Effects of the differences between virtual and physical perception of space on Building Information Modelling

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Abstract

Visualising 3D models of buildings is essential in assisting clients' decision-making process to accept or change design parameters/criteria. However, to achieve effectiveness, 3D virtual representations of built spaces must be perceived as identical to their physical counterpart to be built/refurbished, which is the current assumption by architects and engineers creating 3D space-models and discussing design decisions with clients during design coordination stages of Building Information Modelling (BIM) projects. This research provides contrary evidence to this assumption; evidence that human perception of 3D space sizes/dimensions in virtual models is different from perception of physical spaces with the same dimensions. This was achieved by conducting experiments where diversified participants were asked to evaluate sizes of physical rooms and their equivalent 3D virtual representations; results were then compared. Size evaluation was performed using tangible visual cues for assessment, not generic metric scales, hence eliminating errors due to individual discrepancies in human appreciation of metrics. This paper discusses the experiments conducted in 2 phases: 1) assessing physical spaces, and 2) assessing 3rd person view of 3D virtual spaces (visualisation on screen). After analysing differences between perceived widths, depths and heights recorded in both phases, results showed evidence that humans perceive each virtual dimension differently from its physical counterpart, and furthermore with varying percentages. This indicates that current 3D-modelling BIM authoring software might not be depicting true representations/visualisations of spaces to be built; hence possibly causing clients to issue wrong decisions based on incorrectly perceived space dimensions during the design coordination process.

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1 Introduction

There are several forms of digital space representation used by designers and architects in the construction industry to represent to clients prospective buildings, and try to depict reality faithfully. These representation techniques follow technological advancement. First, CAD tools (Computer Aided Design) provided 2D representations, from which, 3D representations of the objects could be derived using geometric models. In parallel, GIS (Geographic Information Systems) emerged allowing non-graphical attributes to be linked to geometric representation through grids or matrices. Currently, visualisation is depicted using 3D graphical Building Information Models (BIMs), which can be interlinked together or with GIS, with rich non-graphical information attached inside them [1]. The visualisation can either be a solitary model or inside a virtual environment/world e.g. Second Life.

Parsons [2] shows that, with these visualisation tools, both quantitative and qualitative information can be represented about spaces. Quantitative information expresses spatial relationships among people and objects e.g. length, height, size etc., in an absolute or numeric manner, while qualitative information provides a "sense of place", e.g. architectural style of building, sounds, urban characteristics [3]. This research poses the question whether human perception of 3D models' virtual space sizes, represented by this quantitative information, is the same as human perception of the same space in reality that this information represents.

Usually, 3D building information models and computer simulations of them are chosen by designers to communicate themselves with their clients – showing space design ideas, functionalities and sizes. However, there is a possibility that those existing forms of digital visualisation might not portray size and dimensions of a space truthfully hence giving the client a false perception of what the space would actually look like once built. This might result in wrong decisions at design phase based on incorrect information, which would only be realised after construction is complete, rendering it impossible or expensive to change, causing both usability and financial losses. Considering this, methods to visualise space would have to be enhanced or new ones created to depict reality accurately. This also applies to 3D simulations, which allow touring inside or around spaces in a 3D virtual environment to help better perception of them. This permits the user to become integrated in the space, hence enhancing his perception of it. This can be done using two methods [4]: 3rd person view (i.e. watching an animation on screen) where the user can see his avatar moving relative to the space or imagine watching someone else moving, but does not feel embedded inside it himself; or using 1st person view (by wearing a virtual reality Head Mounted Display-HMD) where the user feels immersed inside the environment and completely surrounded by it. As explained by Salamin *et al.* [4], while the 3rd person view provides a more global view of the environment, the 1st person view allows more "presence notion". Also lack of stereo-vision could add trouble evaluating distances, but could be partially compensated by the 3rd person perspective that increases the field of view. Hence a second question, which this research poses, is whether there is a difference in human perception of virtual spaces between 1st and 3rd person views analogous to real-life space perception. The scope of this paper is limited to comparing the difference in perception between real-life spaces and 3rd person view of virtual spaces. The consequent sections will demonstrate what research has been conducted in this area, the gap being explored, and explain the experiments done in this research and their results to answer the questions posed here.

