

A Comparative Study of Virtual Reality Displays for Construction Education

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Abstract - In many construction building systems courses, two-dimensional (2D) diagrams are used in text books and by the instructors as teaching aid. This conventional approach may not be sufficient enough to convey the actual representation of the building system. It can lead to confusion and misunderstanding to students who are particularly new to the subject matter in hand. Research has suggested that a Virtual Reality (VR) environment can be an effective educational tool to enhance the understanding and educational experience of AEC students. There are a number of VR displays that are used by both commercial and academic institutions. However, to date the characteristics of the VR displays that relates to the suitability for teaching and learning building systems are yet to be compared. This paper presents a study to evaluate and compare three VR displays 1) CAVE™, 2) Head Mounted Display (HMD) and 3) Immersive Workbench (IWB) that can be used to assist training and education.

Index Terms - CAVE™, construction, education, HMD, Immersive Workbench, training, Virtual Reality

INTRODUCTION

Building systems are interdependent components that comprise a building such as structural, roofing, side wall, plumbing, HVAC, water, sanitary sewer and electrical systems. Building systems are the building blocks of all construction projects. Therefore, it is common that engineering and construction management programs to include building systems as part of the curriculum. It is also common that two-dimensional (2D) diagrams, textbooks and elements of a building system are used by the instructors as teaching aid. This conventional approach may not be sufficient enough to convey the actual representation of the building system, and can lead to confusion and misunderstanding to students who are particularly new to the subject matter in hand.

Studies have suggested that Virtual Reality (VR) environments could be used as an effective educational tool to enhance the understanding and educational experience of AEC students [1]. The use of interactive three-dimensional (3D)

models (e.g. to depict the construction assembly of wood-frame structural building) displayed on a VR display can be used to assist teaching and learning. Instructors and students can experience real-time interaction with realistic 3D objects. However, the use of VR environments in construction education is still limited. Furthermore, the suitability of VR displays for teaching and learning building systems has not yet been fully evaluated.

This paper is based on a preliminary evaluation and presents a comparison of three VR displays that can be used to teach building systems. The VR displays compared were the CAVE™, the Head Mounted Display (HMD) and the Immersive Workbench (IWB). More specifically, this paper presents the VR displays' comparison in three areas: 1) Suitability for training and education, 2) Location Finding, and 3) Interaction Experience.

THE VIRTUAL REALITY (VR) DISPLAYS

There are two types of VR environments; immersive and non-immersive. This study focused on immersive VR environments. In immersive VR environment, the user becomes completely immersed in a computer generated three-dimensional (3D) world.

The three immersive VR displays evaluated were: 1) the CAVE™ (CAVE Automated Virtual Environment), 2) the Head Mounted Display (HMD), and 3) the Immersive Workbench (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 displays was connected to 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. CAVE Automated Virtual Environment (CAVE™)

The CAVE™ is 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). Due to its size, the user is able to be inside the CAVE™ and interact with the VR environment. Figure 1 and Figure 2 shows an image of a typical CAVE™ display and a user interacting in a CAVE™.

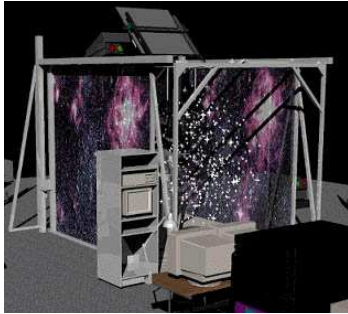


FIGURE 1
A TYPICAL CAVE™ SETUP



FIGURE 2
A SUBJECT IN CAVE™

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 either houses one or two miniature CRT, LCD, or OLED displays with magnifying lenses embedded in a helmet, glasses or visor. In a two displays HMD, slightly offset images are displayed to each eye to give a stereoscopic view. The lenses in the HMD are used to give the perception that the images are coming from a greater distance and to prevent eye strain. HMD display is usually mounted with a head tracking device hence allowing the user to "look around" a VR environment more naturally by simple moving the head and without the need for a separate controller.

In this study the Virtual Research V8 HMD (see Figure 3) 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 in the VR environment (similar to the one used in the CAVE™).



