>2/24/2001 2:45 PM</td>
<td>we change the scheme now the cones are the tower and the cubes interlocking with the cone forms different landing platforms for helicopter.</td>
</tr>
</tbody>
</table>
While the text records do not identify how or why the students were using the 3D space in these ways, we do find records of intense discussion about design, functions and concepts (Table 7).

### Table 7: Excerpt from Chat text of Phase 3: VeDS107 and VeDS110

<table>
<thead>
<tr>
<th>Time</th>
<th>Username</th>
<th>Message</th>
</tr>
</thead>
<tbody>
<tr>
<td>23/2/2001 15:34</td>
<td>hoiman</td>
<td>may be you can make the modification for us... but we think the helipad should a little bit higher than the buildings surround…</td>
</tr>
<tr>
<td>23/2/2001 15:35</td>
<td>pakling@hk</td>
<td>we would modify our objects... so as to connect to your helipads</td>
</tr>
<tr>
<td>23/2/2001 15:35</td>
<td>hoiman</td>
<td>hey I have an idea...can we have some connection to the surrounding buildings... since it is much more meaningful that the helipads can serve the other commercial buildings.</td>
</tr>
<tr>
<td>23/2/2001 15:36</td>
<td>pakling@hk</td>
<td>ok...we would see if we can achieve that...</td>
</tr>
<tr>
<td>23/2/2001 15:39</td>
<td>hoiman</td>
<td>I think a few connections to the adjacent buildings such as the Central Plaza and the Attic building and the Academy for Performing Arts building would be nice...</td>
</tr>
</tbody>
</table>

By referring to the images they saw in the model provided by their distant collaborators, students could engage in design discussion and development of the scheme. VE did change how the students developed and expressed their ideas. This new way was then communicated to the remote team using the design itself and discussion it on chat texts (Table 8).
Table 8  Excerpt from Chat text of Phase 1: VeDS101 and VeDS202

<table>
<thead>
<tr>
<th>Time</th>
<th>User</th>
<th>Message</th>
</tr>
</thead>
<tbody>
<tr>
<td>5:15 PM</td>
<td>Hartmut</td>
<td>where do want to locate your building?</td>
</tr>
<tr>
<td>5:16 PM</td>
<td>Charmaine Tse</td>
<td>We are now designing on the airside</td>
</tr>
<tr>
<td>5:17 PM</td>
<td></td>
<td>We are now using cones to build some mid-air lands</td>
</tr>
<tr>
<td>5:20 PM</td>
<td>Hartmut</td>
<td>are you building on water?</td>
</tr>
<tr>
<td>5:21 PM</td>
<td>Charmaine Tse</td>
<td>no, we are building mostly in the air it’s like an overhanging plaza for the chopper</td>
</tr>
<tr>
<td>5:22 PM</td>
<td>Hartmut</td>
<td>but, do you design it floating in the air?</td>
</tr>
<tr>
<td>5:23 PM</td>
<td>Charmaine Tse</td>
<td>yes; why not</td>
</tr>
<tr>
<td>5:24 PM</td>
<td>Hartmut</td>
<td>describe a little bit your design?</td>
</tr>
<tr>
<td>5:27 PM</td>
<td>Charmaine Tse</td>
<td>we are now starting the control center; the design basically consist of a hanging air plaza and a control center; the plaza as name would be in the mid air and the control center is a bit higher above the plaza. The left over space will create a route for the chopper welcome to the mid-air.</td>
</tr>
</tbody>
</table>

In the questionnaires, the students stated that the medium not only allowed them to communicate with the remote team, but also made it a necessary component for re-representing their design idea. Yet, the medium and a VDS remains new to most of the participants, and students are more used to conventional design studios with face-to-face interaction and communication (Figure 17).
We noticed that participants from BUW tended to deal with more conceptual schemas while HKU students tended to be more factual, specific and they described ideas in tangible terms, possibly reflecting the educational characteristics of the two institutions. With such distinctions, it is notable that the VR environment supported these differences and the collaboration was successful (Table 9).
The complete documentation of the outcomes of this VeDS with its digital models, renderings, chat-texts and annotations of design intend and outcome, etc. can be viewed online at http://courses.arch.hku.hk/vds/veds01/db.
3.5. Summary of Studio Experiments

As described above, two sets of design studio experiments were successfully carried out within IVE. In the first experiment, students worked in pairs to design together a playground in a simple design exercise. In the second experiment, pairs of students formed teams and two teams worked across the network to develop sequentially a design in an immersive environment. We observed the processes of both experiments to identify the degree of form finding, comprehension and communication.

These experiments have demonstrated that a design studio can be conducted productively within an IVE even though the tool is comparatively clumsy. Furthermore, design communication and collaboration led to innovative architectural expressions with a high degree of spatial understanding of the generated schemes. The students could easily engage in design discussions and spatial explorations of their schemes. While problems remain in the technologies, the rapid asynchronous manner successfully enabled students across the world to participate with immediacy in the joint development of a shared design solution. Students presented solutions that would as such not be derived by using non-immersive media. The outcomes show that they took advantage of the 3D design environment utilising methods that dealt with the space comprehensively.

However, these experiments did not clearly identify how the design was influenced by the design environment itself and what influence spatial comprehension may have on the outcomes. As every design studio is not free from individual preferences, and cannot eliminate bias in how its outcomes are
designed, perceived and interpreted, we set up another cluster of experiments under laboratory conditions. There we looked at distinct aspects, such as spatial comprehension, influences of colour, differences of designing within various realms, and translations into a haptic media. We employed a design task that focus on a clear objective and definition. That gave us the possibility to evaluate the outcomes uninhibited of bias.

These studies will be described in the next chapter.
4. Laboratory Experiments

This chapter will describe the experiments we undertook in laboratory conditions and present the report their outcomes.

We took issues arising from the studio experiments into a laboratory environment in order to look at specific aspects affecting architectural design in VE. We engaged architectural students in some very basic design exercises in a laboratory environment. We were able to apply experiences and knowledge gained in the Studio Experiments and extract fundamental comprehension of quality, accuracy, understanding, communicating and reconstruction of designed or experienced architectural compositions.
4.1. Platform and Apparatus

We conducted a series of experiments to examine the understanding of 3D elements in space. These experiments engaged architectural students to describe forms they have examined in VE, so as to investigate the relationship of 3D space within VE as compared to descriptions made in the physical realm.

