A Comparison of Virtual Reality Displays - Suitability, Details, Dimensions and Space

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Abstract **- It is not uncommon that design and constructability errors are not detected until significant progress has been made in projects. Design and constructability errors have the potential to significantly impact cost, time, safety and quality of a construction project. It is envisioned that Virtual Reality (VR) can enhance communication among stake-holders and allow them to visualize design and constructability errors earlier in the project. This paper evaluates and compares three VR displays to view construction assemblies. The three VR displays compared were the CAVE™, a Head Mounted Display (HMD) and the Immersive Workbench (IWB). This paper presents the VR displays': (1) Suitability to display 3D models, (2) Ability to show details and, (3) Ability to convey dimension and space.**

Index Terms - CAVE™, Construction, HMD, Immersive Workbench, Virtual Reality

INTRODUCTION

Given the complexity of most projects, challenging schedules, diversity of the stakeholders and limitations of the current communication media, design and constructability errors are not detected until significant progress has been made on the project. Design and constructability errors inevitably will have negative impact on cost, time, safety and quality of the construction project. Communication among the stakeholders, starting from the owner all the way to the craftsmen, is often recompiled, misunderstood and miscommunicated. This leads to potential design and constructability errors, which resulted to excessive changes, significant delays, and additional unanticipated costs. This is the challenge of delivering and operating a facility today [1].

Currently, most stakeholders' communication is done through meetings, conversations, text documents, physical models, and 2D electronic and paper drawings. Recently, the use of three-dimensional (3D) models has become more common for visualizing projects and determining how components need to come together. However, their use in construction is still limited to non-interactive applications, with minimal user input.

Virtual Reality (VR) technology, when integrated with 3D models, allows users/stakeholders to view 3D scenes from a first-person or third-person point of view, using natural head and body movements to interact with objects within the virtual environment. The stakeholders could view the VR environment using a variety of displays such as the CAVE™, a Head Mounted Display (HMD) and the Immersive Workbench (IWB). Using these VR displays and VR technology, inexpensive rehearsals of major construction processes can be undertaken, and alternative "what-if" scenarios can be tested, in which can minimize design and constructability errors.

This paper is based on a preliminary evaluation which presents a comparison of three VR displays to view construction assemblies. The three VR displays compared are the CAVE™, a Head Mounted Display (HMD) and the Immersive Workbench (IWB). More specifically, this paper presents the VR displays': (1) Suitability to display the 3D models, (2) Ability to show details and, (3) Ability to convey dimension and space.

VIRTUAL REALITY (VR) DISPLAYS

This work focused on immersive VR displays. In an immersive VR environment, the user becomes completely immersed in a computer generated 3D environment. In this type of VR environment, the user is able to see only the computer generated world. The three types of immersive VR displays used were: 1) the CAVE™, 2) the HMD, and 3) the IWB. According to Browning *et al* [2] these displays share the following key features:

a) 3D computer graphics with real-time interactive control
b) A viewer-centered perspective
c) Panoramic binocular or stereoscopic display with a certain field of view (FOV)

Each of the VR display was coupled with a respective tracking system. The tracker either has 3 or 6 freedom (DOF) to track user's body movements (usually hand and/or head). The tracker then sends out signals to the computer, and the computer will display the corresponding perspective view on the VR display.

I. The Cave Automated Virtual Environment™ (CAVE™)

The CAVE™ is a large surround-screen projection VR display that was developed to overcome the limitation of single-user VR display such as the HMD. It is described as a lifelike cubical shape visual display that is made of 3 to 6 walls of screens on which rear-projected images are displayed using three to six projectors (one for each screen). Figures 1 shows a typical CAVE™ setup.

FIGURE 1
A TYPICAL CAVE SETUP

FIGURE 2
A USER USING THE HMD

The CAVE™ display is able to project life-sized stereo images hence instigating the `Illusion of Immersion' that can be felt by the user [3]. The CAVE™ also supports multi-user, whereby several users can share the VR experience while maintaining visual contact, communicating with each other and naturally moving inside the CAVE™ [4].