FIGURE 3
A SUBJECT USING THE HMD

III. The Immersive Workbench (IWB)

The IWB is a portable drafting table like display developed by Fakespace [5]. In general, the IWB is characterized as a stereo projection-based virtual display that provides a large field of view (FOV). Like the CAVE™, the IWB also supports multiple users. The IWB has an adjustable, rear projected viewing plane made out of frosted glass mounted on a frame (see Figures 4 & 5). The plane can be oriented horizontally or at arbitrary angles. A projector projects the 3D computer-generated images onto the viewing plane.



FIGURE 4
THE IMMERSIVE WORKBENCH



FIGURE 5
A SUBJECT
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 6, and 2) An above-ceiling components (ACC) shown in Figure 7. 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 [6]. The FLT format provides polygon optimizations and less prone to geometrical mistranslation.



FIGURE 6
WOOD-FRAME HOUSE (WFH) MODEL



FIGURE 7
ABOVE-CEILING COMPONENTS (ACC) MODEL

METHODOLOGY

The evaluation technique used in this study utilized a combination of formative and summative evaluation technique [7]. 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.

Student subjects 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 were 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 8.

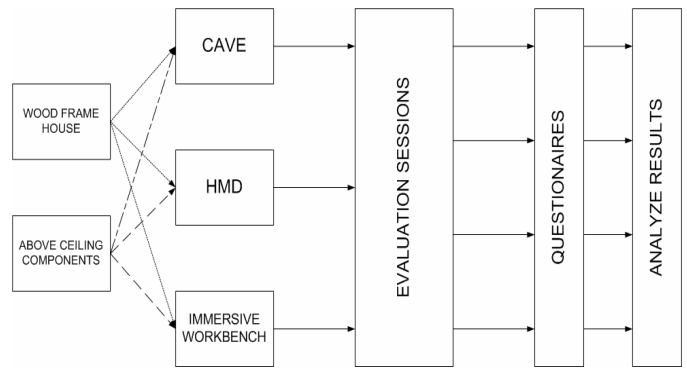


FIGURE 8
OVERVIEW OF THE EVALUATION PROCESS

The objectives of this preliminary usability evaluation were to access 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.

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 the subjects were exposed to each VR display, starting with the CAVE™, followed by the HMD and finally the IWB. In each session, subjects 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. Subjects

Demographic information on the subjects was collected to understand their background and their level of VR exposure/experience. Twenty subjects participated in the study. The majority of subjects indicated that they work well in group settings and are accustomed to working for more than 4 hours a day with computers. *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 subject’s demographic information
- Section 2 was divided into 2 parts and repeated for each VR display. The first part was to allow subjects 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. Subjects 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 subject’s satisfaction or dissatisfaction with the use of VR in construction.

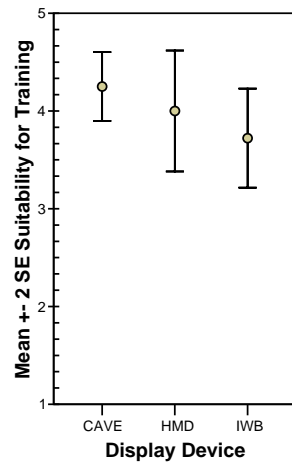
RESULTS AND DISCUSSION

The following sub-sections provide a summary of results for three components of the evaluation: 1- Application to training and education, 2- Navigation and Error-Finding, and 3- Interaction Experience. The mean of the responses, standard error and correlation values were calculated from each questions. These calculations were discriminated by both the VR displays (CAVE™, HMD, and IWB) and the 3D models (WFH and ACC).

I. Suitability for training and education

This section describes the suitability of the VR displays for application to visual training and education. Figure 9 shows the mean and standard error of the subject’s responses regarding suitability for training of each VR display. The circles represent the means and the ends represent two standard errors from the means.

It can be observed in Figure 9 that all the means and standard errors are very similar. 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 for training”. As shown in Table 2, since the significance value of the Levene’s test is 0.574 which is greater than 0.10, there is no reason to believe that the equal variance assumption among the groups (CAVE™, HMD, IWB) is violated. Therefore, the difference between the three VR displays observed in the Figure 9 was due to random variation.