These experiments were designed to identify how designers use and communicate design ideas when using VE or conventional methods of 2D representations. We also explored which factors influence designers during the design process and finally we studied which influence colours may have in the orientation of designers within a 3D environment.

For the purpose of the experimental task, we interpreted an abstract architectural arrangement that can be studied in 2D or 3D environments, a maze based on a symmetrical rectangular grid. A maze is a spatial object with a very apparent objective and simple rules that inherits a considerable challenge for both designers and users (Berer and Rinvolucri, 1981). Since IVE are able to deal with complex 3D structures, an assignment that makes use of the three-dimensionality of VE seemed to be suitable as an instrument for conducting our experiments.

We have developed a software tool called 3D MAZE (Schnabel et al., 2001-2003). This application generates within VE is an interactive structure that is based on a cubic grid. Surfaces can be placed on the grid-lines in order to form spatial arrangement defined by planes that can form, for example, a maze or, in a simple pre-set configuration, a cube. Viewers can then navigate their way through the maze or the cube and inspect the volumes defined. Our networked
application allows immersive or non-immersive interaction, viewing and manipulation of the structure independently of other participants. The users can move freely in every direction in real time, zoom, place and delete walls, as well as see a representation of partners, including their movements and actions. Additionally the tool enables students to experience and study enclosed volumes within a spatial assembly. A given structure can simulate a simplified architectural spatial configuration that can be analysed, interpreted and transcribed, by using immersive and non-immersive media.

This procedure replicates in basic abstract terms, an architectural design process in which volumes and space are determined, in order to generate an overall design.

### 4.2. Cube

The first experiment was designed to investigate and compare students’ understanding of volume and space as described in three different realms of representations. The first condition was a conventional depiction of 3D space with typical 2D architectonic floor plans. The second and third condition used digital 3D models, within either DVE, interactive models displayed on a PC monitor, or IVE, with the help of VR tools and viewed with a HMD. We studied the differences of these conditions may have on an abstract building or volume description as represented by a cube of interlocking and hollow shapes.

This cube was composed of different cuboids, none of which could be inferred from the surface descriptions (Figure 18 and Figure 19).
Built on a symmetrical grid-framework, single, double, vertical, horizontal and angled cuboids configured the cube following a principle of architectural hierarchy and structure (for example, the yellow cuboid is an upright cube representing a vertical axis that connects different levels of the oval structure).

This cube was constructed from eight coloured and easily distinguished cuboids. The colours were used to facilitate easier navigation and perception; while using eight cuboids allowed us to generate a variety of suitable varied volumes without being either excessively complex or too simple (Figure 19).
The assembly of the shapes within the cube can be compared with a block of living and work spaces by the German architects b&k+ (2001). The building volume there consists of spatial modules that are places on top of each other by means of rotation or mirror symmetries to compose a housing loft (Photo 10).

![Photo 10: b&k+ Housing Loft Köln Brett (b&k+, 2001)](image)

**Left:** Modules **Middle:** Inside view of Cuboids **Right:** Building elevation/section

Twenty-four architectural students were asked to explore and study the given cube. Randomly assigned to one of the three representations of the cube (2D plans, DVE, IVE), the students were asked to examine and then reconstruct, in the real world, the interlocking cuboids that formed the virtual cube, using wooden blocks (Photo 11).

![Photo 11: Wooden blocks in eight colours](image)
Since the whole structure was based on a symmetrical grid of four units in each direction (4*4*4), all of the potential volumes could be assembled with cubes of one unit. For all three conditions, the students were given a set of 168 wooden cubes, with 21 cubes available for each colour, which were similar to the colours used in the plans and VE models. The quantity of cubes available in each colour exceeded the amount needed to create each volume (Photo 12).

![Photo 12: Reconstruction process and final volume.](image)

A time limit of twenty-five minutes was given to study the cube and another twenty minutes to rebuild the shapes. After completing the assembly task, the participants had to complete a questionnaire about their experience with the medium and its mode of representation, their strategy adopted for study and assembly, and their understanding of the spatial structure of the cube as a whole, as well as its individual shapes.

4.2.1. Two-dimensional Representation

In the 2D design environment, participants were given five coloured 2D ‘floor-plans’ representing the four levels and top view of the cube (Figure 20).
Figure 20: 2D plans for the 2D condition

The plans were all printed on one sheet of paper, using conventional architectural depiction of solids, voids and walls. To achieve a similarity to standard architectural plan representation and mode of viewing, we chose paper, instead of a screen representation. The plans were in an enlarged scale relative to the wooden cubes. Therefore, in a similar manner to the 3D representations, participants had to scale the studied plans and shapes mentally in comparison of the wooden cubes and the rebuilding of the model.

4.2.2. Desktop Virtual Environment

The students working with the DVE condition used a standard PC, running a web browser with a VRML plug-in (Cosmo Player) to view, interactively, the 3D volume in VRML file format on a conventional 17-inch monitor. The simplicity of the interface was important in the choice of tools in order not to distort the results. This setup allowed the participants to study freely and manoeuvre through and around the volume to their own liking, using mouse or simple keyboard commands only. Throughout their architectural education, the students had extensive training using this setup prior to the experiments (Photo 13).
4.2.3. **Immersive Virtual Environment**

IVE participants used the application *3D MAZE*. This allowed them to navigate and explore the given volume freely within the IVE. The hardware used to drive the IVE was a *Pentium-III* computer, *Kaiser-Proview-60* HMD, a *Polhemus-Fastrak* magnetic tracking device and a *Polhemus-Stylus* (Photo 14).

This is the same equipment and setup we used in the *Studio Experiment*, which was described in the previous chapter (see Section 3.1.). However, in this case
here, the *Stylus* was used as an additional navigation tool allowing the users to move over greater distances.

