Interpretation of Simulations in Interactive VR Environments: Depth Perception in CAVE and Panorama.

Abstract.

Virtual reality (VR) applications are transforming the way architecture is conceived and produced. By introducing an open and inclusive approach, they encourage a creative dialogue with the users of residential schemes and other buildings and allow competition juries a more thorough understanding of architectural concepts. Architects need to heed the dynamics set in motion by these technologies and especially of how laypersons interpret building forms and their simulations in interactive VR environments.

The article presents a study which compares aspects of spatial perception in a physical environment, CAVE and Panorama. In a report, statistical analysis and discussion of the results, the paper addresses three hypothetical assertions – that depth perception in physical reality and its virtual representations in CAVE and Panorama are quantifiably different, that differences are attributable to prior contextual experience of the viewer, and that spatial ability is an important contributing factor.

Results in the two virtual environments tested show consistent differences in how depth and shape are perceived, indicating that VR context is a significant variable in spatial representation. It is asserted that perception of shape and distance display here fundamental conditions of the CAVE and Panorama.

Mullins, M 2006, 'Interpretation of Simulations in Interactive VR Environments: Depth Perception in Cave and Panorama', *Journal of Architectural and Planning Research*, vol 23, nr. 4, s. 328-340.

Introduction

Coop Himmelb(l)au's 'House of Music', on the waterfront of the town of Aalborg in the north of Denmark, is at the time of writing in the final stages of design documentation. The Vienna-based architectural firm's project was the winning entry, ahead of the likes of Zaha Hadid and Henning Larsen, in an interesting and innovative form of competition held in 2003. It was one of the first to require interactive 3D visualization from all entrants and it provides indications of what may be the standard Danish submission requirements for architects in their future presentations to public competition juries. This ground-breaking requirement arose from a desire to improve the decision-making abilities of the 28 person jury. Besides consulting architects, this jury included a relatively large number of non-professionals comprising representatives of the clients, the city council, local business, and the university.

Subsequent to the competition, interviews were held with both professional and layperson jury members by the Danish Building and Urban Research Centre.[1] Despite reporting a generally high degree of satisfaction with the whole procedure, a number of statements surprise (Bertelsen, 2003). For example: "Everyone mentioned that 3D visualizations create similarities between the laymen and the experts, and it helped to knock the experts off their pedestals."[2] Moreover, Bertelsen's accounts point to a poorly executed virtual reality (VR) model as an important factor in rejecting one of the leading contenders. On a question of the influence of VR on the final result, "one of the laymen stated that if the winner was to be found [without the VR models], it probably would have been someone else." Indeed, the large differences in quality of the submitted digital models (Kjems, in press) emphasise the need for architects to heed the dynamics set in motion by these technologies – they are changing the rules of the competition and have major effects on how concepts are perceived, particularly by laypeople.

The House of Music VR models were viewed by the jury at Aalborg University's 'Panorama' theatre, a facility of the Virtual Reality Media Lab[3]. The Panorama seats 28 people in front of a 160 degree cylindrically curved screen, with a radius of 7,1 meters and a height of 3,5 meters, thereby filling the field of vision of the participants. Three projectors are used with slightly overlapping images to display the digital models in an interactive VRML format, allowing viewers to instruct a "pilot" to navigate at will. The Aalborg facility also

[1] The interviews were held on behalf of the national institution responsible for research and educational buildings in Denmark, *Statens Forsknings- og Uddannelsesbygninger* (S-FoU), a body of the national Ministry of Science, Technology and Development.
[2] This and the subsequent quotation are the author's translation from the Danish original.
[3] For more details see: www.vrmedialab.dk/

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includes a computer aided virtual environment - the ‘CAVE’ - a 2,5 x 2,5 x 2,5 meter room with 6 sides (including ceiling and floor) onto which 3D images are projected. Active stereoscopic shutter glasses are used to create a spatial representation of a digital model giving an immersive experience for the user. The user employs a hand-held ‘wand’ - an electromagnetic tracking system - to enable interactive, virtual movement in real-time within or around the building. As the viewer moves inside the CAVE, the correct stereoscopic perspective projections are calculated for each wall. The CAVE was not used in the competition, but its availability and the reported success of the Panorama suggests its further application in this field.

