In this study, we examined the perception and understanding of spatial volumes within immersive and non-immersive virtual environments by comparison with representation using conventional media. We examined the relative effectiveness of these conditions in enabling the translation to a tangible representation, through a series of design experiments. Students experienced, assessed, and analysed spatial relationships of volumes and spaces and subsequently constructed real models of these spaces. The goal of our study is to identify how designers perceive space in Virtual Environments (VEs). We explore issues of quality, accuracy and understanding of reconstructing architectural space and forms. By comparison of the same spatial performance task undertaken within a Head Mounted Display, screen-based and real 2D environment, we are able to draw some conclusions about spatial understanding in immersive VE activity.
1. Introduction

Architects have to use a variety of tools to communicate and express their design. Although some explore design decisions through large-scale models, modelling of the final product is limited, in most cases, by the overall dimensions and resource constraints. To overcome these constraints, architects have used computer aids, including Virtual Environments (VEs), to communicate and present design intentions [1]. Although screen-based VEs are now commonly employed, immersive VE-technologies are typically found in research-laboratories, universities or a few architectural offices. Recent changes in the technology have led to immersive VE-equipment being used not only in specialised professional settings but also for consumer activities such as games and other applications [2]. At the same time, the nature of professional work is changing as communication technologies become cheaply and readily available. Virtual design practices are forming: ones that have offices at different and remote locations, which communicate and collaborate by using VE, work as one large unit and share their expertise [3]. Yet Stuart [4] points out that research on the outcome of results and the opportunities for applying VEs in architectural design are still developing. VEs are employed successfully to study, communicate and present architectural design but are seldom used for the actual act of creation, form-finding and collaboration in the field of architecture [5].

In the past decade many architectural design exercises and professional projects have used Virtual Design Studios (VDS) as a medium for teamwork [6]. In these studios, collaboration was limited to the exchange of text (with the use of chat-channel, web page or email) or images (file-transfer, webpage and whiteboard). VEs were created to offer a common shared involvement in a task rather than an active engagement in a virtual space. Immersive-VEs (IVE), which offer the user an active and real-time interaction with the design, and therefore a real sense of presence, have not yet been used widely for design creation. It has been noted that the qualities of design and the designed products are directly linked to the nature and level of communication and collaboration [7] that has taken place during the design process. In other words, IVEs offer new opportunities in architectural design problems through the involvement in an immersive three-dimensional (3D) medium, in which the user can create, communicate and collaborate [8].

In this context, an immersive Virtual Environment Design Studio or VeDS was conducted [9]. Architectural students worked interactively within an IVE as they searched for an architectural solution for their task. It resulted in conceptual manipulations of space in creating an architectural design. The outcomes of this VeDS showed that participants designed and communicated within the IVE differently: the three-dimensionality of space, form and void was explored in a way that appears to differ from conventional design environments. The analysis of the results indicated the need to carry out further studies to clarify how well 3D forms are
understood in IVEs. Therefore we conducted a series of experiments and looked specifically into the issue of understanding of 3D elements in space. In the study architectural students described forms they explored in a variety of modes, including IVEs. We thus investigated the relationship of 3D space perceived within VE as compared to descriptions made in the physical realm. This article describes these experiments and the implications of the results.

2. The cube

For the purposes of the experimental task, we interpreted an abstract architectural arrangement that can be studied in 2D or 3D environments. We modified a tool, called 3D MAZE [10] that we had used for related experiments [11]. This application generates 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 configuration, a cube. Viewers can then navigate their way through the cube and inspect the volumes defined. This procedure replicates simply, an architectural design process in which volumes and space are determined, in order to generate an overall design; viewers can review the design by traversing the spaces defined. In our experiment the system enabled students to experience and study enclosed volumes within a cuboidal spatial assembly. The viewers were then asked to describe the spaces encountered by building physical descriptions of them. Thus the cuboidal structure simulates a simplified architectural spatial configuration that can be analysed, interpreted and transcribed, using either immersive or non-immersive environments.

2.1. The experiment

The experiment was designed to investigate and compare students’ understanding of volume and space in three different conditions of representation. The subjects were asked to inspect a volume defined by interlocking cuboids. This volume, which was constructed on a 4x4x4 grid framework, was assembled from different cuboids following an architectural hierarchy and structure. Single and double volumes as well as vertical, horizontal and angled shapes defined the volume (Figure 1).

This volume 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 suitably varied volumes without being either excessively complex or too simple (Figure 2).