2 Background

Few former studies have attempted to compare between human space perception of a real and a virtual environment, as demonstrated subsequently, sometimes conducting experiments with static and moving observer or using a tracking and control subsystems to follow the subject. However, there is scarce evidence to indicate endeavours to investigate the following aspects proposed by this study, which are not previously researched. That is to find the percentages of reduction or increase of perception of each individual space dimension separately between virtual and physical spaces, to find percentage accuracy of representation of reality, and hence percentage of adjustment required by 3D-model authoring software for faithful display of virtual spaces.

Previous work done by Witmer and Kline [5] discussed the difference between perceived and traversed distances, both inside virtual worlds. For these variables, two experiments were conducted. The first one used a static observer and the second one, a moving observer. The difference between these 2 results was compared to the difference between perceived and traversed estimates made in a similar real-world environment. However it was not the main goal to make a comparison between each virtual result and its real-world counterpart. The study used static distance cues for the perceived distance experiment, in order to determine the accuracy of stationary observers in estimating distances. The real-world tests aimed to define participants' ability to estimate distances in this scenario. In general the results suggested underestimating of distance from the subjects, for both real-world and virtual environment. However, in the physical world, the errors were smaller probably due to more cues for depth and other dimensions available, as per the authors' theorisation. Unlike their objective, this current study aims to investigate the percentage of increase or decrease in perception of dimensions between virtual and physical spaces.

Another endeavour by Witmer and Kline [5] aimed to analyse the influence of different speeds of movement on participants' estimates of traversed distance in a virtual environment. A questionnaire was completed by participants after they traversed all the routes. It was found that when participants received compensatory cues, the estimated distance increased. But when they moved faster, their estimates were less accurate. The significance of this to the current study is that while the distances measured were not specific directional dimensions inside spaces, evidence was given to the importance of compensatory cues for precision of distance estimation, which was taken into account in the design of this research's experiments.

Another study, also looking for the fidelity of a virtual environment versus a real environment, used a real room and an equivalently modelled virtual room in an experiment. Participants, ranging in gender and age, 20–42 years, explored the virtual room using a Head Mounted Display (HMD) and answered a questionnaire for both situations about their perception of the physical and psychological properties of the room. Participants were asked to measure the room dimensions in meters and centimetres and also the ratios with each other. Results showed that subjects' perception was quite accurate in the virtual environment when compared to the actual sizes, except for the height dimension, but no percentage accuracy was provided [6]. However the majority considered the virtual room as more spacious and brighter than the real room. Yoon *et al.* [6] attributed this discrepancy in their results and with those of Witmer and Kline [5] to size and shape of the rooms, which was small and almost cubic in the first case and larger elongated rectangle in the second. Also the navigation movement was restricted which could have affected perception. As a result, shape ratios were one of the attributes considered within the current research experiments.

As for using metrics to estimate dimensions, according to Henry and Furness [7], *"Very few people feel they can be accurate in expressing distances using a metric system, such as feet or meters, because metric distances are not immediately intuitive".* This is the reason why for the experiments of the research at hand, a desk was used as a unit of measurement or guidance for measuring the dimension of the rooms, and not a metric system. Furthermore, according to Arthur *et al.* [8], there is difference between the judgment of absolute and relative distances in 3D virtual environments.

Another complimentary study by Henry and Furness [7] showed the underestimating increased as the size of space increased and the underestimates for dimensions were quite different from the real condition. This gave evidence for the supposed reasons behind the discrepancy identified between Witmer and Kline [5], and Yoon *et al.* [6]. Findings also reaffirmed previous findings that movement improved perception of space and that the perception of space in simulation conditions is smaller than in real spaces, however again there were no percentage comparisons calculated, which is the goal of the current research. Henry and Furness [7] concluded that small rooms were easy to size up because the participants could see more of the walls without distortion and their human scale helped the distance's judgment. Hernández *et al.* [9] later supported that idea, *"The characteristics of our body in metric terms, such as size, eye height, walking speed, etc. constitute the frame of reference and standard for assessment of distances, position of objects, etc.".*

