Effects of Detail and Navigability on Size Perception in Virtual Environments

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Abstract: Interior designers and architects using three-dimensional (3-D) computer-mediated design visualization strive to more accurately represent and communicate their designs. Today's 3-D computer-aided design software packages are increasingly powerful yet user friendly in displaying rich details, to the extent of looking photorealistic. It is a common understanding that such high-fidelity 3-D images help improve understanding of the presented content. Increasingly, more design professionals use 3-D visualization techniques and interactive walk-throughs in 3-D virtual environments (VE). But beyond the engaging experience of VEs, little is known about how high-fidelity 3-D VEs can contribute to accurate communication of the design and space. In this paper, we empirically explore the impact of detail level and media format on viewer perception, while focusing on spatial size perception. To test the effects, two levels of detail (low versus high fidelity) and two different graphic formats, (a 3-D still rendering image versus a real-time navigable VE) were compared by a total of 72 participants. A 2 × 2 between-subjects design was used to examine the effects of detail level on viewers' size perception in both the 3-D rendering and virtual environment. Findings from statistical analysis of increased visual cue and navigability effects are presented, as well as their joint effect. Theoretical and practical implications of the present study are discussed for anyone interested in adopting advanced 3-D CAD tools for spatial representation and interior design pedagogy.

Keywords: 3-D Display, Virtual Environments, Size Perception, Architecture, Interior Design

1. Introduction

Ever-advancing three-dimensional (3-D) computer-graphic technology helps architects and interior designers better communicate their ideas and visions. Among the many contributions that 3-D computer graphics have made to the field of architecture and interior design, realistic representation of the design is one of the most significant advantages 3-D graphics offer over conventional rendering techniques, which has a great application in interior design education (McConnell and Waxman 1999). Because accurate and honest representation of the designed environment is the designer's responsibility, 3-D computer graphics can help reduce human errors in transferring 3-D spatial information to the two-dimensional screen as a representation form. It is critical for viewers to have accurate visual information so that they are able to review and evaluate the displayed physical environment. For example, structural elements such as dimensions of the space or placement/orientation of openings are especially critical. Since renderings based on high-fidelity 3-D graphics can look realistic, judgments based on inaccurate visual details and other technical settings can easily mislead the viewer. Some unfortunate consequences can be irreversible once the environment is built.

It has become easier to generate photorealistic 3-D visualization with rich visual details from accurate lighting and sophisticated texture information using readily available 3-D computer-aided design (CAD) tools. While computer renderings of 3-D models remain the most common media format for architects and interior designers, virtual environments (VEs) have been increasingly adopted to provide a more engaging experience with real-time interactivity. Although walk-though animations, made out of a number of renderings, can also provide a lively effect, VEs offer a clear advantage over animations because of the time-consuming rendering and editing tasks. However, extra time and skill are still necessary to develop a dynamic VE from the original 3-D model. Despite the assumption that photorealistic, navigable (or interactive) representations promote spatial perception, little information is available to help designers make

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optimal decisions for 3-D CAD-based visualization formats and essential technical settings. This study focuses on visual details, a key aspect directly related to human perception of spatial scale and distance in any media format. The study also compares two format scenarios: a still rendering image vs. an interactive VE.

To examine if and to what extent richer detail and real-time navigation improve the accuracy of spatial size perception, the experiment was designed with four conditions: two levels of detail and two different visualization forms. The study aimed to understand the relative and joint effects of detail and navigability on spatial perception. The impact of detail level and navigability on spatial perception was tested in a 2 × 2 between-subject design. Findings should be useful to anyone utilizing 3-D CAD tools for design visualization. This study will help develop a knowledge base for architects and interior designers seeking to better understand viewers' perception in 3-D representations.

2. Background

One objective in successful digital representation is to deliver accurate information, including the size and other experiential attributes of the space. There are studies on the difference between the perception of a physical environment and its digital representation experienced in immersive VEs, such as CAVE and a panoramic environment (Mullins and Strojan 2005; Liakata-Pechlivanidou, Zerefos, and Zerefos 2005) or animation (North 2002).