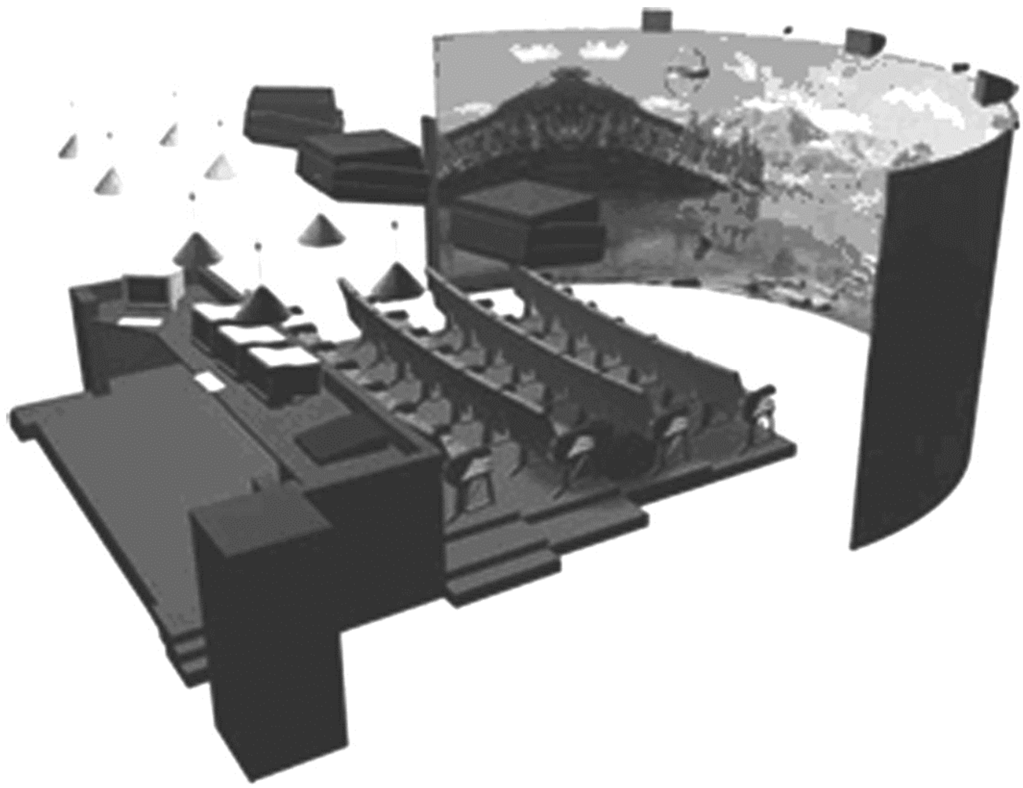

Figure 1: The Panorama in the VRMedia Lab at Aalborg, used by the competition jury for The House of Music competition.

It is not only in competitions where VR applications are transforming the way architecture is conceived and produced. The field of participatory design increasingly uses interactive forms of 3D city models available to a wider public over the internet, in an open and inclusive approach. Inner city upliftment such as the Holmbladsgade and Nørrebro Park projects in Copenhagen support the active residents with GIS based information linked to a 3D city model[4]. They present views and evaluations from both active and marginal groups to politicians and professionals involved in the regeneration project encouraging a creative dialogue with the neighbourhood occupants. As indicated by the building and testing of a “virtual cultural marketplace” in the real Nørrebro park, “as a new meeting place in the electronic neighbourhood”, these attempts can be anticipated to increasingly take VR into use, as the opportunities of available technologies are explored (Holmgren et al., 2004).

In another application, a workshop recently held between urban design students at Aalborg University and local interest groups exemplifies how architecture is given different expression to professionals and laypeople by VR communication. Negotiations between the participants at one point in the workshop turned around the transferring of 2D graphical information to interactive 3D visualisations in the Panorama theatre. It had been proposed that a disused industrial area in Aalborg be transformed into a landscaped urban park. The students first placed a 2D landscape ‘prototype’ on a site plan, hereafter a conceptual representation of vegetation was shown in the interactive 3D city model in the Panorama. This surprisingly led to objections from the participating locals, objections which appeared spurious and contradictory to the student designers (Jensen et al., 2004).

The misunderstanding between the two groups appear to arise from a divide in spatial conceptualisation - or spatial ability - between the students, with training in graphical and digital modelling applications on the one hand, and the invited participants, who generally were well acquainted with the physical reality, that is to say the neighbourhood in question. This ‘spatial abstraction gap’ was exacerbated by the Panorama, as no such differences had been noted in prior discussions that used drawings and small-scale wooden models.

In this connection, it was suggested for further workshops of a similar nature that, before a VR session, one attempts to explain and clarify the character of 3D modelling, in the light of the problem of abstraction and concrete form. It was suggested that this could be operationalised through a gradual shift from the familiar physical (the harbour), to the virtual representation of the familiar (the 3D city model of the harbour), to the design concept (the new buildings, parks and so on) under consideration. This process of increasing ‘representational thickness’, in the transition from the physical to the virtual, will be further researched in this study through empirical testing.

[4] see www.e-kvarter.dk

Figure 2: Negotiations around 2D map. The interactive 3D model can be seen in the background on the Panorama screen.

The incident of misunderstanding, if only briefly recounted in a preceding paragraph, illustrates miscommunication explored in previous work (Mullins et al., 2002; Mullins et al., 2003). Research has been directed into a quantitative and qualitative description of differences in how the lay public and professionals perceive and understand architectural representations across a range of 2D and small-screen types of electronic presentation, particularly those distributed through the internet. In one of these experiments, the level of conceptual abstraction and the approximation to real spatial experience conveyed by images served to differentiate representational techniques into two categories. Thus, a perspective, regardless of drawing media, showing a view from an approximate eye height is here categorised as 'experiential', while a plan - a representational convention seen from above - is categorised 'conceptual'. 'Experiential' representations were found to be closer to the lay public's experience and situated knowledge. As such, the latter were preferred, perceived faster and more accurately, in relation to their intended information content. On the other hand, the abstraction and intellectual coding of information inherent in 'conceptual' representations resulted in longer perception times and greater difficulties in understanding by the lay public. While it was found that both

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professional and lay public had difficulties defining geometrical shapes from ‘experiential’ presentations[5], the results indicated that architectural “intentions” and lay public “expectations” coincide more closely through the means of experiential media.

