VIRTUAL REALITY: FACTORS DETERMINING SPATIAL PRESENCE, COMPREHENSION AND MEMORY

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ABSTRACT: *New advances in 3-D hardware technology have given a boost to the desktop-based approach to building stereoscopic virtual reality (VR) labs such as the iCon lab and the IEL at Penn State and the iLab at University of Missouri. These labs showcase how these new advances can be implemented into an accessible and affordable solution, but still lack evidence on the impact such technology has on spatial understanding. This can be attributed to two aspects: 1) the complexity of VR systems given the number of structural features that collectively comprise a given VR system, and 2) the 'box-centered' approach used by early studies focused on comparing VR to non-VR systems using various media. Our current research builds on a media effects approach to architectural visualization (Balakrishnan & Kalisperis, 2009). Here we take a variable-centered approach to VR technology, identifying its structural aspects (screen size, field of view, stereoscopy etc.) and content parameters (level of detail, level of realism etc.). The advantage is by using a variable-centered approach proposed by Nass and Mason (1990), we can systematically vary these parameters and measure the relative impact on spatial presence and spatial comprehension then, findings from a particular parameter becomes generalizable to another technology that has the same value for the given variable. In our current study, we systematically manipulated field of view (wide/ narrow), stereoscopy (stereo/ non-stereo) and photorealism (photorealistic / hidden line rendering) through a controlled experiment (N=80). Results indicate significant main effects for these technology attributes. The results also reveal trade-offs between parameters which indicate a unique relationship between spatial understanding and each of the variables. These findings are more or less consistent with the Kalisperis et al (2006) study. Theoretical and practical implications are discussed.*

KEYWORDS: *Virtual reality,VR system variables, spatial presence, spatial comprehension, stereoscopy, field of view, photorealism*

1. VIRTUAL REALITY AND VISUALIZATION

Virtual reality (VR) in architectural design and visualization is not a new phenomenon (Campbell & Wells, 1994). The rationale for incorporating virtual reality into architectural design and visualization comes from the ability to experience simulated spaces without having to physically build them. Many of the early explorations of VR systems being incorporated as computing tools for architectural design and visualization were impeded by the technology itself (i.e. slow frame rates, narrow fields of view, etc.). In many cases, the technology was found to inadequately handle the situation necessary for design to occur (Campbell & Wells, 1994). Advances in technology have aided in making VR technology more robust and therefore better able to handle information specific to architectural design and visualization. With the technology improvements over the years, the aspect of the influences of that technology on the context of architectural design and visualization comes into question. Though not specifically focused on architectural design and visualization, Wann and Mon-Williams (1996) explored questions of how VR technology influenced sense of space and spatial perception through specific linkages like depth cues. This leads into the focus of this study, to identify what role newer more affordable virtual reality systems play in architectural design and visualization.

As architectural design and visualization center on the communication of designed space, a better understanding of the influence of VR technology on spatial comprehension and experience measures can provide practical implications on design computing tool development. For instance, one such influence of VR technology could be that of immersion and spatial presence. Campbell and Wells (1994) discussed that immersion worked well in terms of facilitating an understanding of spatial qualities of spaces designed during different stages of the design process. This indicated that immersion could play a role in the understanding of virtual spaces. Following the definition provided by Slater (1999) and later built on by Bowman and McMahan (2007), immersion could be thought of as a direct connection to VR technology, specifically visual immersion. Gaining insights into how the relationship between visual immersion components of virtual reality technology with spatial comprehension and user experience measures could help to establish a better idea of how technology portrays depth cues for spatial perception. This study focused primarily on three areas of visual immersion relating to VR technology: stereoscopy, field of view and, photorealism.