When computer-generated 3-D environments are presented, the human visual system is challenged to integrate the virtual environment on the screen, as well as the frame surrounding the display. If the 3-D image is viewed through a large screen, it can be assumed that the frame will be less noticeable. Objects or spaces of the same physical dimensions can appear to represent different sizes. One reason for this is that the human visual system can take viewing distance into account when judging apparent size (Arnold, Birt, and Wallis 2008). Gestalt theory provides an important insight to understanding the way humans perceive the virtual environment by grouping objects and forming a whole regardless of the parts in the image that is experienced through the retina (Desolneux, Moisan, and Morel 2007). Spatial size perception is also related to distance perception. Although considerable research has been done on distance perception focusing on environmental cues, size perception research has focused on familiarity or has relied on distance information (Haber and Levin 2001). Familiarity effects are based on prior contact or knowledge about the objects. Haber and Levin (1989) argued that distance perception serves very different demands than size perception; distance perception's primary function is to support visually guided locomotion for moving viewers. While size perception is a cognitive process about a physical environment, distance perception is the natural ability to safely move around in the physical environment.

Realism in 3-D visualization can be attributed to many factors, including texture, lighting, shadow and the presence of familiar objects. Higher detail is known to improve spatial understanding (Kalisperis et al. 2006). Affordance judgment is used as a way of gauging the perception of the object sizes in desktop VE and real world settings (Stefanucci et al. 2012). The presence of surface shadow and shading is another parameter that helps spatial perception by providing more information about objects in a 3-D world (Nikolic 2007). McCardle (2002) argues that setting the level of abstraction or simplification is one of the key techniques in designing education curricula for solving architectural and engineering problems. Higashiyama (1977, 1983) conducted studies to investigate the relationship between perceived distance and perceived size across different levels of detail. In these experiments, the viewer was shown squares of various sizes located at a constant distance from him/her and with a high level of detail. The viewers accurately estimated the squares' sizes and also realized that the distance of the standard stimulus was constant. In contrast, under low-detail-level conditions, participants assumed that the squares' sizes were constant, but squares that looked smaller were perceived as being farther away.

During first person exploration of a VE, viewers tend to gain spatial information in much the same way they would a physical environment. Once the 3-D model of a space is developed using a standard CAD tool, several design-representation forms are possible, including still images, animations or VEs. While other forms are one-way presentations, VEs let viewers navigate freely through the space. The term *navigability* in this paper refers to the condition of exploring VEs.

Perception motor theory argues that movement in space enriches one's visual perception and that seeing is almost inseparable from acting (Dember and Warm 1979). When moving through the 3-D world, human perception is based on continuous and ever-changing images rather than on one single image. According to Braunstein (1976), the viewer creates a mental model of the 3-D space through continuous comparison of each momentary view with the one preceding.

Navigability in 3-D VEs emulates the optic flow, resulting in a first person point of view movement in a real-world situation. Palmer (1999) stated that studies in visual cognition say that interactive exploration of space, whether virtual or real, results in greater visual feedback and thus allows better encoding of space. However, the extent to which VE navigability promotes understanding of a displayed space, including spatial size perception, is yet to be discovered.

3. Research Method

3.1. Framework

This study evaluates how the level of detail and navigability in computer-generated visualizations affects the viewer's spatial size perception. Furthermore, this study explores the interaction effect between the two variables' to examine whether navigability could compensate for lack of detail, or vice versa. Based on the literature review in the previous section, the following hypotheses were formulated:

H1: The high level of detail treatment will result in a more accurate spatial perception.

H2: Navigable (VR) treatment will result in a more accurate spatial perception.

A 2 (low vs. high level of detail) × 2 (navigable vs. non-navigable form), between-subjects, full-factorial design was developed for the study. An experiment was conducted in a controlled environment called the Immersive Visualization Lab (iLab) at the University of Missouri. The following paragraphs describe key concepts and operationalization for the present study.

Level of Detail

Three elements in the digital representation were identified as primary factors contributing to high-fidelity computer visualization of interior environments: texture, lighting/shadows and familiar objects with known sizes.

Selected factors that provide primary visual cues for understanding of the space were operationalized as measurable dimensions for high and low levels of detail. The factors selected for the study can be easily controlled by standard 3-D CAD tools to enhance the realism of the represented space. Table 1 summarizes differences between levels of detail in versions of the stimulus.

Table 1: Operationalization of Level of Detail

Low Detail	**High Detail**
	
No texture on objects	Realistic textures
No lighting effect	Advanced lighting (V-Ray photorealistic rendering engine) with ray-traced realistic shadow
People and basic furniture items, including couches and bookshelves, are included.	Books, a piano and a view through windows were added to the high-detail version.