While VR’s attraction may lie in its potential for a higher level of “experiential media”, it is not without its limitations and not only those related to technology. Previous enquiries point to difficulties in conveying measurable properties of spatial attributes such as dimensions, etc. in experiential media (Dave, 2001). Marc Schnabel and Thomas Kvan (2003) conducted an experiment at the University of Hong Kong in which 24 architectural students first studied a 3D volume composed of interlocking cuboids represented either by conventional 2D plans, screen based virtual environments or immersive virtual environments. They were then asked to rebuild the cuboids, using physical models. It was found that the highest degree of accuracy in the reassembly of the cuboids was achieved by participants who had obtained information from the 2D plan drawings; this group had reassembled the cube as a stack of 2D layers without relation to the spatial composition of the eight cuboids. This is perhaps not particularly surprising – the only input to solve the problem given to this group of participants was represented as a series of sectional layers. However, from the remaining samples the report concluded with respect to the virtual environments that “designers’ understanding of complex volumes and their spatial relationships is enhanced within a VE setting” (Schnabel et al., 2003). What may be drawn preliminarily from this study is that the students recreated the object in accordance with the information given them. The immersive environments enabled a fuller understanding of the spatial qualities of the object, precisely because it is spatial qualities that are transmitted in those environments.

The report is of interest to this study in that the representational environments had a direct influence on the built physical object. If simulating spatial experience increases the understanding of the represented building by allowing viewers to identify known places, orientate themselves and appreciate the scale that is involved., interactive CAVE and Panorama should in theory offer better architectural visual and spatial representation, and consequently a reduction in misunderstandings between laypeople and professionals.

Our sense of environment as a three-dimensional space is provided by a variety of depth cues, including occlusion, shading, perspective, dynamic perspective, stereo viewing, field of view and extra-retinal cues such as movement (Slater et al., 2003). Scale and depth are recurring problems in spatial representation.

[5] For these properties, 2D plans for example have been shown to be more effective. A mix of the media, judiciously chosen for information content, is therefore to be recommended; particularly where the architect does not communicate verbally, as for example on the internet.

Even in photo-realistic models displayed on desktop screens, the third dimension of depth is not wholly convincing, relying on the viewer's ability for spatial imagination, while scale is difficult to evaluate without some recognisable object to relate to, such as the human figure. The combination of devices and systems used in virtual interfaces recreate the third dimension of space in a far more immediate manner. This is the so-called 'immersive' technology of CAVE. One's own bodily scale allows judgement of depth and size, reinforced by position-tracking relative to one's direction of gaze. Moreover, the physical distance between observer and represented object, present in all forms of images, scale-models and even the large multi-projector Panorama is removed. The observer and represented object stand in relation to each other as they would do in the physical world.

This background has given rise to the author's present empirical enquiry into the spatial relationship between a physical environment and its VR simulations, specifically the CAVE and Panorama.

Method

While it seems clear that CAVE allows access to a spatial experience of a computer model very different to screen based simulation, little research has been done on the relation of real to virtual space so presented. In an endeavour to contribute to this field, an experiment was designed to create similar visual conditions in all three environments for its participants and allowed a comparison between them for statistical differences in depth perception and shape recognition. To give structure to this enquiry, the study makes three assertions: Less accurate perceptions will be made in virtual environments of CAVE and Panorama, when compared to perceptions in the original physical environment; more accurate perceptions in virtual environments will be found where there is prior experience of the physical environment; professionals perceive shapes more accurately than laypeople[6] in physical and virtual environments.

To test these three hypotheses, a digital 3DSMax model of the VRMedia Lab, Aalborg University, was converted for interactive use in the Panorama and CAVE virtual environments, situated within the VR Media Lab itself.

Test objects were placed in the foyer of the building, comprising 3 shapes (triangle, square and circle) in 3 sizes (ex.100cm, 60cm and 30cm), with a departure point in Eric Granum and Peter Musaeus' set of static

[6] Professionals and laypeople are defined here by the subject's education in architecture or related fields, or otherwise. This is discussed in more depth in a later section of this paper.

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object properties (Granum et al., 2002). The shapes are clearly recognisable and ‘value-free’ objects, which reduce unnecessary variables in the experiment.

The 9 objects were placed so that 3 were visible at varying depths from 3 different standpoints in the foyer. These shapes, positions and standpoints were simulated in the CAVE and Panorama by scaled representations in precisely the same virtual positions. Observation distances were measured in relation to the size of object, where the standard maximum dimension of 100cm of the object = 1 Standard Distance Unit (SDU). Following Granum and Musaeus, a range of important characteristics like inter-object distance and observer-to-object-distance are thus related in a meaningful way to the size property of the objects. In order to be able to refer to the relevant shape descriptions, participants were given a scaled sketch drawing of the 9 shapes before starting the experiment. Questionnaires were developed as multiple choices, for example: ”From standpoint ‘A’, do you judge the visible square shape to be: S1, or S2, or S3? (Choose only one shown on the sketch drawing)”.