2. A VARIABLE-CENTERED APPROACH TO STUDYING VIRTUAL REALITY TECHNOLOGY

Balakrishnan and Kalisperis (2009) proposed a media effects approach for research on architectural visualization and evaluation, building on Nass and Mason's (1990) variable centered approach to studying technology. In this approach, visualization technologies were conceptualized in terms of their structural and content variables and their impact on cognitive, affective and behavioral responses systematically measured. The variable-centered approach was useful to identify what attributes of a given technology influence the experience and assess their relative contributions. Building on Nass and Mason (1990), we broke down VR into its component variables and the potential values for that variable. Please refer to Balakrishnan and Kalisperis (2009) for a more detailed introduction to media effects approach to assessing architectural visualization technology, and Kalisperis et al. (2006) for an illustration of this approach.

Taking a variable-centered approach, our primary research question investigated the influence of visual immersive technology attributes of a VR system on spatial presence, comprehension and memory. Specifically, the study investigated the question; how do individual technology attributes influence spatial presence, comprehension and memory. In addition to the main question, the study also investigated interactive effects between different technology attributes to identify their relative contributions and identify any potential trade-offs between these attributes. The technology variables of interest primarily were focused on the visual aspects of a VR system. These included: stereoscopy which portrays depth through the overlap of dual projected imagery, field of view which encompasses the area of space the human eye can view at any given time during a simulation, and photorealism which presents simulated material in a manner considered closer to that of reality. Often times, stereoscopy was found and considered important to a VR system and therefore including it as one of the technology variables made sense. Field of view also was a logical choice as all simulations provide a space to view using technology such as screens or head-mounted display (HMD). Lastly, photorealism was a software aspect that had been considered an important goal for visualization since its inception. The inclusion of photorealism would provide insight into how necessary photorealism actually was for visualization.

3. RESEARCH METHODS

3.1 Operationalization of technology variables

Several technology variables were utilized as conditions of the study: stereoscopy, field of view, and photorealism. Each technology manipulation related to a different virtual reality system aspect. All the manipulations were limited to a dichotomous (high-low) presentation to better explore each variable.

Stereoscopy was defined as "a technique for creating the illusion of depth and 3D imaging while presenting a different image to each eye" (Baños R. M., Botella, Rubió, Quero, García-Palacios, & Alcañiz, 2008). Stereoscopy was a binary dimension and was commonly cited as either being on or off (Schuchardt & Bowman, 2007). Likewise, this study also treated stereoscopy as either on (or enabled) and off (or disabled).

Stereoscopy in the literature had given mixed perspectives on its importance towards spatial comprehension and user experience measures. In many cases, stereoscopy was found significant when grouped with other technology manipulations. Bennett, Coxon and Mania (2010) found a positive influence of stereoscopy on memory of objects in a space, but cautioned it was only when the objects were contextually consistent with the space. IJsselsteijn, de Ridder, Freeman, Avons and Bouwhuis (2001) found a significant positive effect on presence especially when the displayed information was in motion. Similarly, Hendrix and Barfield (1995) established a relationship between stereoscopy and presence, determining that added illusion of depth increased a participant's sense of presence. Taking these studies into consideration, stereoscopy was suggested to not necessarily have a direct main effect on the outcome variables. Instead the interaction of stereoscopy with the other manipulations was more preferable for finding significance.

Field of view (FOV) had several operational definitions in the literature, often pertaining to different technologies. As such, this study had chosen to focus on one definition which combined the aspects of screen size and geometric field of view (GFOV). Throughout this study, the two manipulations will be referred to as narrow FOV (defined as a small screen size and a narrow GFOV) and wide FOV (defined as a large screen size and wide GFOV).

Field of view generally refers to the physical field in which a user can see a simulated space. In other words, the screen or monitor and how much of a user's direct and peripheral vision was filled. Humans generally have a specified field of view of 200 degrees horizontally and 170 degrees vertically (Zikic, 2007). Based on the normal field of view for an average human, a virtual reality system should try to match those values using technology through two aspects: 1) adjusting the physical peripheral view of the individual and 2) adjusting the simulated peripheral of the camera. Due to the two needs of simulating field of view in a virtual environment, FOV consists of two mechanisms: display (DFOV) and geometric (GFOV) (Banton, Thompson, & Quinlan, 2001). The differences in the two types lie in what the focus is on. For DFOV, the focus was on the hardware (i.e. the display screen) enabling a virtual environment to encompass a certain portion of a user's field of vision whereas a GFOV represented the software aspect (i.e. the camera view) which allowed the user to see inside the virtual environment. Lastly, it was important to note that when field of view was increased both vertically and horizontally; the amount of screen space enlarges, indicating a relationship with display size.