Navigability

In this study, *navigability* refers to the opportunity to interactively explore a digital representation from a first person, egocentric point of view. Navigability was operationalized as whether or not the subjects had the opportunity to interactively explore the virtual environment from a perspective view. In the non-navigable condition, the subjects were presented with a single computer-rendered image of the space. In the navigable condition, the participants had the opportunity to move through the VE from a first person point of view using a joystick.

Size Perception

Spatial perception is operationalized in this study as the accuracy with which a simple object experienced in the real world can be recreated in the virtual environment. Therefore, the relationship between the size of the virtual representation and that of the actual object is used to assess the accuracy of spatial perception. This measurement of spatial perception is based on the operationalization developed by Wagner (2006). In Wagner's size-perception experiment, a "comparison stimulus" (of adjustable size) and a "standard stimulus"(of constant size) are physically present in the lab, and participants are asked to adjust the comparison stimulus until its size appears to match that of the standard. In this setting, the ratio of the perceived size over the actual size is used to analyze the data.

3.2. Experiment

In order to improve the internal validity of the experiment, all possible variables that could confound the study were controlled. These variables include distance from the screen, the place where the standard was located, the way the lab was illuminated during the experiment and the exposure time. Demographic factors such as gender, age, academic major and previous experience with the experiment facility were measured for statistical analysis. The participants were randomly assigned to one of the four experimental conditions. Each experimental run was balanced to ensure that the number of participants was equal in all four conditions, as shown in Table 2.

Table 2: 2 × 2 Between-Subjects Experiment Design for the Study

Level of Detail Navigability	***Low***	***High***	***Total***
Non-navigable (still image)	*n* = 18	*n* = 18	36
Navigable (VE)	*n* = 18	*n* = 18	36
Total	36	36	72

Participants

A total of seventy-two college students enrolled in the architectural studies department of a university in the Midwestern United States were recruited for the experiment (Interior Design n = 33, Architectural Studies n = 37, Others n = 2); fifty-two of the seventy-two were female, and participants' ages ranged from nineteen to thirty. The median height of the group was 5 ft. 5 in. (SD = 3.88 in.). All participants had normal or corrected-to-normal vision and were randomly assigned to one of the four experiment conditions.

Stimuli

For this study, we created a virtual model based on the Korman house by Louis Kahn. The space was modeled in AutoCAD 2009 and 3-D Studio Max 2009 to correspond to the two distinct detail levels. The model was converted into an interactive VR model using EON Reality Studio, a VR authoring software for navigable capability. The stimulus was presented on a large, 2.5 × 1.8-m (8 × 6 ft.) rear-projection screen in the lab. In order to test the effect of navigability, half the participants used a joystick to navigate freely through the space, while the other half of the participants only saw a predefined, rendered view of the room. An unfamiliar object (a green cardboard box) was created as a physical reference model for the size-estimation task. The box was then placed in a corner of the lab, approximately 8 ft. from the participants and 4 ft. from the projection screen (Figure 1).

Procedure

Upon arriving at the lab, participants were greeted and informed of the study procedures. First, a questionnaire on demographic information was administered. Then the participant was led to the experiment area of the lab with a seat in front of a large projection screen. This area was visually separated from the entrance area by a partition. Prior to the experiment, the participants assigned to the navigable condition were given a brief demo session of how to navigate a sample 3-D space while using a joystick. After the demo session was completed, the actual experiment's 3-D VE stimuli was presented to participants for two minutes. After the navigation task, participants were asked to adjust the size of the green box located in the middle of the screen's living room space so it matched the size of the green cardboard box situated in the lab. Participants were able to change the dimensions of the virtual box using the up/down keys on the keyboard in front of them.

After the task was completed, participants were given a post-task questionnaire that included items regarding the variables of the study. Responses were entered using a tablet computer. Upon completion of the experiment, participants were asked not to share its content or procedures with others while data collection was in progress.

Figure 1: The experiment's setting showing the stimulus displayed on screen with the standard and comparison boxes

4. Analyses and Results

In order to answer the primary research question, a series of analyses of variance (ANOVAs) were performed. Hartley's test of homogeneity of variance was used for testing the equality of variances within each group; the result revealed that the data set was homogeneous. A manipulation check ensured that the operationalization of the chosen variables was successful. An independent t-test was performed to check participants' perceptions of the VE's detail level, and the results $t_{tv}(70) = -3.90$, $p \leq .001$ confirmed that participants in the high-detail condition perceived the stimulus as being more detailed (M = 5.83), compared with the low-detail condition (M = 4.54). After scanning the data for outliers, data from two participants were excluded because their responses were more than three standard deviations from the mean. Based on participants' adjustment to the standard stimulus, the SPS index was created: SPS = (|C-S|/S) × 100), where SPS = size perception score, P = size of the comparison, and S = size of the standard.