The participants in the experiment comprised 68 subjects in an age range of 20 – 65, and with an average age group of 25-35 years. One result was rejected due to technical failures in the CAVE during the participant’s interview. Subjects were questioned individually. On completion of each presentation of each question, the relevant section of the questionnaire was filled out by the interviewer. These answers could be subsequently tested for accuracy, relative to actual shape positions recorded in the foyer.

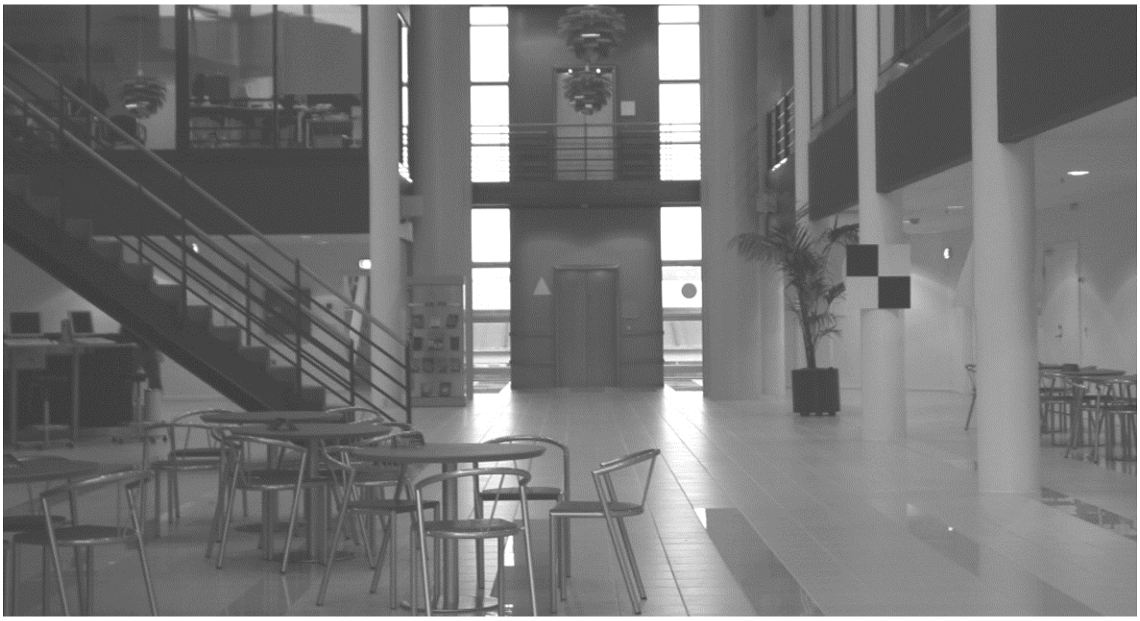

Figure 3: The foyer with shapes in place for the experiment (Standpoint C).

Mullins, M 2006, 'Interpretation of Simulations in Interactive VR Environments: Depth Perception in Cave and Panorama', *Journal of Architectural and Planning Research*, vol 23, nr. 4, s. 328-340.

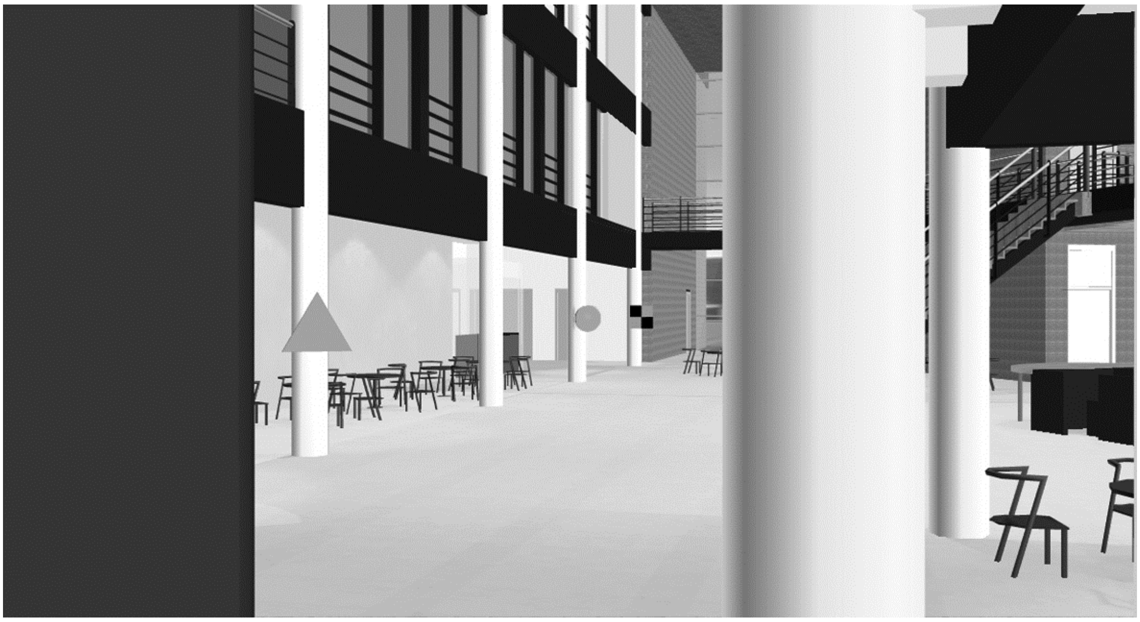

Figure 4: A screen capture of the Panorama simulation (Standpoint B).