Hendrix and Barfield (1995) found the GFOV did increase sense of presence as the field of view increased. It was interesting the authors mentioned both the 50° and 90° manipulation together in comparison with the 10° manipulation. This could have been due to the small variation in findings between the 50° and 90° results. This provided some insight into using only a wide-narrow manipulation of FOV as opposed to a series of varying manipulations. Ragan et al (2010) found a wide FOV did significantly improve recall accuracy when dealing with procedural memorization. The authors did note they were surprised to find their hypothesis about wide FOV reducing recall time not being significant. This finding suggested that wide FOV could increase accuracy but possibly not speed of memory.

Lastly, photorealism was also sorted into two manipulations to reduce redundancy in operationalizations: photorealistic and hidden line. The photorealistic manipulation was defined as the render of the 3D space using high quality textures, lighting, and shadows. This manipulation was consistent with various studies also focused on level of realism (Meijer, Geudeke, Egon & Broek, 2009). Hidden line was also the render of the 3D space but without textures and only solid black lines outlining the contours of the shapes within the space. The hidden line manipulation was selected as a definite contrast to the photorealistic render. Meijer et al (2009) found photorealism useful for increasing spatial knowledge within the virtual environment. Slater, Khanna, Mortensen and Yu (2009) found ray-traced rendered environments, a higher level of realism, produced higher ratings of subjective presence. Little to no research was found on the influences of photorealism on spatial memory as related to the operationalizations used in this study.

3.2 Measures for spatial presence, spatial comprehension and memory

Spatial presence was a variable highly linked to user experience and immersion in VR. Several self-report questionnaires existed for capturing spatial presence in virtual environments. In the case of this study, the MEC-Spatial Presence Questionnaire by Vorderer et al (2004) was adapted. Two aspects of the MEC-SPQ were specifically used, self-location and attention allocation, due to a perceived relationship with VR technology. Self-location was defined as the feeling of being located in a simulated space (Wirth, et al., 2007). From this idea came the relationship of self-location with embodiment where, embodiment occured in virtual environments due to sensory engagement on different channels (i.e. vision, hearing, etc.) (Biocca, 1997). Through this connection to visual aspects of technology, the measure of self-location could be explored as a measure of spatial presence while manipulating visual immersion factors of a VR system. Similarly, attention allocation related to voluntary and involuntary attention being given towards some aspect of a virtual environment, usually dealing with spatial cues provided by some aspect of the virtual environment (Wirth et al, 2007). In addition to the spatial presence measures, reality judgment was adapted from Banos et al (2000). Reality judgment dealt with how well the VR technology portrayed the virtual environment to each individual.

Spatial comprehension stemmed from the larger construct of spatial cognition which spanned several concepts including spatial knowledge. Comprehension could be rationalized to deal with understanding and in the case of the concept of spatial comprehension; an understanding of spatial aspects. The measurement of comprehension through a self-report method focused on accuracy of reporting dimensions of objects in relation to one another was a common practice in the literature (Zikic, 2007). For this study, the width, depth and height of the simulated room were used.

We used recall measures to capture the extent to which participants could remember elements from a given architectural space. A free recall task to list the items the participants were exposed to in the given scene. They were also administered a cued recall task, aimed at measuring their recognition of elements in the scene. Here they would indicate “yes” or “no” against a series of images to identify if those elements were indeed in the scene.