### 4.3. Maze

In the same context, we carried out another set of individual experiments to gain a deeper understanding of designs done within VE. The objective of our study is to identify how designers perceive architectural space in VE. We examined the differences between 2D and 3D environments on the form finding of a design process. Firstly, we explored whether colour assists designers. Secondly, we conducted two experiments to investigate the relative effectiveness of VE (immersive and non-immersive) by looking at the creation, interpretation and communication of design. We conducted experiments within different realms of design: one being a real 2D environment, the next being a screen-based DVE and the third being an HMD-based IVE. The task was to create collaboratively a 3D maze together with text-based communication. We investigate issues of quality, accuracy, understanding and communication of architectural compositions.

After completing the collaborative design task, every participant completed a questionnaire that enquired about their experience with the medium, and its mode of representation, their strategy of design, their understanding of the spatial structure of the maze and the ability to collaborate with their partners.
4.3.1. Monochrome versus Polychrome Maze

The use of colours is a common means to help distinguish elements in an environment. Porter and Mikellides (1976) point out that people have certain connotations towards certain shades of colours: red being the colour of danger, blue representing the sky and the green nature, etc. According to Mahnke (1996), colour is a major factor, which has biological and psychological influence on humans.

We therefore consider colour as an important element, which can influence the performance within a VE. We assumed that colour aids designers to orient themselves while working in a VE. It is commonly assumed that people will locate themselves better in coloured VE than in an environment in greyscale. We therefore assumed that architects might design more complex and richer structures in a VE with the help of colour as a spatial cue.

Since colour is a significant aspect of an architectural environment that can influence the behaviour of its users (Mahnke, 1996), we investigate whether colour also has an effect on the outcome of a design process within a 3D environment. For this purpose, we set up two conditions using the condition of the next section (4.3.2). One being a polychrome environment, in which the maze and its walls of each dimensional plane has its distinct colour (red, yellow and blue), the other being the same series of test in monochrome display, in which the maze, its structure and all elements are in shades of grey only.
4.3.2. Two-dimensional versus DVE Maze

We selected randomly eighteen pairs of architectural students, who did not take part in the above-described ‘Cube’ experiment (see Section 4.2) or Studio Experiment (Chapter 3.). We asked them to design 3D mazes within a symmetrical grid, defining four fields in each spatial direction in remote collaborative design sessions.

Predefined features were entrance and exit on opposite corners of the maze-structure and a time limit of thirty minutes for each design session. The arbitrarily assigned team partners used PC with 17-inch monitors and mice, keyboards or electronic pens as input devices. They could communicate via a text window (Microsoft NetMeeting) which recorded a description of the design process for further analysis. Previous studies showed that in chat texts, participants maintain the same amount of high-level design exchanges, while the design is not different from the condition of higher bandwidth communications (Kvan et al., 2000b). Additionally the software enabled both partners their own independent view of their common structure, as well as to observe their partner’s design actions or movements in the 3D model displayed on the monitor.

In the 2D design environment, participants could draw on a whiteboard-software (Microsoft NetMeeting). The participants could choose either to use a blank ‘sheet’ to sketch onto that or to use a grid template that we provided. Each ‘page’ of the template represented one levels of the maze structure (Figure 21).
Figure 21: Template for the maze in the 2D condition

For the DVE condition, students used the above-mentioned 3D MAZE application (see Section 4.1.) to design their maze (Figure 22).

Figure 22: Grid framework (4 fields in each direction) for the 3D condition with chat window

4.3.3. DVE versus IVE Maze

For this experiment, we selected new pairs of architectural students. Sixteen randomly assigned duos who had not taking part in any of the other experiments,
were given the same task and used the same configuration as described in the section above (see Section 4.3.2.).

The participants using the DVE-condition used a screen-based VE again, working on a computer, monitor and mouse as hardware, and a chat-software and 3D MAZE as software. Students of the IVE-condition used the same equipment of the immersive ‘Cube’ Experiment (see Section 4.1.), with HMD, magnetic tracing and Stylus, as well as 3D MAZE and chat-software (Photo 15).

Analogue to the setup of the VeDS (see Section 3.1.) an assistant dealt with the communication to the remote team, in order to minimize the cognitive workload onto the designer (Figure 4).

4.4. Results of Laboratory Experiments

We have identified three significant outcomes that are valid for all of the above-described experiments. Firstly, we demonstrated clearly that it is possible to successfully comprehend, converse and create architectural design in VE within
laboratory conditions. Although, some compromises had to be made due to the technical complexity of the VE systems.

Secondly, IVE enhanced students’ ability to examine and communicate complex volumes or influence them positively to conceive and experience their design. Participants reported that the creations, interactions and understandings of their designs and their representation are direct related to their imagination. It seemed as if the students communicated directly with their models, being part of them, and were not distant observers or designers of a scaled or translated model.

Thirdly, analyses of the results suggested that VE permitted students to explore spatial structures or express their ideas more thoroughly and fluidly. Hence, they took more advantage of the three-dimensional space. In contrast to that, students using a 2D medium appeared to deal with stacks of 2D levels only. Therefore, they did not explore extensively the three-dimensionality of the overall structures.

In the following sections, I will report individually of the outcomes of the laboratory experiments.

4.4.1. Cube

The results demonstrated that the presentation medium greatly affects perception and with that the understanding of volumes and enclosures, as in our cube experiment. Students who explored and investigated the spatial relationships within the two VE settings of the volumes had a better spatial understanding of the individual cuboids that formed the 3D configuration, but mostly failed to re-
assemble the parts into one cube. Whereas, students working in the 2D medium rebuilt the cubes in general successfully by treating the structure as stacks of 2D levels. By doing so, they did not relate to the spatial properties of the eight cuboids. The evaluation of the questionnaires supports these findings. Subsequently, we can conclude that VE offer designers a greater 3D appreciation of space and volumes, while the initial evidence may have suggested the opposite.

Figure 23 shows that students working in the 2D condition achieved the greatest degree of accuracy in rebuilding the volume compared to the other two VE conditions (Figure 25).

![Figure 23: Percentage of correctly reconstructed cuboids: 2D condition](image)

We noticed, however, that complex cuboids and expanded over several layers, such as the white and light blue shapes, were less accurately recreated than those within one layer, for example the red cuboid or those which were in a single stack, as in the case of the yellow cuboid (see Figure 19). Even after rebuilding the cube, the students did not fully comprehend the gestalt of the cuboids, except those that were within one layer or being single-stacked. Thus, the success in recreating a formal relationship was based on the ability to memorise and copy a
number of plans layered on top of each other, and not on a 3D appreciation of a spatial composition of cuboids (Photo 16).