While in the CAVE™, the user's head and hand are tracked by two separate tracking systems. The hand tracker is a "wand-like" device with which allows the user to navigate through the 3D virtual world. The head-tracker mounted on the stereo glasses will track the user's head movement and display the correct perspective view.

II. The Head Mounted Display (HMD)

The HMD is the one earliest VR displays to be invented. In 1968, Ivan Sutherland developed the HMD to display computer-generated images [5]. It enables users to completely be immersed in the virtual world. A typical HMD houses 2 miniature displays (screens). The viewer is immersed and completely isolated from the real world and can only see the computer-generated images. In the pilot study the Virtual Research V8 HMD (see Figure 2) with a 640 x 480 resolution and a 60-degree field of view (FOV) was used. The HMD used the IS-900 VET tracking system to track both the user's head and hand. A wand-like device was used to allow user to navigate the in VR environment (similar to the one used in the CAVE™).

III. The Immersive Workbench (IWB)

The IWB is a portable drafting table display developed by Fakespace [6]. It is characterized as a stereoscopic projection-based virtual display that provides a large FOV. Similar to the CAVE™, it is also a multi-user display that supports multiple users viewing at the same time at high resolution, stereoscopic and tracked images [4]. The IWB has an adjustable, rear projected viewing plane made out of frosted glass mounted on a frame (see Figures 3). The plane can be oriented horizontally or at arbitrary angles. A projector displays the computer-generated 3D image onto the viewing plane.

FIGURE 3
A USER USING THE IWB

The user's head is tracked using a Polhemus Fastrak tracker mounted on stereo glasses, so the user can view the 3D model from different perspectives. Another Fastrak tracker is also used to allow the user to rotate the 3D model displayed on the IWB.

DEVELOPMENT OF THE 3D MODELS

Two construction 3D models were developed: 1) A wood-frame house (WFH) shown in Figure 4, and 2) An above-ceiling components (ACC) shown in Figure 5. The 3D models were developed using Autodesk VIZ, an industry-standard software for 3D architectural modeling. It provides a good 3D modeling interface with the capacity to import from and export to various 3D and image file format.

Once the 3D modeling process was completed, the models were saved into the *.3DS file format. The 3DS file format was used due to its stability over the years and it maintains the texture coordinates map assigned to the 3D model's faces. Other file formats such as DXF and DWG formats have undergone version changes, which at times can cause incompatibility during conversion and translation. To view the 3D models using the respective VR displays, the 3D models had to be converted into the Multigen's Open Flight (*.FLT) format using the Polytrans' NuGraf graphics/model conversion software [7]. The FLT format provides polygon optimizations and less prone to geometrical mistranslation.

The evaluation technique used in this study utilized a combination of formative and summative evaluation techniques [8]. The formative evaluation includes observational user studies and post-hoc questionnaires that are designated to solicit users' satisfaction or dissatisfaction of the use of VR displays as an effective tool in teaching building systems. The summative element compares the three VR displays' abilities to display the 3D models in relation to the tasks given to the subjects.

FIGURE 4
WOOD-FRAME HOUSE (WFH) MODEL

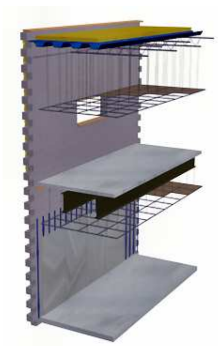

FIGURE 5
ABOVE-CEILING COMPONENTS (ACC) MODEL

METHODOLOGY

Students were used to evaluate the two 3D models (the wood-frame house and above-ceiling components) displayed using the three VR displays (CAVE™, HMD and IWB). A set of questions was designed to collect students' feedback and comments. Results were then compiled and analyzed using SPSS software. A summary of the evaluation process is shown in Figure 6.

The objectives of this preliminary usability evaluation were to assess the effectiveness, suitability and usability of the CAVE™, the HMD and the IWB for displaying 3D construction related models. This paper presents three components of the evaluation: 1- Suitability for training and education, 2- Location Finding, and 3- Interaction Experience.