3.3 Participants and procedure

Participants for this research (N=85) were recruited from among undergraduate students at the same mid-western university. The average age of the participants was 20.67 years (S.D. = 1.72) and 64 percentage were females. The participants were randomly assigned to one of the eight experimental conditions. They were first briefed about the research procedures and their informed consent obtained. Next, the participants completed a brief questionnaire which captured: demographic information, their computer usage for academic and leisure activities, their familiarity and expertise with various 2D and 3D software, and 11 items measuring their immersive tendencies from the Witmer and Singer (1998) Immersive Tendency Questionnaire (e.g. “How often do you become so involved in what you are doing that you lose all track of time?”). The stimulus based on the experimental condition was then presented to the subject who was allowed to focus on the image for 3 minutes. The participants then completed the spatial presence instrument. Subsequent to this, the participants estimated the width, depth and height of the simulated room for spatial comprehension. The spatial memory of the participants was assessed through both free recall and cued recall tasks. In the free recall task, the subjects listed the items they saw in the room. For the cued recall task, the participants identified items recalled in the room from a set of images of objects. In both recall tasks, the number of correct responses was used as a measure of their memory.

3.4 Stimulus material

The interior of a residential room was used as the stimulus material for this study. Depending on the experimental condition, half of the subjects were presented with a photorealistic rendering and the other half with a hidden line rendering of this room. Please see Figure 1 below for the photo realistic and hidden line renderings. Depending on the experimental condition, the images were presented either in stereo 3D or non-stereo and either in a wide field of view or a narrow field of view. The subjects were seated approximately six feet away from the screen and in the wide field of view, the image extended to their peripheral vision whereas in the narrow condition, it did not.

Fig. 1: Operationalization of high (top) and low (bottom) photorealistic condition.

3.5 Index construction and preparation for data analysis

Immersive tendencies of the participants were measured using an 11-item scale. An immersive tendency index was constructed by averaging the items and showed good reliability (Chronbach’s α = 0.78). Principal component analysis was conducted to analyze the dimensionality of the 19 items measuring different dimensions of spatial presence. Using the scree plot, three factors accounting for 65.79% of the variance were identified. On rotation using the Varimax procedure, 15 of the 19 items loaded clearly on to the three factors with their highest loading exceeding 0.6 and the other two loadings less than 0.4. Four items that cross loaded on multiple factors were excluded from further analysis. The rotated solution captured three factors and three corresponding indices: spatial presence (Chronbach's $\alpha = 0.94$), reality judgment (Chronbach's $\alpha = 0.91$) and attention (Chronbach's $\alpha = 0.81$) were created by averaging the respective items. Before proceeding with statistical analysis exploring the primary research questions, all assumptions, including normality, of the data were verified and confirmed.

4. RESULTS & IMPLICATIONS

Analysis of variance (ANOVA) was carried out to assess the impact of the three VR system variables on the dependent variables of interest in this study. Data pertaining to a number of potential confounding variables including gender, age, academic standing, computer use and experience with 3D modeling tools and gaming were collected among others and used where appropriate as covariates to improve accuracy. The following sub-sections describe the findings with respect to the three dependent variables of interest.

4.1 Spatial Presence

The factorial analysis of variance conducted on presence indicated a significant main effect for *photorealism,* $F(1,76) = 4.75$, $p < 0.05$. Participants who were presented with the photorealistic image reported a greater sense of presence ($M = 3.17$) than those who were presented with the hidden line rendering ($M = 2.51$). The ANOVA also indicated a significant main effect for *field of view*, $F(1,76) = 18.28$, $p < 0.001$. Participants in the wider field of view reported a greater sense of presence ($M = 3.75$) than subjects in the narrow field of view ($M = 2.12$). Results did not indicate a significant main effect for stereoscopy on presence, $F(1,76) = 2.12$, $p = 0.15$. Also, the results did not show any two-way or three-way interactions.