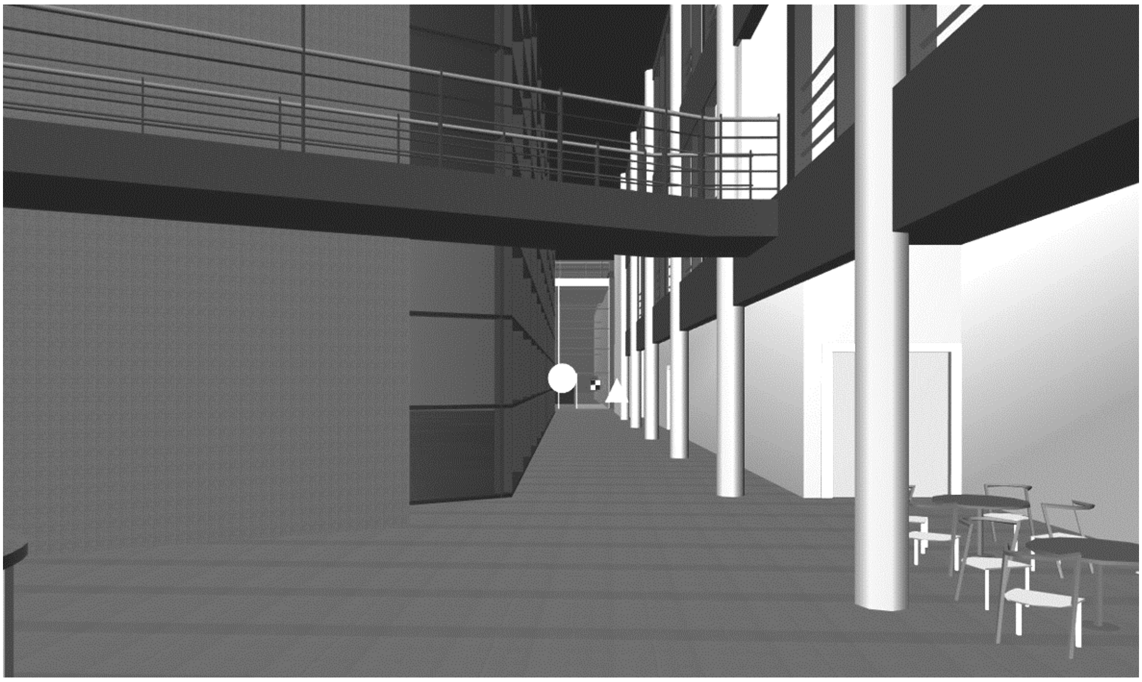

Figure 5: A screen capture of the CAVE simulation (Standpoint A).

Data Analysis

Hypothesis Test A: Less accurate perceptions will be made in virtual environments of CAVE and Panorama, when compared to perceptions in the original physical environment.

Data collected from 67 questionnaires was analysed for correct and incorrect answers. For each participant, 9 questions were asked in each of the physical, CAVE and Panorama environments, giving a total of 27 answers per participant. Scores in each environment were examined for normality[7].

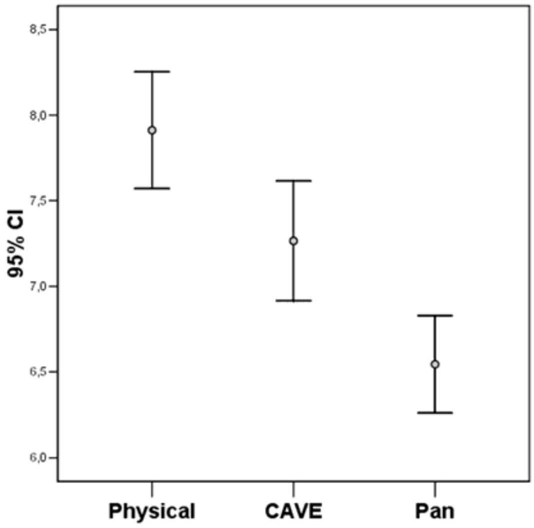

Figure 6: Error bar chart around mean accuracy scores in three different environments, showing 95% confidence levels.

Means scores were found for each environment. The error bar chart for these scores, see fig.6, shows only small areas of overlap and in the case of a Physical to Panorama comparison, no overlap at all. Confidence levels around the means of scores in the 3 environments are 95%. This suggested that there is a significant difference between the population means.

Since data were not normally distributed, a Friedman's one-way ANOVA, repeated-measures[8] test was performed on the three conditions. Results gave a chi-square of 34.36 with an associated two-tailed probability value of 0.001. These results confirm that significant differences in accuracy scores are related to the environment in which they are viewed.