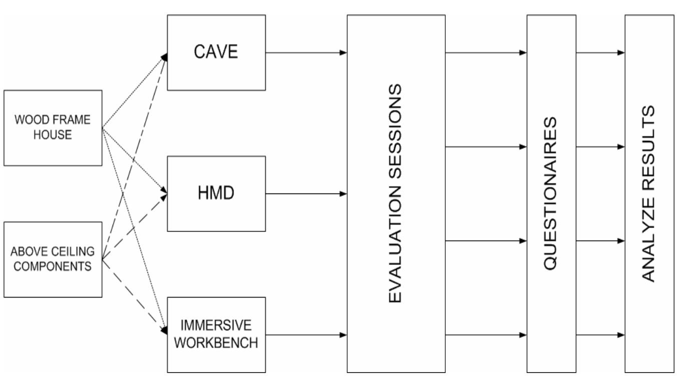

FIGURE 6
OVERVIEW OF THE EVALUATION PROCESS

Results obtained from this preliminary study can be used as guidelines to conduct future evaluations on any VR displays. Evaluations can include personnel from the Architecture/Engineering/Construction (AEC) industry whereby they will perform more complex construction related tasks such as costing, planning, scheduling, training etc, in a VR environment.

I .Evaluation

The evaluation was divided into 3 sessions and in each session users were exposed to each VR display, starting with the CAVE™, followed by the HMD and finally the IWB. In each session, users were asked to perform the following tasks:

- Task 1 - Familiarize themselves with the VR navigation control devices, conduct a closer inspection of the displayed 3D model and understand the relation of the components and general details of the 3D model.
- Task 2 - Navigate through the 3D models and go to a specific location.
- Task 3 - Identify any flaws/errors found in the 3D model. Each 3D model had some errors purposely embedded in the design. In the wood-frame house model there were 5 design errors, and in the above the ceiling model there was 2 design flaws.

II. Users

Demographic information on the users was collected to understand their background and their level of VR exposure/experience. Twenty users participated in the study. The majority of the users indicated that they work well in group settings and are accustomed to working for more than 4 hours a day with computers. Table 1 summarizes users' information.

TABLE 1
USERS DEMOGRAPHIC INFORMATION

Total Users	**20**
Gender	
Male	17
Female	3
Age Group	
18-25	15
26-36	5
Study Level	
Undergraduate	11
Graduate	9
Major	
Building Construction	14
Architecture	6

III. Questionnaires

Questions were designed to elicit subjective responses and used a 5-point Likert scale, where 5 represented the highest rating and 1 the lowest. The questionnaires were divided into three main sections.

- Section 1 was to obtain user's demographic information
- Section 2 was divided into 2 parts and repeated for each VR display. The first part was to allow users to evaluate and rate the VR exposure and/or experience with regards to the tasks performed and the VR display in use. The second part was to solicit the overall rating of VR exposure and/or experience
- Section 3 dealt with the issue of comparing the three VR displays. Users were to rate which of the three best suited the overall task performed and to provide any recommendations for using VR in construction projects. This section also included questions to solicit user's satisfaction or dissatisfaction with the use of VR in construction.

RESULTS AND DISCUSSION

The following sub-sections provide a summary of results for three components of the evaluation: 1- Suitability to display the 3D models, 2- Ability to show details and, 3- Ability to convey dimension and space. The mean of the responses, standard error and correlation values were calculated from each of the questions. These calculations were discriminated by both the displays (CAVE™, HMD, and IWB) as well as the models (WFH and ACC).

I. Overall Suitability

This category dealt with the overall suitability of the three VR displays to display the two 3D models. Figure 7 shows the mean and standard error of the user responses. The squares and triangles represent the means for the WFH and ACC respectively.

It can be observed in Figure 7 that all the means and standard errors are very similar. Figure 7 also shows that the WFH model (which was single-layered, less detailed and relatively large in size) was slightly more suitable (higher means) to be presented on all three VR displays than the ACC (multi-layered and with very fine details). Using the General Linear Model (GLM) Univariate computation it was determined that there was no statistical significant difference between the three VR displays with regards to suitability to present the 3D models. Table 2 shows that all significant values are greater than 0.05. Therefore, the difference amongst the three VR displays observed in Figure 7 was due to random variation.