A recent study by Saleeb and Dafoulas [10] conducted a series of experiments inside Second Life with 84 participants who were asked to partake in short consecutive e-learning sessions inside 15 selected 3D virtual learning spaces, inside which they were encouraged to navigate, then asked individually to evaluate their sizes in terms of number of people they perceive each room can withstand (using a questionnaire). Results showed that discrepancy increased as the space sizes increased, which supports findings by Henry and Furness [7]. In another set of experiments by Saleeb [11], 77 students, diversified in age and gender, were asked to take an e-learning session inside 3 identically shaped and designed, but differently sized rooms inside Second Life. Amongst other factors outside the scope of this paper, students were asked for the optimum space size they enjoyed that best emulated a real-life classroom. Their vote preferred the room 8 times bigger than the average classroom in real-life, saying this was the most equivalent to physical classes; contrarily, the virtual room that was exactly the same size as an average real-life classroom, was identified as being too small. This adds more evidence to the fact that virtual dimensions are perceived as smaller than their counterparts in reality, hence the significance of this research to affirm this and attempt to find percentage differences between virtual and physical perception of space dimensions.

A most recent study by Broecker *et al.* [12] concluded their inability to affirm that certain depth cues significantly improved depth perception of virtual geometry. Another research by Chen *et al.* [13] examined possible differences between how users physically reach for and locate virtual objects, and that was by asking 16 students to locate edges of identical physical and virtual boxes in a CAVE environment. Their results concluded that human performance in virtual environment was less accurate (greater error) than in the physical environment.

3 Research rationale and description

According to Billger *et al.* [14], *"for most computer graphics, the objective is not producing correct simulations of reality, but visualisations that look good"*. This might be acceptable for the gaming industry but not suitable for conveying depictions of future building spaces accurately to clients in the construction industry. Hence the objective of the research at hand, is to determine the level of difference between virtual and real perception of space in an attempt to rectify this to provide more realistic 3D visualisations of spaces for clients and users. This section explains the qualitative and quantitative methods/tools that were chosen, i.e. experiments and survey questionnaires depicting participants' perception, their sampling and variables considered. The scope of this research includes using only the software Sketch Up, with V-Ray photorealistic rendering plugin to visualise models with utmost quality and realism, and the plug-in TriDef that will be used by the sample. Also for the present study, Virtual Reality will be defined as a computer-generated 3D world that allows the user to feel present and interact with the world in real time [14].

A randomised sample of 18 students participated from different disciplinary backgrounds at Middlesex University, UK (Engineering, Architecture, Graphic Design, Health, Business, Law, Media), diverse in culture and aged 18 to 30. They were 8 males and 10 females. Exclusion criteria for selection were any visual disorders, epilepsy, tendency for motion sickness, claustrophobia or sensitivity to flashing lights. The participants partook in two experiments for each of 3 different sized rooms, detailed later. One experiment was performed in the real-life room, and the other in its virtual replica. Each experiment – described subsequently –

was divided into two parts – with the participant static in the room, and the other whilst moving in it, to test previous research findings that movement enhances perception of space size. For the virtual experiments, three different conditions were tested: 1) 3rd person view without the virtual reality HMD, 2) 3rd person view with the HMD and 3) 1st person view – with the HMD and 3D immersion enabled (using the plug-in TriDef).

For all experiments, the following control and extraneous variables were kept constant so as not to affect the results: time of day, experiments' procedure, researcher facilitating the experiments, same room colours and content; and only one independent variable was changed/tested i.e. width or depth or height of the room, with keeping the other 2 variables constant. The scope of this paper is only to demonstrate results of comparing between the 3rd person views (not the 1st person view) and real life view. The real-life experiments were conducted in three rooms inside Middlesex University. Room A was 16x7m, Room B 9x7m, and Room C 9x3m. Height of all 3 rooms was the same. Room B was used as the control experiment and the other 2 rooms chosen specifically to resemble one of Room B's dimensions and to be either half or double the other dimension, as seen from the rooms' measurements. This was to fix all dimensions except one, which would be the independent variable, to compare results of rooms together against. The depth of room B was almost half of room A (56%), and the width of room C was almost half of room B (43%). These ratios were chosen as close as possible to 50%, limited by availability of rooms at Middlesex University.