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[7] The Kolmogorov-Smirnov goodness-of-fit test was used to test for normal distribution. Data in the first hypothesis test were found to be not normally distributed. The data with additional variables in the following two hypotheses tests were found to be normally distributed. The specific tests used in the subsequent analysis were chosen accordingly.

[8] "Within-subjects effect": all participants responded in each environment. "Between-subjects" variables are the professional /layperson grouping and the process direction, in which different participants were tested.

3 pair-comparisons were then carried out between the conditions, physical – cave; physical – panorama; and cave - panorama. Wilcoxon tests on two-related samples show associated two-tailed probabilities as: p=.009; p=.001; and p=.001 respectively, with Z values of -2,603; -5,503; and -3,556 respectively.

It can therefore be concluded that that participants made less errors in shape recognition in the physical environment, and more errors under the conditions of the CAVE and Panorama, with the level of error being highest in the Panorama condition. It can also be concluded that such differences are highly unlikely to have arisen by sampling error.

Hypothesis test B: More accurate perceptions in virtual environments will be found where there is prior experience of the physical environment.

The data collected from the 67 questionnaires were grouped into two separate randomly assigned participant procedures: from Physical to Virtual (procedure P_V); and from Virtual to Physical (procedure V_P)

In procedure P_V, participants answered questions starting in the physical environment, followed consecutively by the CAVE and Panorama environments. Procedure V_P participants followed the reverse order. Procedure P_V tests the prior experience hypothesis by enabling a measurement of results in the Panorama when participants have already experienced the physical reality of the simulated environment. These results can be compared to Panorama results in procedure V_P, where participants started in Panorama and have not yet experienced the physical isomorph[9].

Confidence levels around the means of scores in the 3 environments, illustrated in the error bar chart (see fig.7), show relatively large areas of overlap, particularly for the P_V direction. This was interpreted as showing that the ‘procedure’ independent variable has low influence on accuracy. However, in the case of the V_P variable, confidence levels overlap to a much lesser degree, suggesting that significant differences in means may be found there, and particularly between physical and Panorama. Overlap between the Panorama mean scores of both procedures, while showing some overlap, is also less pronounced than for the other environments. This was interpreted as showing that the differences in the procedures would be found to be greater in Panorama than in CAVE or physical.

[9] Used here in the sense of ’iso’ = ’same’; ’morph’ = ’form’.

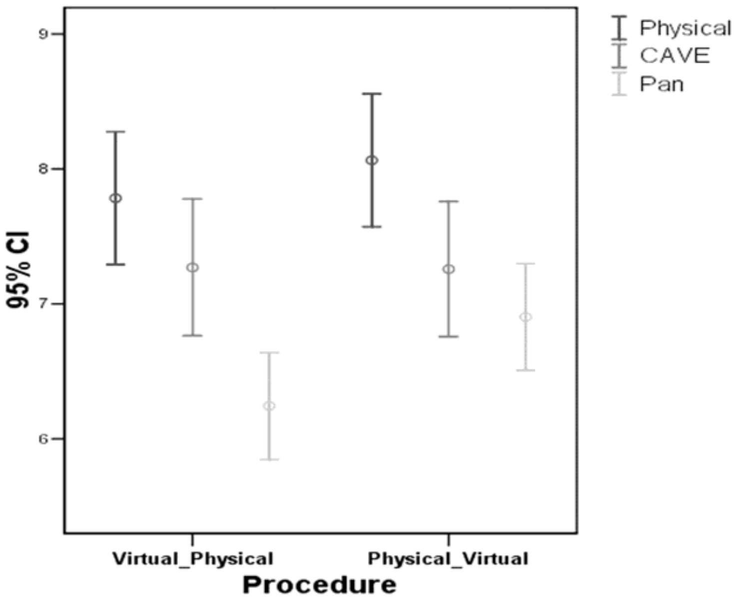

Figure 7: Error bar chart around Means of Correct Answers in Environment by Procedure, showing 95% confidence levels.

Procedure V_P participants in the Panorama condition obtained fewer correct answers (Mean=6,24, SD=1,19) than did the Procedure P_V participants in the Panorama condition (Mean= 6,90, SD= 1,08). An independent t-test revealed that if the null hypothesis (stating equal means for Panorama scores in the two procedures) were true, such a difference between the two procedures would be highly unlikely to have arisen (t = 2,381, df = 66, p = 0,02). Results comparing the physical and CAVE environments for both procedures respectively were not statistically significant.

It can therefore be concluded that that P_V participants made less errors in shape recognition in the Panorama than did V_P participants. It can also be concluded that such differences are highly unlikely to have arisen by sampling error. Comparative differences between procedures for the physical and CAVE are inconclusive.

Hypothesis test C: Professionals perceive shapes more accurately than laypeople in physical and virtual environments.