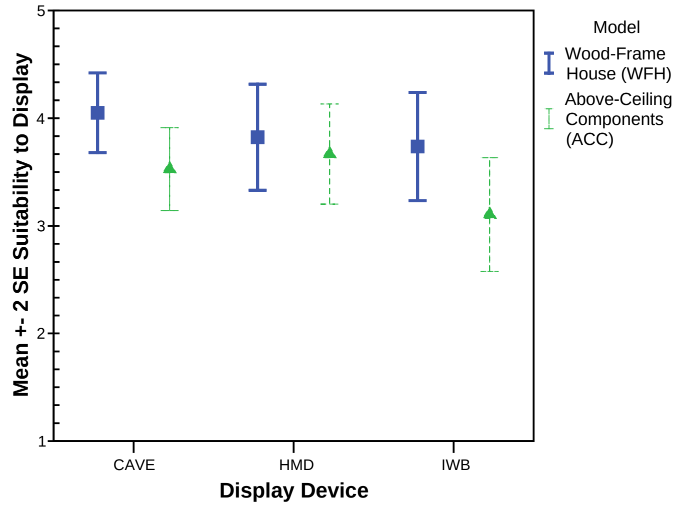

FIGURE 7
SUITABILITY OF THE DISPLAYS TO PRESENT MODELS
MEANS AND STANDARD ERRORS

TABLE 2
MULTIPLE COMPARISONS
REGARDING SUITABILITY OF VR DISPLAYS

Dependent Variable: Suitability to Display

	(I) Display	(J) Display	Mean Difference (I-J)	Std. Error	Sig.
LSD	CAVE	HMD	.04	.24	.851
		IWB	.37	.23	.103
	HMD	CAVE	-.04	.24	.851
		IWB	.33	.24	.173
	IWB	CAVE	-.37	.23	.103
		HMD	-.33	.24	.173
Tamhane	CAVE	HMD	.04	.22	.996
		IWB	.37	.23	.302
	HMD	CAVE	-.04	.22	.996
		IWB	.33	.25	.479
	IWB	CAVE	-.37	.23	.302
		HMD	-.33	.25	.479

Based on observed means.

Although there was no statistical significant difference in the suitability of the three VR displays to display the 3D models, some users commented that the CAVE™ was more suitable that the others. This could be attributed to the CAVE™ ability too produce a large field of view (FOV), so that the sense of immersion is greater. Other users commented that it might be easier to visualize the 3D model if the IWB were tilted at an angle (instead of flat). Some users perceived some improvements in visualizing the 3D model when the IWB was tilted at a 45 degrees angle. Due to its limited FOV and occlusion of the physical world, users felt that the HMD was the least suitable. Finally, users suggested that the overall interaction would be improved if a virtual representation of their hand was implemented.

II. Ability to Show Details

This category is concerned with the ability of the VR displays to show details of the components of the 3D models. Figure 10 shows the mean and standard error of the user's responses regarding the ability to show details of each VR displays. The squares and triangles represent the means for the WFH and ACC respectively.

It can be observed in Figure 8 that the means and standard errors are very similar for the CAVE™ and HMD. However, the IWB has lower means with both 3D models. Furthermore, Table 3 shows that the significant values for the IWB are lower than 0.05 in all cases. Therefore, the IWB ability to show details is statistically significant than the ability of the CAVE™ and HMD to show details.