Three viewing conditions were used. The first condition was a conventional depiction of 3D space with typical 2D architectonic floor plans; the second and third conditions employed digital 3D models; in the second condition users viewed the cube in a Desktop-VE (DVE) by

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manipulating an interactive model displayed on a PC Monitor. In the third condition, viewers experienced the model in an IVE. Twenty-four architectural students were asked to explore and study the given volume. The students were randomly assigned to one of the three representations of the cube. They were asked to examine the volume and then reconstruct, in the real world, the interlocking cuboids that formed the virtual volume, using wooden blocks (Figure 3).

A time limit of 25 minutes was given to study the volume. A 20 minute period was allowed to rebuild the volume using the blocks. Since the structure is based on a grid of four units in each direction, all of the potential cuboids can 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 (Figure 4).

Finally the participants were asked to complete a questionnaire describing:

- their experience with the medium,
- its mode of representation,
- the strategies adopted for study and assembly
- their understanding of the spatial structure of the volume as a whole and its individual component elements.

2.1.1. 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 5).

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. So, in a similar manner to the 3D representations, participants had to (mentally) scale down the studied plans and cuboids in creating the wooden model.
2.1.2. Desktop virtual environment representation

Participants working with the DVE-condition used a standard computer, running a web-browser with a VRML plug-in (Cosmoplayer [12]) to view, interactively, the 3D volume in VRML file format on a conventional 17 inch monitor. This allowed them to manoeuvre through and around the volume to their own liking, using mouse or keyboard commands (Figure 6).

2.1.3. Immersive Virtual Environment representation

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 Head Mounted Display (HMD) [13], a Polhemus-Fastrak magnetic tracking device and a Polhemus-Stylus [14] (Figure 7).

2.2. Results

In short, it was found that the perception and understanding of the volumes were significantly different in the three conditions.
Students working in the 2D condition achieved the greatest degree of accuracy in rebuilding of the volume (Figure 8). Those shapes that were present in several layers such as the white and light blue cuboids were less accurately recreated than those within one layer (for example the red shape) or simply penetrating vertically (for example the yellow shape). Even after rebuilding the volume, they did not fully understand the arrangement of the cuboids within the volume, except single-height forms that were confined within one layer.

In contrast to the study and rebuilding strategies of the participants working with 2D reference data, students working with the two VE conditions explored and investigated the spatial form and relationships of the shapes in a more holistic way and therefore had a better understanding of the three-dimensionality of the volume and its components. Distinct shapes within the structure were comprehended better and rebuilt more accurately. Sometimes participants placed shapes in an incorrect orientation or location within the volume (such as upside down or back to front), however the cuboid was generally recognized correctly and was placed in the correct context (Figure 9).

Even taking into account the fact that certain shapes were actually assembled correctly but placed wrongly, the success-rate in the VE-conditions was much higher than for those working in the 2D condition.
(see the hatched area in Figure 10). However, if one cuboid is dislocated it is then impossible to complete the whole volume correctly. Consequently, in such cases the overall completion rate was lower.

Interestingly Figure 10 shows that participants using the two VE-conditions had an equally good understanding of the 3D shapes and spatial relationships, despite the participants’ relatively low success rate in rebuilding the whole volumes. Additionally we can conclude from the completion rates in Figures 8 and 10 that the more complex shapes were, relatively speaking, better perceived within the VE-context than in the 2D condition.

The analysis of the statement on strategies gathered from the interviews revealed that the participants in the DVE and IVE conditions studied and tried to rebuild each form as one element (Figure 8). They understood each cuboid in relationship to its neighbouring ones in the volume. According to statements in the questionnaires the relationship and actual form of each cuboid were better understandable than they would have been in a set of conventional plans. Participants studied the cube from inside and outside. The interlocking cuboids were interpreted as connecting volumes and not as a stack of layered units. Yet this caused problems in the assembly of the cube. Since the wooden block-units were not adhesive the reconstruction had to be carried out layer by layer and unit by unit (Figure 4).

By contrast, students using the 2D medium analysed the cube as a stack of 2D layers without relating this to the spatial composition of the eight cuboids. Analysing the questionnaires students confirmed this observation (Figure 11). The students working with the 2D condition reported that they memorized the various ‘floor plans’ and rebuilt the volume layer by layer. They did not create a mental 3D image of the individual cuboids by studying or rebuilding the layers. The participants never explored the internal and external relationship of the cuboids to each other within the volume.