![Sample solutions of the 2D condition: rebuilt cube](image)

Photo 16: Sample solutions of the 2D condition: rebuilt cube

Notably, despite the relatively low number of completion of rebuilding the cube, the two VE conditions still illustrate that the students developed a sound appreciation of 3D volumes and spatial relationships. Even complex cuboids of the structure were comprehended and rebuilt.

When rebuilding the cube, participant placed cuboids sometimes in an incorrect orientation or location within the cube (such as upside down or back to front). Then again, the gestalt of cuboids were generally recognised and remembered correctly or placed in correct context with other cuboids but then in an incorrect orientation (Figure 24).

![Typical configurations](image)

Figure 24: Typical configurations

- **Left:** A single sub-unit of a cuboid in a correct colour and position
- **Middle:** A cuboid in a correct shape and position
- **Right:** A cuboid in a correct shape but wrong position
Considering that certain shapes were actually assembled correctly but placed wrongly, the completion rates of both VE conditions are much higher. This is shown by the hatched area in Figure 25. However, as soon as one cuboid is dislocated, it is then impossible to reassemble the whole cube correctly. Consequently, in the overall completion rate is lower than in the 2D condition. Interestingly, Figure 25 also illustrates that participants of the two VE conditions had comparatively an equally comprehension of all cuboids and their spatial relationships, despite the overall relatively low completion rates in rebuilding the whole cubes. Finally, by comparing the values of Figure 23 and Figure 25 we can extract a correlation between the complexity of a cuboid and its spatial comprehension. With the increasing complexity of a cuboid within the VE-conditions the spatial comprehension is, relatively speaking, higher than within the 2D condition.

![Figure 25: Percentage of correctly reconstructed cuboids: 3D conditions](image)

**Left:** DVE condition  **Right:** IVE condition

In our experiments, the wooden cube-units were not adhesive. That means that a reconstruction method, in which whole cuboids were put together spatially, was not possible. The cube had to be assembled more or less unit by unit and layer-
by-layer (Photo 17). This method of re-assembly was more difficult than anticipated, since parts of the cube could fall apart.

![Photo 17](image)

**Photo 17:** Attempt to rebuild cube with whole cuboids

We analysed statements in the questionnaires on the strategies of studying and rebuilding the cube. We found that participants of the VE-conditions examined the cube and its elements from inside and outside; unlike the students of the 2D-condition who studied the cube principally ‘layer by layer’ (Figure 26, left). Similar patterns of strategies were employed in the re-assembly of the cubes. Students attempted to re-assemble the interlocking cuboids as whole volumes in the VE-conditions. While the students, who studied the 2D plans, rebuilt the cube as a stack of layered units (Figure 26, right).

![Figure 26](image)

**Figure 26:** Comparison of percentage of participants adopting different strategies

*Left:* in the study task  *Right:* in the reconstruction task
Statements of the questionnaires also showed that students of both VE conditions comprehended the relationship of the cuboids to their adjacent ones. They claimed that the relationship and the actual form of each cuboid were better understood than they would have been in a set of conventional plans. Subsequently the participants of both VE conditions studied each cuboid as one element and tried first to rebuild the cuboids and then assemble them into the cube. This turned out to be challenging since the cuboids did not stick together as single units (Photo 18).

Comparing the average time spent on the study and reconstruction tasks among the three conditions, we found that students needed significantly different time to study the cube. This result shows the very different nature of the three conditions and the ability to comprehend and read the same structure. Due to the nature of 2D plans and depictions, all levels of the cube can be viewed at once. While the VE-conditions expose their content only by navigation through and around the cube. Surprisingly all participants completed the reconstruction of the cube without any significantly difference in time, despite the different methods of comprehension, study and partly tricky task to re-assemble the cube (Table 10).
Table 10: Time spent on the study and reconstruction tasks

<table>
<thead>
<tr>
<th>Study Task (Mean)</th>
<th>Reconstruction Task (Mean)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D</td>
<td>7.75 mins</td>
</tr>
<tr>
<td>DVE</td>
<td>25.00 mins</td>
</tr>
<tr>
<td>IVE</td>
<td>16.50 mins</td>
</tr>
</tbody>
</table>

The participants of the IVE condition were able to use the hard- and software to some benefit; all of the cuboids were recognised and at least partly rebuilt. Contrary to our assumption, the results show however, that their overall performance in reconstruction was worse compared to the other conditions (Figure 23 and Figure 25). In the questionnaires, the students noted that the problems with technology and equipment were significant inhibitors in the IVE-medium. They reported that settings in terms of scale and speed of movement for ease of use outside the virtual model were not adequate for actions taken inside the model. This finding is consistent with claims by Wong (2000). Furthermore he also reports that the weight of a HMD plays a significant role in the degrading a user's performance within IVE.

Given the inconvenience of using a headset-IVE, it is striking how poorly the DVE users performed. In fact, Vacca (1996) reports of potential problems DVE interfaces have on the experience of 3D content. Yet nowadays, interactions are very common and all subjects had several years of experience of desktop computing with 3D content.
4.4.2. Maze

I reported above how students working in a 2D context limited themselves to stacking layers of descriptions for making the 3D cube. We find a similar result in the maze experiment. In the majority of resulting cases of the 2D condition, the students produced four 2D mazes piled on top of each other (Figure 27).