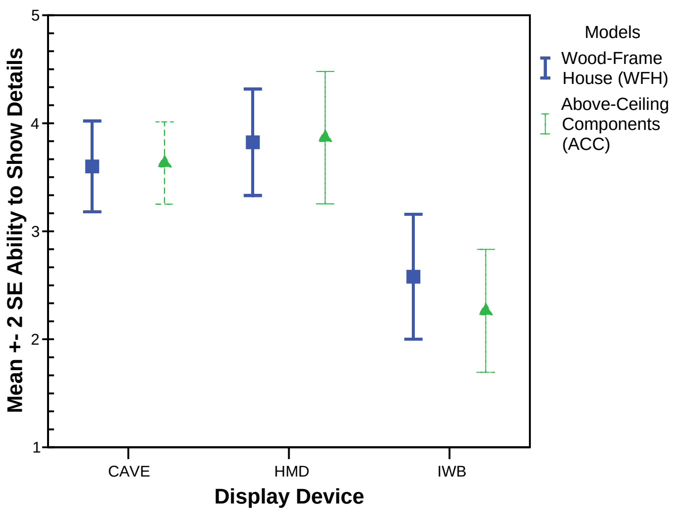

FIGURE 8
VR DISPLAYS ABILITY TO SHOW DETAILS
MEANS AND STANDARD ERRORS

This difference indicates that users were able to see details of the components in both 3D models more clearly when they were using the CAVE™ or the HMD. This could be attributed to the CAVE™'s ability to display the 3D models in true life-sized scale, its larger FOV, and user's ability to view the 3D models more naturally. In the case of the HMD it could attributed to the brighter display than the IWB. Also, similar to the CAVE™, the HMD displays life-sized 3D models.

TABLE 3
MULTIPLE COMPARISONS
REGARDING VR DISPLAYS ABILITY TO SHOW DETAILS

Dependent Variable: Ability to Show Details

	(I) Display	(J) Display	Mean Difference (I-J)	Std. Error	Sig.
LSD	CAVE	HMD	-.23	.26	.376
		IWB	1.19(*)	.25	.000
	HMD	CAVE	.23	.26	.376
		IWB	1.42(*)	.26	.000
	IWB	CAVE	-1.19(*)	.25	.000
		HMD	-1.42(*)	.26	.000
Tamhane	CAVE	HMD	-.23	.24	.712
		IWB	1.19(*)	.25	.000
	HMD	CAVE	.23	.24	.712
		IWB	1.42(*)	.28	.000
	IWB	CAVE	-1.19(*)	.25	.000
		HMD	-1.42(*)	.28	.000

Based on observed means.
* The mean difference is significant at the .05 level.

III. Ability to Perceive Dimensions and Space

In this category, users were asked to rate their perception of dimension and space of the 3D models in the VR environment. In this study perception of dimension was defined as being able to approximately estimate the length, width and height of the components present in the 3D models. Perception of space was the ability to feel whether an area within the models was adequate in spatial size to place other objects.

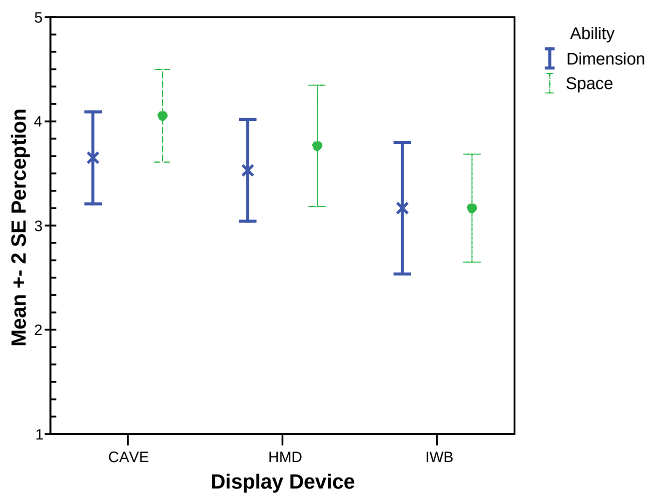

FIGURE 9
PERCEPTION OF DIMENSIONS AND SPACE WITH DISPLAYS
MEANS AND STANDARD ERRORS

Figure 9 shows the mean and standard error of the users' responses regarding the perception of dimensions and space with each VR display. The crosses and circles represent the means for the dimension and space respectively. It can be observed in Figure 9 the CAVE™ has the highest mean values for the perception of dimensions and space.

Table 4 shows that all significant values are greater than 0.05. Therefore, the difference amongst the three VR displays observed in the Figure 9 was due to random variation, hence no statistical difference amongst the VR displays with regards to perception of dimensions. However, Table 5 shows that the significant values for the IWB with respect to the CAVE™ are lower than 0.05 in all cases. Therefore, the perception of space of the IWB is statistically significant to the perception of space of the CAVE™. This might be possible because the 3D models in the CAVE™ were displayed in true life-sized, while the 3D models in the IWB were presented at a miniature scale.