With a between-subjects design, a factorial ANOVA was performed on participants' SPS. The results are summarized in Table 4. A statistically significant main effect for the level of detail was observed, $F(1, 69) = 8.04$, $p < .01$. Subjects from the high level of detail condition (M = 9.83, SD = 7.58) scored significantly lower (more accurately) than those from the low-level condition (M = 15.66, SD = 10.59). Furthermore, there was a statistically significant main effect of navigability, $F(1, 69) = 11.60$, $p < .01$. Those who were assigned to the navigable condition (M = 9.33, SD = 7.86) estimated more accurately than those in the non-navigable condition (M = 16.35, SD = 10.06).

Table 3: Mean and Standard Deviation of SPS by Condition

	Non-navigable	*Navigable*
Low detail	M = 19.53 (SD = 10.87)	M = 12.00 (SD = 9.15)
High detail	M = 13.18 (SD = 8.31)	M = 6.67 (SD = 5.31)

Table 4: Two-Way Analysis of Variance for SPS

Source	***SS***	***df***	***MS***	***F***	***p***
Detail	597. 00	1	597. 00	8.04**	.006
Navigability (Nav)	861.61	1	861.61	11.60**	.001
Detail × Nav.	4.55	1	4.55	.06	.805
Within	4900.71	66	74.25		
Total	6361.38	69			

* $p < .05$, ** $p < .01$, *** $p < .001$

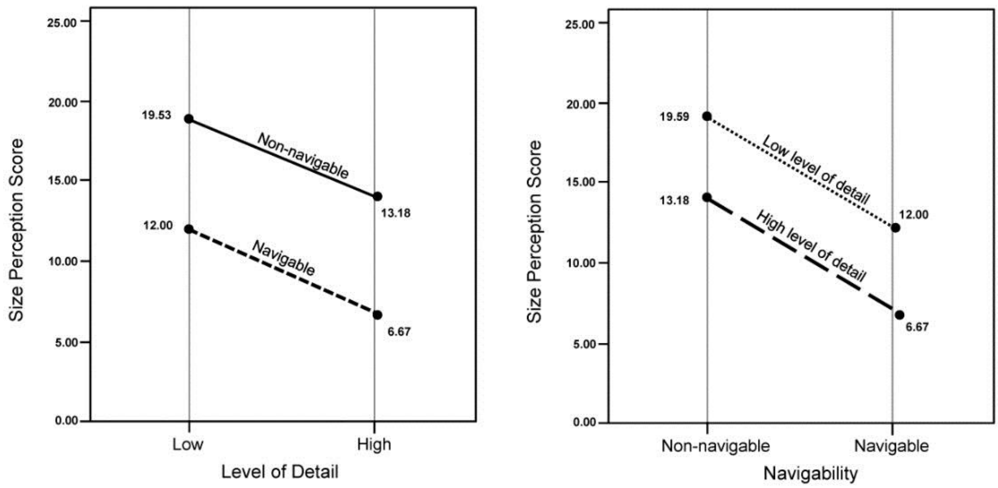

Figure 2: Main Effects: Level of Detail and Navigability

The interaction between level of detail and navigability was not significant: $F(1, 69) = .007$, $p = .936$. Although not statistically significant, the results still indicate that using interactive technology has a significant impact on spatial size perception, comparable to that of realistic rendering, arguing for its use in the architectural design process. Based on the data, the result for the low-detail and navigable group is almost equal to that of the high level of detail and non-navigable group. It reveals that the same level of perception one acquires with a highly realistic static representation can be acquired with an abstract representation of an architectural space, provided one can interact with it from a first person point of view.