![Figure 27: Typical 2D maze solution](image)

By contrast, in the VE condition, it was largely impossible to determine a conclusive path through the mazes; the mazes were ‘open’ on their sides and too many grid-fields were left empty (Figure 28).
This ‘openness’ made it difficult to trace an explicit path with turns, alternative routes or dead-ends. A maze is a continuous compilation composed of many spaces or nucleuses. Each of these nucleuses reacts with the neighbouring one, by repeating or being different. The collection and combination of all sub-spaces then creates the overall gestalt of the maze. Since it was not possible to trace an unambiguous path through the maze, we looked at the individual nucleuses that assembled the maze. This gave us an understanding of the richness and the complexity of the maze. With this method, we were able to interpret the various designs of the maze-like structures and formulate divergences in the design behaviours in all conditions equally. This method does not allow us to make qualitative evaluation of the design outcomes. Yet it allows us to compare the various outcomes on a micro-level of detail. Starting from this level of detail, we are then able to understand and examine the overall structure of the maze. Subsequently we subdivided the grid-structure into its sixty-four individual cells and we analysed the number of walls and their directions in space (Table 11).
Table 11: Types of nucleuses (maze cells) by its number of walls

<table>
<thead>
<tr>
<th>Empty</th>
<th>Floor</th>
<th>Opposite</th>
<th>Side</th>
<th>Corner</th>
<th>Cover</th>
<th>Corner</th>
<th>Tunnel</th>
<th>Dead-end</th>
<th>Enclosed</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
</tbody>
</table>

In the next two sections below, I will report on the outcomes of the various maze experiments more detail. First, I will look at the various designs of the mazes and their complexity within the three conditions by comparing them with each other. Then I will analyse the content of communications during the experiments between the team partners.

4.4.2.1. Complexity

By comparing the 2D with the DVE condition, the resulting mazes show that students using the 2D medium occupied more nucleuses of the maze and spending significantly more time in designing the whole maze (Figure 29).

![Figure 29: 2D versus DVE Maze](image)

Left: Average number of occupied nucleuses Right: Duration of exchanges

Interestingly thus it appears that mazes designed in the 2D condition had a large portion of cells composed of one to two walls only (such as ‘Floor’ and ‘Side’),
while mazes of the DVE condition used all types of nucleuses more equally distributed (Figure 30).

![Figure 30: Comparison of 2D and DVE conditions in cell types](image)

Analysing the results of the VE conditions, we did not anticipate that IVE users generally created clearly defined mazes, with complete paths and closed volumes, whereas DVE users created incomplete and loose structures with walls scattering around and with few connections between cells. This is particularly interesting, since the total number of walls and occupied cells in both conditions are the same (Figure 31).

![Figure 31: Comparison of DVE and IVE conditions of total numbers of walls](image)

This indicates that the gestalt of a maze and the way, in which individual nucleuses are connected, are factors that cannot only be measured by our analysis of counting walls alone. The design environment, the tool and the visual
composition play a vital role within a creative process. Consequently, the resulting maze designs should be seen in the context they were created in and intended to be experienced. To obtain a better understanding, the following figures show the outcomes of two VE conditions. Figure 32 illustrates the results of the DVE condition, while Figure 33 displays the designs of the IVE participants. We have to acknowledge that the below shown re-representation, a 2D printout of a selected view, does not reflect the properties of the media of creation. Besides, the students were asked to design a maze within their assigned medium only that will be viewed and experienced within their medium of design only.
Figure 32: Resulting mazes created by DVE participants
A further analysis of the individual nucleuses demonstrates that there is a significant difference between the group of ‘low density’ nucleuses that have only one, two or three walls, and the ‘high density’ nucleuses, which have four, five or six walls. From Figure 34 we can extract that in the majority of cases, DVE users created mazes consisting of ‘low density’ nucleuses, whereas IVE users produced mazes with ‘high density’ ones.
The 3D MAZE software is able to track the movement of the participants during their design process. Examining the location of the students while they were creating the maze, we found that a fundamental difference in their preferred point of view and presence. Students of the IVE condition worked mostly from within their mazes, while DVE users preferred to work from outside their mazes to generate their design (Figure 35).

This means that students of the 2D and DVE condition created the maze from an external point of view, akin to traditional design methods, whereas IVE participants designed from inside out, akin to a maze user’s point of view. This reveals a certain distance to the design by using 2D and DVE as media of creation.
Finally we investigated the difference colour may have on the outcomes. Hereby, there were some much-unexpected differences between the monochrome and polychrome experiments. We noticed that polychrome mazes had a large portion of nucleuses composed of ‘low density’ with one to two walls only, whereas monochrome mazes showed a much broader range of nucleuses, significantly larger in the range of ‘high density’ ones (Figure 36).

Contrary to our expectations, students of the monochrome condition succeeded in designing mazes effectively. They created by far more mazes that used ‘high density’ nucleuses than students using a coloured environment. Hence, they were not affected negatively by the lack of colour as clue of orientation.

4.4.2.2. Communication

Similarly, to the chat protocol analysis that we carried out in the VeDS (see Section 3.4.2.2.) we also investigated the content of communication between the teams of all three conditions. The analysis of the chat communications shows that all teams engaged in collaborative work. The teams of the 2D medium
discussed design issues significantly more often compared to the 3D media (Figure 37).

![Figure 37: Comparison of 2D and DVE conditions of total number of text exchanges](image)

In order to understand the communication between the team partners better, we subdivided the session of communication into three phases of ten minutes each. Comparing the average percentage of different communication contents, the DVE and the IVE conditions show a similar phenomenon. Both groups discussed issues related to the design of their mazes considerably more than other teams. Furthermore, users of DVE condition talked significantly more about matters rising from the interface of their setup than IVE users (Figure 38, left). We reported about similar findings in the cube-experiment (see Section 4.4.1.). IVE users communicated more about navigation issues. As shown in Figure 35 they predominantly designed from inside out. From time to time, it was therefore necessary to gain overview or find the team partner. Overall, there was no significant difference in the total percentage of communication relating to the navigation through the maze, (Figure 38, right).
Finally, we observed in both groups that design issues were significantly more frequently discussed than other topics. ‘Design’ exchanges were steadily decreasing among DVE users, whereas in the IVE condition, the percentage of exchanges of design-content had decreased in the middle phase, but it increased again in the last phase (Figure 39, left). DVE users increasingly talked about irrelevant (or ‘null’) topics, while for IVE participants, there was almost no change for ‘null’-content (Figure 39, right).

As already mentioned above, also the evaluation of the questionnaires revealed that generally, participants had more difficulties to navigate within the DVE condition than inside the IVE. In addition, the students stated that it was easier for them to understand their own design with its three-dimensionality within an
IVE than a DVE. They claimed in both settings equally that the design task was challenging and the collaboration with their team partner was satisfying.