The subjects were able to use the IVE system to some benefit; all of the cuboids were recognized and at least partly rebuilt. The results do show, however, that their overall performance in accuracy of reconstruction was
substantially worse than for the other conditions. In the questionnaire the students noted that the problems with the technology and equipment were the significant inhibitors in the IVE-medium. Wong [14] reported that the weight of the HMD plays a significant role in the degrading users’ performance within IVE. Recognising this problem we used an improved light-weight HMD. However, other technical difficulties exist. Participants reported that settings for ease of use outside the virtual model were not adequate for actions taken when inside the model; for example, when they approached the model, the speed of approach was correct; but when inside the cube, the speed was too high. Given the significant problems in using an immersive system to experience the IVEs, it is striking how relatively poorly the DVE users performed. This is especially so since desktop interaction is very common and all subjects had several years of experience of desktop navigation using a mouse and keyboard.

3. Discussion

The students who worked from the printed plan representations did reconstruct the cube most accurately. Observing their processes of reconstruction, however, they engaged in replication of each ‘floor plan’ one at a time, stacked one above the other. Thus, they did not exhibit a spatial understanding of the volume. The IVE group’s reconstructions were the least complete, but in contrast, the results showed that users of IVE do indeed ‘read’ the volumes better than when working from 2D representations. The results also suggest, unfortunately, that IVE tools are still so limited that the characteristics of the systems inhibit their application use in design tasks.

This study builds upon previous experiments in communication between designers in VE which compared their actions with their actions in paper environments, and looked at how they collaborate with partners to solve 3D tasks. We carried out an architectural VDS that applied issues of VE to a more realistic architectural design scenario [16]. We then reduced the question of volumetric understanding to an abstract problem-solving task in order to test issues that arose from the VeDS. In both scenarios our findings are similar. We have found that it is important for architects to use
(particularly in certain design stages) a tool that reflects the three-dimensionality of their design. An IVE has the capability to do this. Translating spatial ideas using a 2D design-medium apparently reduces the exploration and communication of volume and space. We demonstrated this with our abstract description of the 3D cube. Assessments of questionnaires and observations during the experiment have confirmed that students memorized 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.

This result is similar to what we observe in studio teaching, where students often examine a typical architectural building description, in which 3D-space is perceived and translated into two-dimensional elevations and plans, but fail to comprehend the three-dimensionality. For example 2D depictions in plans or elevation of Scharoun’s Philharmonie in Berlin cannot describe or convey the volumetric qualities of the building (Figure 12).

VEs offer designers the potential of a greater overall 3D understanding of space and volumes. Yet in the majority of cases only the users of 2D media were able to rebuild the prescribed volume nearly without any error. But they did this without appreciation of the volumetric expression or the component shapes (Figure 8 and 11).

On one hand users of IVE can change their viewpoints and escape gravity, but on the other they maintain the 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. As a result IVEs provide an immediate feedback to users, which is not possible within CAD or traditional design media. Designers can therefore work more three-dimensionally since every object within IVE is experienced through movement and interaction. This
possibility offers a different ‘conversation’ with the design that otherwise is not obvious or possible. Additionally, spatial issues can be addressed in a manner akin to the real world. The process of design 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. The experiences seem valuable even in spite of the technology used and the abstract realism of IVE.

4. Conclusion

An experiment was conducted in which students studied a 3D volume composed of interlocking cuboids. They used either conventional 2D plans, screen based VE or IVE and rebuilt the same target volume using a physical model. The process was observed in order to identify the degree of spatial-understanding achieved and the effectiveness of media related communication. This study has demonstrated, despite the fact that 2D representation of 3D space is the pre-dominant medium to understand and communicate spatial arrangements, that designers’ understanding of complex volumes and their spatial relationships is enhanced within a VE setting.

While most research has focussed on using IVE for presentation purposes, we have demonstrated that these tools have significant contributions to the design process by enhancing perception and understanding of 3D volumes. From this experiment we have identified that a direct translation of information into other media is potentially problematic, suggesting that the method of rebuilding has a role to play in this process. Consequently, the field is too complex to be able to account for all aspects in this research. However, we conclude that IVE offers architects new opportunities for the actual act of creation, form finding and collaboration in 3D space.

Our experiments demonstrated that the problems of VEs are not insurmountable. Because technical solutions are constantly evolving, difficulties resolved and equipment is becoming more sophisticated and easy to use. Working with VEs architects can explore alternative solutions to those achieved in conventional design methods. This is despite the challenges of visual perception, mental workload, errors, comprehension of design and its communication and the different frequency of creation-feedback-modification loops. Since IVEs increasingly play a role in the design and form finding of architectural creations, virtuality becomes, in that sense, reality. In this experiment we have identified that such form finding may be better in IVE than in other media but that the representation of these forms in other physical media may require better tools. Following Gibbons and Kvan’s findings [18] this suggests that techniques that produce physical representations on demand, such as rapid prototyping (RP) may have a significant contribution to make to a design process that involves IVEs.
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