The scores collected from 67 questionnaires, as described above, were grouped into ‘Professionals’ and ‘Laypeople’ for all three environments. Confidence levels around the means of these groups’ scores in the 3 environments, illustrated in the error bar chart (see fig.8), show relatively large overlapping of bars. For the professional group particularly, this indicates that their accuracy scores were similar in all environments. Any differences in means could be due to sampling error. In the case of the layperson group, confidence levels overlap to an obviously lesser degree, suggesting that significant differences in means may be found there.

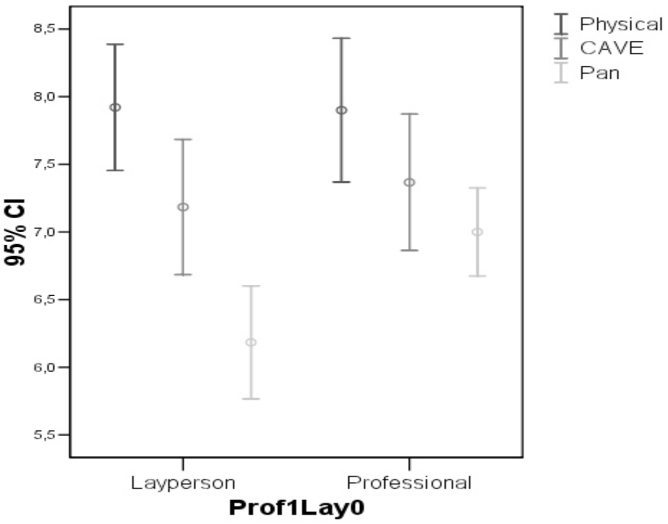

Figure 8: Error bar chart around Means of Correct Answers in Environment by Professional and Layperson groups, showing 95% confidence levels.

Layperson participants in the Panorama condition obtained fewer correct answers (Mean=6,18, SD=1,27) than did the professional participants (Mean= 7,00, SD= 0,87). A directional, independent t-test revealed that if the null hypothesis were true, such a result would be highly unlikely to have arisen (t =3,002, df = 66, p = 0,002). Results for the physical (t = -,061, df = 66, p = 0,952) and CAVE (t = -,515, df = 66, p = 0,603) environments were not significant.

It was therefore concluded that professionals perceived the shapes more accurately than laypeople in the Panorama environment. In the Physical and CAVE, results were inconclusive.

Summary of Results

Findings from the preceding analysis of conditions and variables created by the experiment can be summarised as follows:

Less accurate depth perceptions were made in the CAVE and Panorama, when compared to their equivalent in the original building. The Panorama is prone to give rise to more error and CAVE gives rise to less error.

More accurate perceptions in virtual environments were found where there was prior experience of its physical equivalent. This implies for example, that while knowledge gained in virtual experience is not reliably transferred to its equivalent physical context, knowledge gained in physical contexts is transferred more readily to its virtual simulation.

Laypeople were more prone to errors of perception in the Panorama. Professionals, who generally have better spatial ability through their training, will perform better in this environment. These differences are however minimal in CAVE, which is attributed to the lower degree of abstraction and higher degree of experiential representation provided.

Discussion of Results

It has been demonstrated, in previous studies, that spatial ability and visual imagery influence academic performance in engineering courses, but can be increased through appropriate instruction (Potter et al., 2001). It was shown that students with low scores on tests of spatial ability, and in particular three-dimensional spatial perceptions, were at risk as regards passing graphics courses. After receiving training, their performance on tests of three dimensional spatial perceptions improved. This would also strongly suggest that developed spatial ability, gained through learning, is an attribute found in architectural graduates, and that a lesser developed spatial ability will be found in both those who do not pass certain courses (and are thus less likely to graduate), as well as those who have not studied in this or related fields. Spatial ability is thus a primary quality in differentiating and defining 'professionals' and 'laypeople', in that the former are (by definition in this study) educated in the fields of architecture and related fields.

The less accurate results found in the experiment for laypeople in the Panorama may be better understood when seen in this light. It follows that increasing spatial ability will reduce differences between the groups. Results also indicate significantly better overall accuracy of response in the CAVE than in the Panorama. This is attributed to the relatively higher degree of immersion and movement possible in the CAVE. As James Gibson writes: "A motionless observer can see the world from a single fixed point of observation and can thus notice the perspective of things. It is not so obvious but it is true that an observer who is moving about sees the world at no point of observation and thus, strictly speaking, cannot notice the perspective of things. … each object is seen from all sides, and each place is seen as connected to its neighbour. The world is not viewed in perspective" (Gibson, 1986). The CAVE conditions, in simulating the dynamic perspective Gibson alludes to, are measurably closer to physical conditions than Panorama, which in turn can be anticipated to offer better spatial simulation than small-screen models, drawings and scale models. This being the case, CAVE and Panorama are attractive tools for training spatial ability.