While the overall score for presence across conditions were relatively low, the findings were consistent with the previous results from Kalisperis et al. (2006). Presence is an important aspect of simulating spatial experience and one can conceptualize virtual reality systems as presence enabling technologies. The findings for presence validate current emphasis placed by CAD software developers on photorealistic real-time renderings relying on improved hardware capabilities of the video cards. Earlier, given limited capabilities of graphics cards, improved photorealism often had to be at the expense of interactivity. With ever improving capabilities of graphics cards, highly photorealistic, yet interactive VR environments are possible using desktop based VR systems.

Results for field of view were consistent with results reported by Zikic (2007). Most desktop computers have a narrow field of view and the results from this study indicated the importance of wide field of view in enhancing presence. Designers of virtual reality systems for training and simulation where an increased sense of presence is important must take this into consideration. Where large screen displays are not physically possible due to space limitations, one can rely on head mounted VR systems to achieve an increased field of view.

4.2 Spatial Dimensions

Participants were asked to estimate the width, depth and height of the simulated living room space. The width, depth and height responses were converted to accuracy scores by dividing with the corresponding correct response. A score of 1.0 indicated accurate perception of that dimension. Scores above 1.0 indicated the participant over-estimated the distance and scores below 1.0 indicated under-estimation. When estimating the *width*, results showed a significant main effect for *photorealism*, $F(1,76) = 5.91$, $p<0.05$. The results were counter-intuitive. Participants in both photorealistic and hidden line conditions under-estimated the width of the room. However, those in the hidden line condition were more accurate in estimating the width of the room ($M=0.80$, with 1.0 being 100% accurate) when compared to those in the photorealistic condition ($M=0.63$). When estimating the *depth*, results indicated there were no significant differences between the *photorealistic* and the *hidden line* conditions, $F(1,76)=0.04$, $P=0.85$. Similarly, there were no significant differences between the different levels for *field of view,* $F(1,76)=1.70$, $p=0.20$ or *stereoscopy*, $F(1,76)= 0.23$, $p=0.63$. While estimating *height*, there were no significant main effects, but there were significant interactions between *realism* and *field of view*, $F(1,76)=8.81$, $p<0.01$, as well as between *realism* and *stereoscopy*, $F(1,76)= 6.05$, $p<0.05$. For narrow *field of view*, participants estimated the height more accurately in the *photorealistic* condition ($M=1.16$) compared to the *hidden line* condition (M=1.56). For the wider field of view, the opposite held true. Participants estimated the height more accurately in the *hidden line* condition (M=1.13) compared to the *photorealistic* condition (M=1.39). Please see Figure 2 below for the interactive effect between realism and field of view on height estimation.

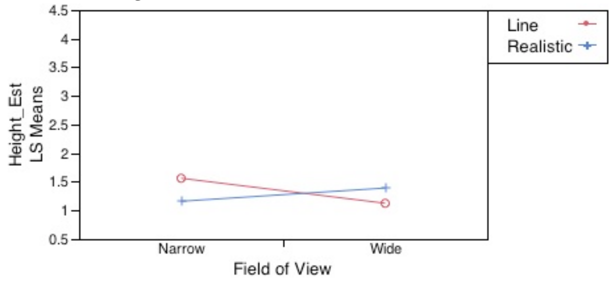

Fig. 2: Interactive effect between realism and field of view on height estimation.

For stereoscopic display, participants in the *photorealistic* condition were more accurate in estimating the height (M=1.19) when compared to those in the *hidden line* condition (M=1.53), who tended to over-estimate much more. For non-stereoscopic display, the opposite results held true. In that case, participants in the *hidden line* condition tended to be more accurate in estimating height (M=1.16) when compared to those in *photorealistic* condition (M=1.37), who tended to over-estimate. Please see Figure 3 below for the interactive effect between photorealism and stereoscopy on height estimation.