Before conducting the experiments, the rooms were completely emptied except for one visual cue, a cubical plain desk, which was placed inside to aid the participants with assessing the width, depth and height of the room (figure 1). The same was done with the other rooms, using an identical desk to eliminate any added variable that might affect the results. These rooms were then modelled/ virtually replicated exactly using Sketch Up, as a representative of 3D model authoring software used in the construction industry and BIM projects. Sketch Up was used for ease of use and free accessibility. All dimensions, openings, colours, textures, materials, fittings were replicated exactly including the visual cue desk and its exact position in the room. A visual cue was used to rely on relative instead of absolute sizes, thus avoiding discrepancies in humans' ability to measure using metric scales, as identified in previous research.

Figure 1: Left: Room A in reality before removing furniture, opening window. Right: Virtual Room A modelled in Sketch Up 2013.

In the real-life static experiment, the participants were seated individually in a desk and asked to observe the room then answer a questionnaire (detailed subsequently). In this situation they had to analyse the space, only moving around head and body whilst seated. Then, the participants were asked to walk around the room and feel the space to answer the next questions. These steps were the same for all three rooms and the participants experienced the rooms in a random order, to eliminate the effect of order on the results. For the virtual experiments, in the static condition, two images were shown to the participants representing width/height and depth/height from which they were asked to evaluate the dimension sizes (figure 2). For the moving condition, a simulation was displayed to them, while looking at a computer screen, of movement around the whole room, where the camera height was positioned at human head height of 1.7m. Those techniques were experimented with and without wearing the HMD (figure 3) and then were compared to the experiment of static and moving observer in the physical world. These steps were the same for all three rooms. To overcome the effect of bias in measurement from performing a physical followed by virtual experiment in the same room, or vice versa, they were separated by 4 weeks so participants would have little recollection of their previous answers, not influencing them. The HMD used was Sony HMZ T1P. The 3D immersive view using TriDef was not turned on during this condition – the purpose of the HMD was only to restrict field of view, eliminating any distraction from the surroundings to investigate if results differ from not wearing the HMD.

Figure 2: Left: Room B depth/height virtual image for static experiment. Right: Room B width/height virtual image for static experiment.

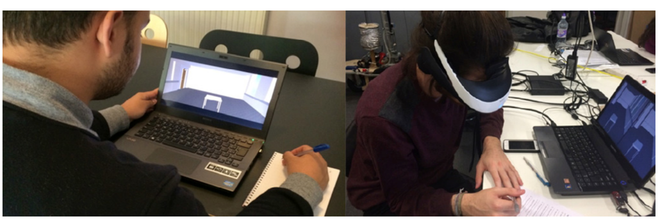

Figure 3: Left: Participant during a virtual experiment looking at the screen. Right: Participant during a virtual experiment wearing an HMD.

At the end of each experiment, the participants were asked to answer a questionnaire about how they felt the space they had experienced. The first part of every questionnaire was about the static condition, followed by a repeat for the moving condition. This was done by asking them how many desks they perceived could fit, side by side or on top of each other, in each of the respective width, depth and height of the room. The position of the desk was constant in both physical and virtual views, and thus used as a measuring unit instead of relying on participants' judgement of size in metres, which might be flawed and inconsistent. The participants were then asked about the whole area: "How many desks in general do you feel can be placed in this room taking into account suitable spacing between them?" Between the two conditions, they were asked about how the movement affected their perception (Bigger, Smaller, Higher, Shorter). The questionnaire was repeated in exactly the same manner with the virtual experiments.

Another important factor to consider was brightness and light contrast of the rooms and its effects on size perception. According to Egusa [15], the perceived depth or distance increases with increased brightness differences. Hence an additional question in each questionnaire was added about the scale of brightness of the environment. The participant was asked to describe the brightness using a numbered scale option (1 for dark, 2 for shadow, 3 for medium light, 4 for bright and 5 for too much light). This was repeated for the static observer and moving observer for all questionnaires and rooms physical and virtual.

After conducting the experiments, the outlier values were determined by running frequency distributions for each group of questions and rooms, for the purpose of eliminating errors and prepare the data for analysis. The results were charted for each room separately including the two conditions for physical world experiment and four conditions for virtual world ones.