5. Discussion

This study demonstrated that highly detailed digital representations, and the ability to navigate through a space, enhances the viewer's accurate judgment of the size of the space. Rapidly advancing computer graphic technology (i.e., photorealism for built or unbuilt environments) has become more accessible for architects and interior designers. Photorealistic computer representations of 3-D objects and environments are now commonplace. We found in this study that photorealism can better communicate accurate spatial understanding with the use of familiar 3-D objects such as furniture, lighting fixtures and cars. The findings show the presence of these objects directly improves size perception. Advanced lighting and rendering engines have become more affordable and are included in most standard 3-D CAD software without having to purchase additional programs. The findings of this study could also be applied to various types of emerging technologies such as Augmented Reality and Holographic displays.

This research shows that high-fidelity graphics using advanced rendering results in a more accurate spatial perception. In addition, objects in building information modeling (BIM) software come with many built-in attributes, including object texture. The findings demonstrate how these attributes help enhance perception. In the early phases of the design when the focus is more often on the form and space than on details and materiality, navigability can act as a very useful feature to improve spatial accuracy and to enhance spatial presence. It is useful to conceptualize design with visualization tools such as spatial-presence enabling tools (Balakrishnan, Muramoto, and Kalisperis 2007). The findings validate simple walk-through features, such as the one in SketchUp, and suggests the usefulness of augmenting modeling tools that lack navigability with VRML (Virtual Reality Markup Language) browsers or plug-ins such as VR4MAX or RTRE to visualize spaces from a first person point of view. In summary, the study validates recent efforts of software companies to improve realism and interactivity by taking advantage of the improvements in graphic processing units, processors and RAM.

This study was a focused effort to examine two factors from a multitude of variables involved in architectural visualization. An evaluation of the findings needs to take into consideration some of the study's key limitations. The first limitation is that of measuring spatial perception, which is a multidimensional construct. In this study, the operationalization of spatial perception was focused on accurately recreating a known object from the physical environment, rather than on explicitly identifying spatial dimensions. Future studies could focus on the impact of detail level and navigability on other dimensions of spatial perception, building on a more specific aspect of spatial perception. In this study, lights and shadows were considered as part of the higher level of detail condition. In the future research, it will be informative to manipulate lighting factors separately to examine the effects of lights and shadows apart from other details.

Another limitation of the study was that each independent variable had only two levels. With two levels, one can identify only the presence or absence of an effect but cannot detect curvilinear effects. The use of more than two levels in each independent variable could lead to finding curvilinear relationships, which can identify any ceiling effect to detail level or navigability, beyond which it fails to improve spatial perception. This understanding will help redirect computing resources to other areas that need improvement. The detail level comprised a number of subcomponents in this study; future studies should take a more nuanced look at the relative contribution of light and shade, textures and so forth in improving spatial perception.

6. Conclusion

The results support the two hypotheses, indicating that both level of detail and navigability result in a more accurate perception of size. However, the interactive effect was not significant, suggesting that a high level of detail cannot compensate for lack of navigability or vice versa. We found that a high level of detail yielded a more accurate size perception compared with the low level of detail. This is consistent with Kalisperis and colleagues' (2006) findings on the impact of level of detail and level of realism on spatial understanding. Our finding also supports Dember and Warm's (1979) theory of cue. The presence of realistic textures, advanced lighting and shadows provided more depth cues and was found to promote size perception in space. Additionally, familiar objects of known size, such as a piano and books, helped improve size judgments with a frame of reference. The results extend the findings of Henry's (1992) study. He stated that experiencing objects in three dimensions helps viewers easily understand the objects. Similarly, Kalisperis et al. (2006) demonstrated that more visual information leads to a more accurate estimation. It is worth noting while a high level of detail could provide useful referencing information for better size perception, high level of detail may also cause an increase in cognitive processing of the additional information.

In this study, the navigable display of space yielded more accurate spatial perception scores. This finding is consistent with the motor theory of perception (Dember and Warm 1979, Gibson

1966), which suggests exploration of space enriches participants' perception in physical environments. According to Welch (1986), viewers try to reduce the discrepancies between the ever-changing frames they are experiencing in a given period by fine-tuning and improving their perception. A recent study by Balakrishnan and Sundar (2011) indicated that even a couple of additional degrees of freedom for movement could enhance a participant's measured spatial situation model and spatial presence, (the sense of being in the 3-D space). The results from the current study also validate such findings. The present study empirically tested two contributing factors (level of detail and navigability) to better understand human perception of digitally represented spaces; this further improves the ability of design students in the process of "abstract modeling" (Wu and Weng 2013). In summary, the results indicate that theories of spatial perception from the real world can be extended to the computer-simulated environment where non-cognitive spatial depth perception is rarely available.

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