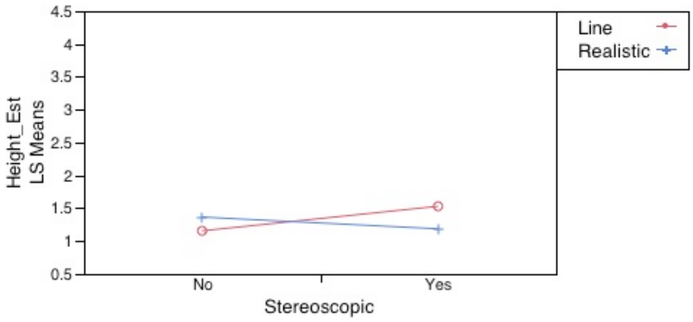

Fig. 3: Interactive effect between realism and stereoscopy on height estimation.

The findings for height estimation, particularly the interactive effects involving photorealism provided some interesting clues into the impact of these system variables on spatial comprehension. When the FOV was narrow, (i.e. when the scale was small), realism improved accuracy, perhaps by providing more spatial cues through texture and detail. However, when the FOV was large, there seemed to be an additive effect of bottom up cues resulting in over-estimation. This suggests the need for elements in VR environments like avatars that will help participants relate to spatial dimensions more easily than relying on more difficult bottom-up cues like that of texture and detail. The interactive effect between stereoscopy and realism indicated that realism was helpful in improving accuracy for stereoscopy; as it resulted in over-estimation of height for the non-stereo condition. This indicated the importance of perspectival depth for accurate height perception. Findings for dimension estimations needs further analysis and follow up research before one can meaningfully discuss implications in depth. We hope to achieve this in our follow up research.

4.3 Memory

For the *free recall* variable, the three way interaction between the independent variables approached significance, $F(1,76)=2.86$, $p<0.1$ indicating the collective influence of those variables. Results also indicated significant main effects for all three independent variables. For free recall scores, there was a significant main effect for *photorealism*, $F(1,76)= 7.35$, $p<0.01$, *field of view*, $F(1,76)=18.55$, $p<0.0001$, and *stereoscopy*, $F(1,76)=4.24$, $p<0.05$. Participants in the *photorealistic* condition recalled more objects from the room (M=13.70) than those in the *hidden line* condition (M=11.62). Similarly, participants in the *wide field of view* condition recalled more objects (M=14.84) than subjects in the *narrow field of view* condition (M=11). The result for stereoscopy was counter intuitive. Participants in the *non-stereo* condition recalled more objects (M=13.93) than in the *stereo* condition (M=11.70).

These main effects should be interpreted in light of significant interactions between *photorealism* and *field of view*, F(1,76)=4.05, p<0.05. For narrow field of view, there was little difference between those in photorealistic condition (M=11.18) and those in the hidden line condition (M=10.54). For wide field of view, participants in photorealistic condition recalled more objects (M=17.00) than those in the hidden line condition (M=12.65). Please see Figure 4 below for the interaction between photorealism and field of view on free recall.

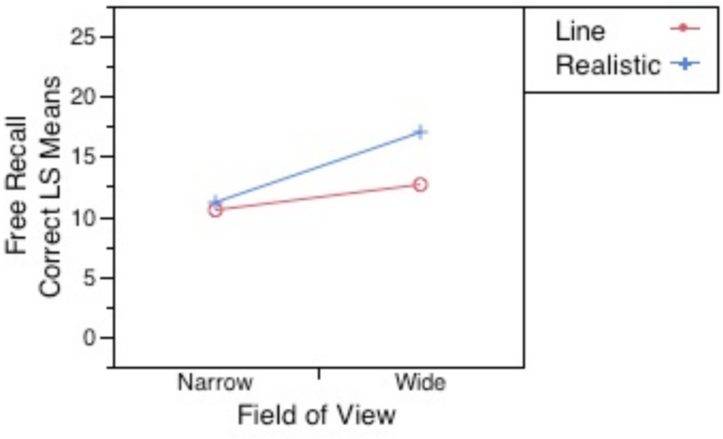

Fig. 4: Interactive effect between photorealism and field of view on free recall.