4 Discussion of results

Primary results revealed that in control room B, the perception of space decreased from real to virtual representation, in width, depth and overall area and to some extent in height. The only condition where this didn't happen was in the height variable in the static condition of the virtual experiment with the participants using the HMD glasses. The decrease of perception from the real to the virtual world also happened in all experiments in the other two rooms that were not control rooms, but with varying percentages as discussed below. The following figures compare room B (control room) with the room that has almost double of its depth, A, and the room that has half of its width, C.

Comparing the amount of difference in perception, the values 69%, 68% and 56% fidelity were found as indication for the decrease of perception from real to virtual experiments in room A for the width, depth and general numbers of desks, respectively, in the static condition. The same comparison for static observer was found for the room C and the numbers found were 88%, 78% and 71% for the width, depth and general numbers of desks, respectively. The numbers for the control room, B, were 91%, 84% and 88% for the width, depth and general numbers of desks, respectively. Those numbers can indicate that by increasing the depth by almost twice in room A, there was a significant increase in the difference of space perception between Real and Virtual worlds – the virtual was perceived as being much smaller than the real.

However, a much less increase in the difference of space perception between Real and Virtual environments happened when the width was decreased by almost twice in room C. One of the reasons for the general increase in difference of space perception might be because the rooms, A and C, had more of a rectangular ratio to the shape of the room than room B, which was used as control. Hence this increased the depth sensation, making it more difficult to perceive correctly in the virtual state as depth is the dimension further from the eye. However, since room C was much smaller than A, there is a possibility this made it easier to perceive its dimensions correctly, hence compensating for the depth issue and making the difference in perception less. This could indicate that different shapes affect human perception of real and virtual spaces; however this is outside the scope of this research and is one of areas recommended by the author for future work.

Another important factor to eliminate the effect of is the difference in brightness between the physical and virtual room and its effect on difference in space perception between them. According to the results, the average brightness perception was extremely similar for all physical and virtual views of each room.

- Room A: real-life experiment 3.11/virtual experiment no HMD 2.89/virtual experiment with HMD 3.33
- Room B: real-life experiment 3.54/virtual experiment no HMD 3.35/virtual experiment with HMD 3.54
- Room C: real-life experiment 3.17/virtual experiment no HMD 2.83/virtual experiment with HMD 3.04

Because of this high similarity, the influence of this variable was considered low on the difference in perception between real and virtual spaces, although this is recommended for further investigation in future, since the virtual results with no HMD was slightly less.

General results showed that there is a difference between perception of space in the physical and 3D virtual environments, which ranges between a reduction in height from 4%–9%, in width from 9%–31%, in depth from 18%–32%, and in numbers of desks for the whole area from 12%-44%, for the static condition. For the moving condition, the numbers were 3%–7% for height, 5%–25% for width, 16%–29% for depth and 8%–21% for general numbers of desks (figures 4, 5 and 6). Height was the least affected, which contradicts findings by Yoon *et al.* [6] founded in their study, that subjects made more errors in evaluation of height in both the real and virtual environments. This contradiction might be due to possible miscalculations due to human unreliable ability of using metric scales, like the one used by Yoon *et al.* [6] in their study. To counteract this problem, this research used a desk in both worlds, real and virtual, as a cue for the participants and a means to measure dimensions relative to each other. Considering this, the height could have been least affected by the increase or decrease of dimensions because it is the smallest dimension in the room, thus less liable for distortion as indicated in the literature.

The depth was the highest affected variable. This might be because it is the dimension furthest away from the eye, thus might be perceived less accurately. With movement inside the spaces, these ranges became smaller, giving evidence that movement possibly enhances space perception as indicated in the literature

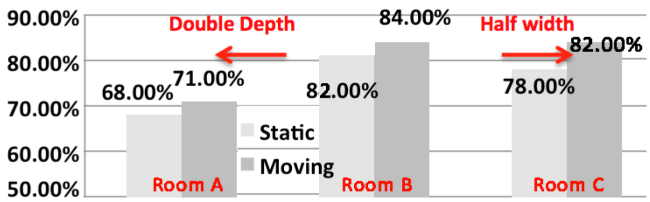

Figure 4: % Perception fidelity from Real to Virtual spaces: depth dimension.