We also compared the communications among mono- and polychrome team members. Unexpectedly, the monochrome teams engaged in fewer discussions about navigation, orientation or interface than the polychrome. Students designing a monochrome maze also communicated design issues significantly more often and longer than those designing a polychrome one (Figure 40).

Figure 40: Comparison of mono- and polychrome conditions of categorised chats

These findings are in almost the same manner as our analysis of the maze nucleuses (see Section 4.4.2.1.)

Finally, we saw the need to examine the nature of the communication relating to design issues. We used the definition by Schön (1984) and made use of the protocol coding-schema of a related experiment by Gao and Kvan (2004). We identified the percentage of ‘Framing, Moving, Reflecting’ of the two conditions, which are shown in Figure 41.
It is notable that the groups working in the polychrome condition engaged in framing activities significantly more frequently than in moving or reflecting, whereas participants of the monochrome setting reflected on their design almost as much as they framed it. This gives us some understanding why the monochrome groups were communicating overall more about design issues than the other groups (Figure 40).

4.5. Summary of Laboratory Experiments

Two sets of related laboratory experiments were successfully accomplished. In one, students examined a 3D cube composed of interlocking cuboids, either using 2D plans, screen based VE or IVE, and then they rebuilt this cube and its cuboids using a real physical model. In the second experiment, pairs of students formed teams and worked remotely together to design sequentially a 3D maze using again the three realms of either 2D plans, DVE or IVE. In these studies, the procedure was observed in order to identify the degree of spatial understanding and the effectiveness of media related communication. Both experiments have
confirmed that design within VE enhances the understanding of spatial and cognitive issues and can lead to architectural results that explore space more three-dimensional.

Yet, the outcomes of all of our experiments show that VE conditions are less ‘complete’. At the same time they can illustrate that users of VE do indeed ‘read’ the volumes and spaces better than when working in 2D representations. That means that the students had a constant understanding of the different volumes and spaces or an understanding of their design and their spatial relationships. Distinct shapes of the cube we understood and rebuilt or clear design strategies applied that made use of the three-dimensionality and the omni-directional structure of the maze. The results also show that VE tools have to evolve technically to better support performance and a smooth flow of design.

From the cube experiments, we found that students using VE understand the spatial relationships and gestalt of the cuboids better. They were able to comprehend easily the 3D appearance and partly rebuild the cuboids. Yet due to the complexity of the various cuboids, they were not very successful in re-assembling these cuboids into the original cube. Participants using the 2D medium succeeded greatly in fulfilling the task. They reproduced floor plans without an appreciation of the overall composition of the interlocking cuboids.

Correspondingly, the results of the maze experiments demonstrate that designers within VE explore the space more vigorously by working into all dimensions of the 3D structure. This led to more complex 3D solutions, which allow managing spatial arrangements in an enhanced way, compared to those of the 2D environment. Again, it the outcomes demonstrated that the 2D medium limited
students to explore the 3D space. They designed several independent mazes laid out horizontally and then piled on top of each other. The resulting 3D mazes exhibit no deeper exploration of the vertical possibilities within the maze. Interpreting the results of DVE medium was most difficult, which may relate to the narrow FOV of a screen-based environment. The resulting mazes remain for the most parts open to all directions. Finally, the outcomes of the IVE condition reveal a thoughtful exploration of the available three-dimensionality. Furthermore, the results are readable from outside as well as from inside, organizing void and solid elements as part of the overall gestalt. We learnt that colour does not necessarily improve the designer’s understanding within any of the realms. Still, colour is an element of hierarchy and clue for orientation.

We identified in all experiments that 2D representation of 3D space is the predominant medium to understand and communicate spatial arrangements. Subsequently it is the unanimous successful media of depiction. Nevertheless, VE enhance designers’ comprehensions of complex volumes, their spatial relationships and their ability to explore space three-dimensionally.
5. **Discussion and Contribution to Design in VE**

The results of experiments confirmed that designers using VE indeed can reduce the distance between the imagination and the realisation of a design scheme. The very different nature of VE allows architects to create designs that make use of the properties of VE that other tools do not offer. Designing within VE significantly enhance the designer’s understanding and communication of 3D architectural space.

The results also showed, unfortunately, that IVE tools are still so cumbersome that the characteristics of the systems inhibit their effectiveness and sole use in design tasks. Furthermore conventional design methods are the predominant media, which architects are accustomed to. This reduces the effortlessness to use VE as media for design.
Design studios and designers making use of VE can assist and influence positively their engagement with their design. Consequently, VE can play a more prominent role aiding and amplifying the creative process.

5.1. Conclusion of Experiments

This thesis reported of two clusters of design experiments in VE that were successfully accomplished. In one, pairs of students formed teams and two teams worked remotely within an IVE to develop sequentially an architectural design in a design studio setup. In another, students worked alone or in pairs to analyse and design an abstract architectural arrangement within a laboratory environment. The outcomes were compared with conventional methods of architectural design, using 2D media or physical models. In both clusters of experiments, the processes were observed to identify how and why form finding, comprehension and communication can be enhanced within VE activity. These experiments demonstrated that design conception, communication and collaboration in VE can lead to materially different results. As expected, the students conceived innovative forms of design expression and conveyed productively the 3D gestalt of their schemes. The experiments confirmed that immersive and non-immersive VE enhance conception, perception and understanding of spatial volumes.

We have found that it is beneficial for architects to use a tool that reflects the three-dimensionality of their design. The interactivity of VE in the design process, the direct feedback of cause and effect, and an enhanced collaboration offer architects a new way to explore, design and communicate spatial
constructions. Kalay (2001) points out that particularly the growing complexity of design projects creates increased specialisation to deal with the numerous issues involved in the process. This specialisation evokes the need of an ever-growing number of collaborating partners, requiring a high-level communication and understanding of the design. The setup of our experiments successfully demonstrated how teams of designers worked together to produce a joint design. While most research has focused on IVE used for presentation purposes, we have demonstrated that these tools have significant contributions to the design process by enhancing spatial comprehension and perception of 3D volumes. Nevertheless, VE tools have to evolve so that their use becomes as simple as paper and pen.

5.2. Implications and Impact on Design

We developed our experiments based on reported results of prior research in design collaboration and communication using real and virtual environments (Schmitt, 1998). We carried out an architectural virtual design studio that took the issues of VE into a complete architectural design scenario. Then we transferred our experiences of the VeDS to some experiments with abstract problem solving.