For *cued recall,* the results were similar to those for *free recall*. A significant three-way interaction between independent variables, F(1,76)=4.97, p<0.05, indicated the combined effect of the three independent variables on cued recall. There was a significant main effect for *photorealism*, F(1, 76)=14.82, p<0.001. Participants in the *photorealistic* condition recalled more objects (M=24.60) from the image list than those in the *hidden line* condition (M=22.14). There was a significant main effect for field of view, F(1,76)=33.94, p<0.0001 and participants in the *wide field of view* condition recalled more objects (M=25.87) compared to those in the (M=21.47). The results also showed a significant main effect for stereoscopy, F(1,76)=6.88, p<0.05, similar to free recall. Participants in the *non-stereo* condition recalled more objects (M=24.63) than those in the stereo condition (M=22.44). The above main effects should be interpreted in light of the significant two-way interaction between *photorealism* and *field of view*, F(1,76)=12.88, p<0.001. For *narrow field of view*, there was little difference in cued recall scores between *photorealistic* (M=21.50) and *hidden line* (M=21.3) conditions. However, for *wide field of view*, participants in the *photorealistic* condition recalled more objects (M=28.7) than those in the *hidden line* (M=23.01) condition. Please see Figure 5 below for the interaction effect between *photorealism* and *field of view* on cued recall.

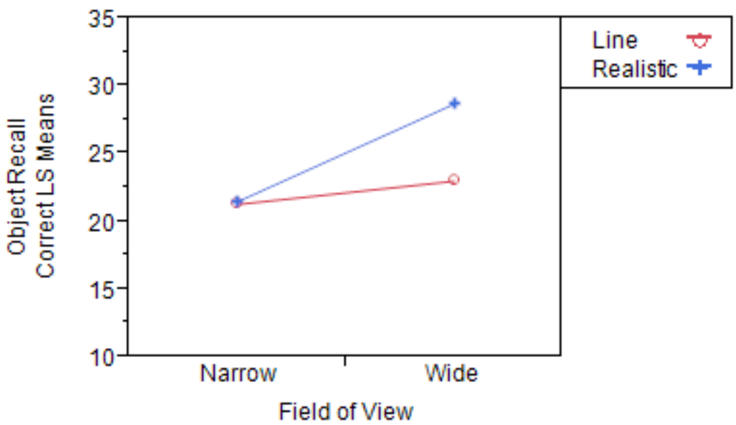

Fig.5: Interactive effect between photorealism and field of view on cued recall.

The above results, particularly the interactive effects, indicated the importance of photorealism in improving memory. While a wider field of view improved memory for objects, photorealism was found to significantly improve memory. Higher realism may have helped participants to easily distinguish between various objects and read them as independent items when compared to the hidden line rendering. This has implications for development of VR environments for simulation and training, particularly those that involve visual search tasks.

5. LIMITATIONS AND DIRECTIONS FOR FUTURE RESEARCH

The majority of the participants in the study was drawn from design disciplines and as such limits the generalizability of the findings beyond that of the design professions. Findings for stereoscopy maybe have been limited by the use of a still image for the stimulus. Since architectural space is best experienced through exploration, we are planning follow up studies which allow participants to interactively explore spaces. We hypothesize this will also enhance self-location and possibilities for action, two dimensions of spatial presence (Wirth et al., 2007). Since many of the findings from Kalisperis et al. (2006) were replicated in this study, independent variables for future research can be operationalized at more than two levels. This would confirm if some of the main effects detected in this research, are indeed linear in nature. This study detected some counter intuitive results, particularly in the case of stereoscopy for recall measures. Future research should further investigate this issue by taking into careful consideration potential explanatory mechanisms and the research design should strive to rule out alternative explanations. Another limitation of this study was the conceptualization and operationalization of photorealism in this study. While the Kalisperis et al. (2006) study looked at realism and level of detail as two separate variables, in this study we focused primarily on realism. It may be more beneficial to operationalize these concepts as the number and type of cues provided. This will allow us to explain and the results building on the vast body of relevant literature related to visual cognition in psychology. Our current research projects are exploring interactive effects of navigational affordances of virtual reality system variables for spatial presence and spatial comprehension.

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