The experiment also indicates the clear directional difference, measured in accuracy scores, between moving from the physical environment to the CAVE and thence to the Panorama (procedure P_V), and the reverse, that is, to the physical from the Panorama (procedure V_P). Following the line of reasoning developed in the previous paragraph, the first sequence represents a gradual shift from perceptions of actual objects to their increasingly abstract representations of space. It may be objected that an improvement in scores may be expected as a result of participants learning to recognise the shapes by repetition through 3 consecutive environments. This would predict a relatively higher score in the final environment, being Panorama in the case of procedure P_V and Physical in the case of procedure V_P. However, by comparing the two physical scores from the procedures, the tests show that knowledge gained initially in Panorama and CAVE does not affect physical scores significantly, as would be expected if the 'learning hypothesis' were to hold true. Knowledge first acquired in the virtual environments was not as effectively transferred as was the reversed process. Representations in the virtual environments appear to be considered with a degree of disbelief by participants when comparing to their physical isomorphs. Further tests may show that spatial-learning in VR environments, to avoid merely becoming virtual spatial-ability, maintain a close relationship with physical environments.

The differences in results may also be attributed to various deficiencies in the representations. At the time of experiment for example, real-time shadows creation by the software used was not possible, and this certainly affects perception of depth and shape. Although this situation is already being improved by newer software[10], the CAVE and Panorama were tested in the state that they were being used for various decision making processes, such as the architectural competition for Aalborg's House of Music, and the participation workshop already described above. Moreover, the notion that virtual reality will, at some future time, resemble 'reality' exactly is logically absurd, in the case of architectural representation. While it may be argued that VR becomes its own reality as it were, a metaphor for physical space "whose signified is always retreating or becomes itself the signifier" (Barthes, 1997), an object cannot be the same as its representation. That is to say, there will always be an 'abstraction gap' of some order between object and its virtual representation, notwithstanding Ivan Sutherland's early proposition of an "ultimate display", indistinguishable from reality (Sutherland, 1965). Indeed, one may question if improved realism in virtual environments will significantly

[10] The VR Media Lab in Aalborg has subsequently installed a Linux driven PC cluster enabling easier conversion of model files to VR4Max, an add-on to the commonly used modelling software 3DSMax. The hardware now comprises three Intel P4, 1.7GHz CPUs with NVidia GeForce4 Ti4600 graphic cards and 1GB memory.

increase the accuracy measure employed in this study. This however remains a question to be answered in the future.

Sense of Virtual Place: a metaphoric extension of the body

The experiment has simulated knowledge gained via bodily immersion in virtual context. It has narrowly focussed on depth and shape recognition. While the study follows the positivist conventions of statistical testing of empirical hypotheses, it will seek to relate results to a broader context of experience. “There are wholes, the behaviour of which is not determined by that of their individual elements, but where the part-processes are themselves determined by the intrinsic nature of the whole” (Wertheimer, 1925). The generalisation of the results to describe attributes of the virtual context will be justified in the sense that the experiment describes repeated, part-processes in the context of different ‘intrinsic wholes’. By comparing isomorphic part-processes, comparisons may be made regarding the identity of wholes. Results in the two virtual environments tested show consistent and significant differences in how depth and shape are perceived, indicating that VR context is a major determinant of variations in spatial response. In the aspect of ‘identity of virtual place’, the present study thus supports the view that spatial experience is intrinsically related to its context.

Michael Polanyi wrote: "Our body is the ultimate instrument of all our external knowledge, whether intellectual or practical" (Polanyi, 1983).The notion that spatial knowledge has an intuitive or hidden dimension may allow a deeper understanding of how the viewer relates to place in virtual environments. In relating Polanyi’s ideas to architecture, Chris Abel writes of tacit knowing: “It may be surmised that place identity itself is a function of tacit knowing, by which individuals come to dwell in a place not only physically but also by metaphoric extension of their own bodies” (Abel, 2000). Depth perception is a measurable aspect of the ‘metaphoric extension of the body’ referred to by Abel which, taken as a whole, bestows spatial identity and which is a function of tacit, situated knowing.

Where VR represents the built environment and where there is an intention that object and representation correlate to some degree, the ‘picture’ represents the world as it is intended for this metaphoric bodily extension into place. Yet, even where there is an intention ‘in good faith’, there is much room for error in the communication between architects and those toward whom they direct their ideas. We find an explanation for this in acknowledging the essential paradox that underlies representation in images – that the picture can seem like the world, but the world does not seem like a picture - a paradox which applies to the virtual as much as it does to conventional analogue media.

To achieve what might described as an adequate thickness to the representation of situated knowledge, the study's results suggests that an ideal sequence for the presentation of architectural ideas to laypeople would progress from the built environment context, through CAVE to Panorama, followed by conventional physical models and drawings. This process moves in a direction from the experiential toward the conceptual. In terms of architectural education, this 'ideal sequence' may imply a teaching curriculum in for example computer skills, which would start with VR spatial exercise and progress through 3D rendering, lighting and modelling and end with 2D CAD software, a method inverse to those generally prevalent. While the study found that increasing spatial qualities of representation improved accuracy, it also suggests that learning through VR maintain a close relationship with the spatiality of physical environments. Not least, in the case of architectural schools, where the potential to accelerate students' spatial abilities by learning through virtual reality, may occlude such considerations.

It is asserted that perception of shape and distance made in the 3D virtual contexts of the experiment, display here their fundamental conditions; not those of fortuitously chosen processes, but those that concern the character of the CAVE and Panorama, in which the dialogue between the real and the imagined takes place in the context of virtual spatiality.

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