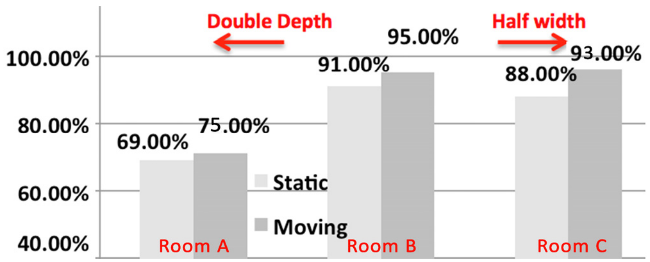

Figure 5: % Perception fidelity from Real to Virtual spaces: width dimension.

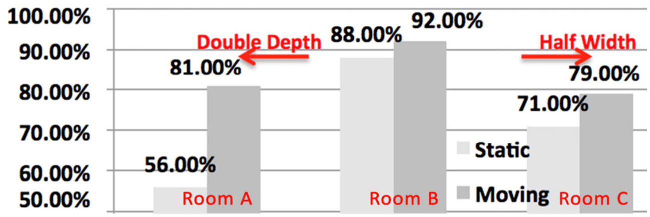

Figure 6: % Perception fidelity from Real to Virtual spaces: overall floor area.

section. The difference in perception for the number of desks that the participants felt could be placed in the room area, involves the combination of two dimensions, width and depth. This merged effect creates a more complex relationship, which needs further investigation.

One final observation was that the results obtained for using the HMD in 3rd person view in the virtual experiments were not significantly different from those conducted without the HMD. Hence there is no apparent effect from restricting the surrounding field of view of participants on perception of the virtual spaces.

5 Conclusion

The goal of this research was to investigate the percentage differences between space perception in the real world and virtual environments. The aim of this was to guide the adjustments needed to improve and evolve this form of space representation, to enhance 3D visualisation of spaces during the design phases of Building Information Modelling and allow more accurate representation of the real spaces, thus ensuring better decision making from clients. The percentage differences in perception uncovered in this research could provide guidance to software developers to include appropriate changes in the visualisation engines of their software to counteract for these differences in perception.

The median values of reduction in perception from physical to virtual space were approximately: 7% in height for the static observer and 5% for the moving observer. These values show that this dimension was the least affected and most accurately perceived. In width, it was approximately 20% for the static observer and 15% for the moving observer. In depth, the least dimension perceived accurately, it was approximately 25% for the static observer and 22% for the moving observer. For general numbers of desks, median reduction in perception was approximately 29% for the static observer and 15% for the moving observer. Movement inside the virtual space using simulations was seen to reduce the percentage infidelity in accurately assessing dimensions of the virtual space.

There are several factors that can be considered for future work: 1) A greater sample of room sizes can be examined to investigate effect of size on perception. 2) Different room shapes and depths can be examined to evaluate their influences on perception 3) A larger number of participants can be used in the experiments with more age ranges, to improve the representation of the overall population of users. 4) Different 3D authoring software can be used to investigate if results change for different software with different photorealistic capabilities, and different brightness/contrast visualisations.

An additional factor outside the scope of the current research is the effect of setting vision to a focal depth at infinity, which can happen in virtual worlds maybe causing eyes to tire while looking for cues in the space – hence affecting perception of space size. This can be investigated in future using filmed views of the real world as control. However this was not done in this research since the author wanted to find the fidelity of perceiving space as clients do so, i.e. directly looking at a 3D model on screen or experiencing it in real-life when built.

An important conclusion to take into consideration here is that it is not sufficient to alter the representation of the whole virtual model equally (e.g. increase the whole volume by a certain percentage). On the contrary, each dimension has to be altered differently by visualisation engines of 3D authoring software, to achieve truthful perception equivalent to reality. Furthermore, results show that underestimating the size increases as the depth increases and overall size of space increases. This is consistent with Henry and Furness [7] assertion that humans size up small rooms more accurately than larger rooms because they can see more of the whole space without distortion. This means that softwares' compensation for dimension representation might also need to differ based on different space sizes, to allow clients better perception of reality.

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