In a similar context Dave (1995) also confirms that VE is a constructive tool to support the design and communication process at least in establishing co-presence for a shared experience in spatial review. Yet how is this support extended to a design setting? Other VDS results have exhibited a lack of
collaboration and communication (Kvan et al., 2000a), however, our experiments showed the opposite. Chat-protocols show participants remarking to each other that the collaborative experience was satisfying. That means, within VE the exploration of space, volume and location is enhanced and site-specific problems are not only better recognised, but also possibilities are investigated. This is an improvement over other forms of design sharing that is analogous to the conclusion drawn by Campbell and Wells (1994a).

Using a 2D medium to translate spatial ideas apparently reduces the exploration and communication of volume and space, at least in the design examples of both the helipad and maze that I have presented here. Coherent to our findings, Dorta (2001) concludes that VE have significant impact on the activities of communicating 3D information within a design process caused by the impact of VE on the cognitive aspects of the design activity: the formation of 3D mental images, visual perception and mental work load. The results of cube experiment support those findings. VE permit an enhanced understanding of spatial compositions. In other words, using VE as medium to design spatial 3D compositions, designers can pursue ideas with a smaller cognitive workload.

While users of VE can change their viewpoints and escape gravity, they also maintain the feeling of presence within the digital 3D models are generated with the intention of conveying overall design intentions similar to physical models, constructed to improve the perception of designs developed by drawings. As a result, IVE provide an immediate feedback to users that are not possible within CAD or traditional design media (Chen, 1995). It appears, therefore, that designers can work more three-dimensionally within VE since every object is
experienced through movement and interaction. The design is created as a whole entity within space and not as a 2D planar representation. This possibility offers a different ‘conversation’ with the design that otherwise is not obvious or possible. In addition, spatial issues can be addressed in a manner akin to the real world. The design process becomes more immediate, in some aspects, with the tools available enhancing the translation of the designers’ and users’ mental intention into spatial objects and 3D design decisions. Subsequently these possibilities have an impact on the quality of the resulting design. The experiences seem valuable even in spite of the amount of technological overhead used and the abstract realism of VE.

Assessments of questionnaires and observations during the experiment have confirmed that within a 2D environment students memorised the individual ‘floor plans’ without comprehending their spatial connection. This results in a very particular and ‘layered’ description of a building. This is probably because, to understand and communicate 3D space, architects are trained with a strong emphasis on thinking and reading two-dimensionally using the traditional architectural languages of plan, section and elevation. Introduced the 15th century 2D scale drawing is the way architects communicate architectural design until today. Contrary to this established method, users of IVE do not necessarily translate scales or dimensionalities. Very often we can observe in studio teaching, where students often examine a typical architectural building description, in which 3D space is perceived and translated into 2D elevations and plans that they fail to comprehend the three-dimensionality of the studied architecture. For example 2D depictions of plans, elevation or photos of Hans
Scharoun’s *Philharmonie* in Berlin cannot describe or convey the volumetric qualities of the building (Photo 19).

![Scharoun’s Philharmonie, Berlin](image)

**Photo 19:** Scharoun’s Philharmonie, Berlin Exterior, Interior and Plan (Bürkle, 1998)

VE offer designers the potential of a greater overall 3D understanding of space and volumes. Yet, in the majority of cases, only users of 2D media were able to rebuild our prescribed volume nearly without any errors, but they did this without appreciation of the volumetric expression or the component shapes. Only in very recent years architectural design is evolving beyond the traditional language (Gruber et al., 2003). Architects discover new ways and different tools to communicate their design. Hereby VE can help them to explore and express ideas unlike traditional methods.

A similar phenomenon happens within the academic and educational environment. Less than a decade ago many schools of architecture did not allow students to deliver CAD drawings for design projects assuming that those limit the exploration and understanding of design. In fact, the early experiments in using the computer in the design process quite often failed only because of the restrictions of the available hard- and software. Today, students are familiar with CAD software even before they enter the university (Dokonal and Hirschberg, 2003). Still many questions remain unanswered and new questions arise in the relationship between architectural design and digital media. Architectural design
is both an imagination and the ability to convey this idea. The teaching of architectural design has now the possibilities to make use of the advantages that VE can offer without losing the qualities of the established conventional methods. Yet too often however, in using digital media and VE tools the students are more knowledgeable than the teachers are. All those changed the dynamics of architectural education. Yet, this has to be reflected in how we teach.

Interestingly, all mazes built in the DVE condition appear incomplete and many walls appear to be scattered around. We speculate that the FOV of a computer screen creates an impression of enclosure or ‘tunnel vision’ for the users. Despite the fact that participants could move around and explore freely, they placed walls only at certain key locations, which then define complete paths even if those are not articulated or do not exist as closed structure. Further investigation is needed to test this interpretation. However, it is notable that a VE allows a clear understanding and communication of the 3D design-intent, even if the gestalt seems incomplete (Figure 42).

![Figure 42: ‘Tunnel vision’ of DVE and zooming out of a MAZE result](image)

Our experiments have shown that IVE can support an instantaneous, direct, scale-less and intuitive control over a 3D design. However, as of today, the capabilities of VRAM or similar applications do not match the sophistication of today's CAD software; it can supplement, but not replace, other design media. An immersive and easy-manageable environment is needed before VE can
change effectively the design process outside our research conditions. This can then be used broadly in normal architectural and related applications.

However, it appears to be not as simple as just placing a designer in a VE. The technology needs to be investigated further. Assumptions about what works and what does not work need to be challenged. A much wider debate of academics and professionals is needed to explore and develop the various opportunities VE offer to the education and production of architectural design. This discussion must be lead in parallel to the development of technology issues such as usability, interface and navigation. Those have to be further developed to reach the same ease to use and familiarity as any 2D media. Problems with the working environment clearly limit what the designers can do. In particular, clumsiness of gesturing and limited FOV constrains the use. The HMD hinder users. Problems particularly encountered were the wiring entangling arms or legs; interference of and sensitivity of the tracker; lack of precision in gesture recognition and insert-points of elements; polygon size of models; frame rate of display, rendering and calculation time of models; cost of equipment; limited ability to support multi user and multi viewpoints. These are all issues that deserve attention.