TABLE 4
MULTIPLE COMPARISON
REGARDING PERCEPTION OF DIMENSIONS WITH DISPLAYS

Dependent Variable: Perception Dimensions

	(I) Display	(J) Display	Mean Difference (I-J)	Std. Error	Sig.
LSD	CAVE	HMD	.12	.37	.746
		IWB	.48	.36	.190
	HMD	CAVE	-.12	.37	.746
		IWB	.36	.38	.343
	IWB	CAVE	-.48	.36	.190
		HMD	-.36	.38	.343
Tamhane	CAVE	HMD	.12	.33	.977
		IWB	.48	.39	.524
	HMD	CAVE	-.12	.33	.977
		IWB	.36	.40	.750
	IWB	CAVE	-.48	.39	.524
		HMD	-.36	.40	.750

Based on observed means.

TABLE 5
MULTIPLE COMPARISON
REGARDING PERCEPTION OF SPACE WITH DISPLAYS

Dependent Variable: Perception Space

	(I) Display	(J) Display	Mean Difference (I-J)	Std. Error	Sig.
LSD	CAVE	HMD	.29	.36	.432
		IWB	.89(*)	.36	.017
	HMD	CAVE	-.29	.36	.432
		IWB	.60	.37	.111
	IWB	CAVE	-.89(*)	.36	.017
		HMD	-.60	.37	.111
Tamhane	CAVE	HMD	.29	.37	.823
		IWB	.89(*)	.34	.041
	HMD	CAVE	-.29	.37	.823
		IWB	.60	.39	.352
	IWB	CAVE	-.89(*)	.34	.041
		HMD	-.60	.39	.352

Based on observed means.
* The mean difference is significant at the .05 level.

CONCLUSIONS

This preliminary study has provided important information with regards to the three VR displays evaluated. It was found that there is no statistical difference amongst the CAVE™, HMD and IWB with regards to their suitability to present the 3D models. It was also found that the CAVE™ and HMD were better than the IWB to show details and to perceive space. The results from this preliminary study can serve as a reference for construction stakeholders in deciding the suitable VR display to be used for visualization of construction activities, for the purpose of reducing design and constructability errors.

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REFERENCES

[1] Beliveau, Y., Cakir, O. and Rodriguez, M., "A Graphical/Geometric (Visual) Common Language for the AECO2 Process", *Proceedings from the Specialty conference on Fully Integrated and Automated Project Processes – ASCE Computing in Civil Engineering*, Sept. 26-28, 2001.

[2] Browning, D., Cruz-Neira, C., Sandin, D., Defanti, T. and Edel, J., "Input Interfacing to the CAVE by Person with Disabilities", 1994. Available at: http://www.evl.uic.edu/EVL/RESEARCH/PAPERS/DREW/sun9f.html

[3] Cruz-Neira, C., Sandin, D. and DeFanti, T., "A. Surround-screen projection-based virtual reality: the design and implementation of the CAVE", *International Conference on Computer Graphics and Interactive Techniques*, Proceedings of the 20th annual conference on Computer graphics and interactive techniques, 1993.

[4] Czernuszenko, M., Pape, D., Sandin, D., DeFanti, T., Gregory, D. and Maxine D., "The ImmersaDesk and Infinity Wall Projection-Based Virtual Reality Displays", Published in May 1997 issue of Computer Graphics. Available at: http://www.evl.uic.edu/pape/CAVE/idesk/paper.

[5] Sutherland, I., "A Head-mounted Three Dimensional Display", *Proceedings of the Fall Joint Computer Conference*, pp. 757-764, 1968.

[6] AVD, "Advanced Visualization Solutions". Last visited on: April 2006. Available at: http://www.fakespace.com/

[7] Polytrans, "Polystrans" Last visited on: April 2006. Available at: http://www.polytrans.com/

[8] Hix, D., Edward Swan II, J., Gabbard, J., McGee, M., Durbin, J. and King, T., "User-Centered Design and Evaluation of a Real-Time Battlefield Visualization Virtual Environment", *Proceedings of IEEE Virtual Reality*, pp. 96-103, 1999. Available at: http://ieeexplore.ieee.org/iel4/6131/16390/00756939.pdf