Finally we recognised that the translation of design from VE into other media is potentially problematic (Gero, 1999a), suggesting that developments may be needed to facilitate the making of physical models. Similar to Gibson and Kvan’s (2002) findings this suggests that other technologies such as rapid prototyping or automated construction methods may have a significant contribution to make to a design process that engages VE. Synergies between the different realms, media
and technologies can be developed in a collaborative environment that fosters the evolution of new kinds of forms and structures.

5.3. Contribution to Knowledge

The research undertaken in this thesis has not only moved the VDS for the first time into an IVE but also has demonstrated that architectural design within IVE defines design in a new, unforeseen and materially different way. IVE offer settings that enhance an architect’s understanding and communication of 3D space. In response to Gero’s question (1999b) (see Section 2.6) this thesis moves us closer towards a better understanding, and it demonstrates that architectural design is significantly enhanced within IVE through a deeper understanding of the 3D space. This thesis has demonstrated that VE minimises the distance between the imagination of a design and its representation within an architectural design process. Digital tools are increasingly playing a role in bridging this gap yet the translation from imaginary to digital and physical often poses a major barrier. Most tools of VE are only used for presentation or simulation. Designing within VE, moving back and forth from and to the original idea, may minimize this divergence. This empowers designers to express, explore and convey their imagination with fewer differences in order to engage actively into architectural design. Dorsey and McMillan (1998) see the need for CAAD systems and their users uncover the potential of VE. By comparison with representations using conventional media, this research has demonstrated that conception, perception and understanding of spatial volumes within VE contributes to the quality,
accuracy, understanding and designing of architectural space and forms. This has not previously been verified by any other research or study.

5.4. Future Research

Designing within VE offers new opportunities of expression to designers. Thus, the field is rich for exploration. This research has demonstrated for the first time that the distance between the imagination of an architectural design and its representation, communication and realisation can be reduced or bridged by using VE in early design stages. Yet this field of design within VE is still emerging and hitherto no strategy is developed how VE can enhance the act of designing and by that the quality of the resulting architectural design. The extent of the differences, the shortcomings of conventional design methods and proposals that improve architectural design techniques need to be more defined and thoroughly investigated. Then we are able to place this research into a larger body of knowledge that improves human design creations.

The thesis focuses on interaction within VE as well as the initial design process. Since some studies suggested that low-bandwidth CSCD, via text or spoken word, enhances the exploration of design issues. It may be of interest to directly compare or combine low-bandwidth CSCD with a setting using IVE, which is not only by its technical implications of high-bandwidth but also offers multiple streams of communication methods. This merging of media may offer a distinction and symbiosis, which conventional CAAD tools cannot offer. Additionally, with the ever-evolving technologies around CAAD, it may be
possible to have more interaction within IVE or move the act of design away from its abstract and isolated realm by blending it together with reality. This Augmented Reality (AR) setting can explore how virtual component can be directly applied in a real building process (Seichter, 2003). Similarly to the expressive methods to cross over different domains moving freely between media and realms, the artist Man Ray expressed and communicated ideas in photograms, which he called ‘Rayographs’ (Photo 20, De l'Ecotais, 2002). Asger Jorn blended over each other virtual and real media to convey spatial expressions. Emulating a painting by Pablo Picasso, Jorn used a ‘light pen’ and photography to re-present sketches by Utzon (Photo 21, Weston, 2002).

These artworks lie in the tradition of artists who push media to explore new interpretations both of the media themselves and of their artworks. Imagination was expanded into a new dimension, while virtuality was interpreted in a new way. It became its own reality that complimented the physical realm in its own right. Yet these methods are can be translated by employing current technologies.
The potentials of VE are obvious and omni-present, yet they are not explored fully to their own capacities. As Maver (1973) postulates: “Design follows its own paradigms.” Therefore, it evolves and re-establishes itself by its own developed expression.
6. REFERENCES

6.1. References


Arthur, K. W.: 2000, Effects of field of view on performance with head-mounted displays, *in Department of Computer Science*, University of North Carolina, Chapel Hill, NC, USA.


Dorta, T. V.: 2001, L’influence de la réalité virtuelle non-immersive comme outil de visualisation sur le processus de design, in Faculté des études supérieures, Université de Montréal, Montréal, Canada.


Kvan, T., Wong, J. T. H. and Vera, A. H.: 2000b, Supporting Structural Activities in Design: A Multiple-Case Study, in A. Chan, S. Chan, V. L. Hong and V. Ng (eds) Proceedings, Hong Kong Polytechnic University, Hong Kong, pp. 116-120.


Marcus Aurelius: ca. 180, tr. 1634, Twelfth Book in M. Casaubon (ed.)
Meditations (Ta eis heauton); First English translation: Marcus Aurelius Antoninus the Roman emperor, his meditations concerning himselfe treating of a naturall mans happinesse; wherein it consisteth, and of the meanes to attaine unto it. Translated out of the originall Greeke by Meric Casaubon, Vol. 12, vii, M Flescher, Richard Mynne, London, pp. 201.


Wong, W. S.: 2000, A virtual reality modeling tool for students of architecture, *in Department of Architecture*, The University of Hong Kong, Hong Kong.


6.2. Apparatus

http://arch.hku.hk/~marcaurel/mazespec.html

Adobe Photoshop, Adobe Systems Incorporated, San Jose, California USA,
http://www.adobe.com/photoshop

AutoDesk 3DStudio VIZ, Autodesk, Inc, San Rafael, California, USA,
http://www.autodesk.com/viz


Kaiser Proview 60, Kaiser Electro-Optics Inc. Carlsbad, CA, USA,
http://www.keo.com/index.html


Microsoft NetMeeting 3, Microsoft Corporation, Redmond, Washington, USA,
http://www.microsoft.com/windows/netmeeting


Polhemus Fastrak and Polhemus Stylus, Magnetic motion tracking and input device, Polhemus, Colchester, VT, USA, http://www.polhemus.com
VRAM - A Virtual Reality Aided Modeller, see Regenbrecht et al. (2000), Bauhaus University, Weimar, Germany