Display	N	Mean	Std. Error of Mean
CAVE	20	4.25	.18
HMD	17	4.00	.31
IWB	18	3.72	.25
Total	55	4.00	.14

FIGURE 9
SUITABILITY FOR TRAINING
MEANS AND STANDARD ERRORS

TABLE 2
LEVENE’S TEST OF EQUALITY OF ERROR VARIANCES(A)
REGARDING SUITABILITY FOR TRAINING

Dependent Variable: Suitability for Training			
F	df1	df2	Sig.
.562	2	52	.574

Tests the null hypothesis that the error variance of the dependent variable is equal across groups

Figure 10 shows the mean and standard error of the subject’s responses regarding “suitability for education” of each VR displays. The circles represent the means and the ends represent two standard errors from the means. It can be observed in Figure 10 that all the means and standard errors are again very similar.

Table 3 show the significance value of the Levene’s test of 0.455 which is greater than 0.10. Therefore, again there is no reason to believe that the equal variance assumption among the groups (CAVE™, HMD, IWB) is violated and it can be stated that the difference between the three VR displays observed in the Figure 10 was again due to random variation.

Although that there was no statistical significant difference in the “training and education suitability” of the three VR displays, some subjects preferred the CAVE™ as compared to the HMD and IWB because they believe that the CAVE™ displayed life-sized 3D models that can easily be inspected, hence enabling them to address the issue of building constructability. Subjects commented that by using the CAVE™, life-sized 3D virtual prototypes can be created instead of constructing physical mock-ups.

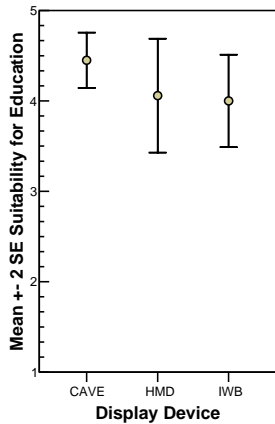


FIGURE 10
SUITABILITY FOR EDUCATION
MEANS AND STANDARD ERRORS

Display	N	Mea n	Std. Error of Mean
CAVE	20	4.45	.15
HMD	17	4.06	.31
IWB	18	4.00	.26
Total	55	4.18	.14

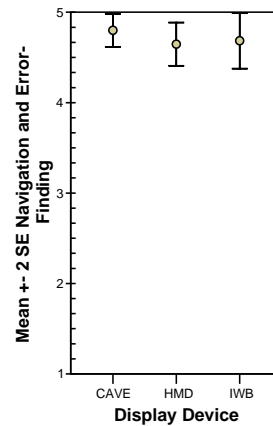


FIGURE 11
FINDING LOCATIONS USING
MEANS AND STANDARD ERRORS

Display	N	Mean	Std. Error of Mean
CAVE	20	4.80	.09
HMD	17	4.65	.12
IWB	19	4.68	.15
Total	56	4.71	.07

TABLE 3
LEVENE'S TEST OF EQUALITY OF ERROR VARIANCES(A)
REGARDING SUITABILITY FOR EDUCATION

Dependent Variable: Suitability for Education			
F	df1	df2	Sig.
.799	2	52	.455

Tests the null hypothesis that the error variance of the dependent variable is equal across groups

Table 4 show the significance value of the Levene's test of 0.167 which is greater than 0.10 and there is no reason to believe that the equal variance assumption is violated. Therefore, the difference between the three VR displays observed in the Figure 10 with regards to finding the specified locations was due to random variation.

TABLE 4
LEVENE'S TEST OF EQUALITY OF ERROR VARIANCES(A)
REGARDING FINDING LOCATIONS

Dependent Variable: Finding Locations			
F	df1	df2	Sig.
1.851	2	53	.167

Tests the null hypothesis that the error variance of the dependent variable is equal across groups

The issue of education using VR environment is interesting. Despite technical limitations, a VR environment is the most effective form of information technology for providing multi-sensory experience that includes visual, auditory, and to some extent haptic/tactile cues. These features may allow for learning with the opportunity to reflect on actions and strategies to improve performance. A study by Bowman *et al* [8] has shown that VR can enable students/users to learn and understand information better than when using conventional methods of learning. In our study, some subjects indicated that they preferred the IWB over the HMD for education purposes because the IWB provides an overview of the 3D model (similar to a miniature physical model) and allows multiple viewers to look at the same 3D model together.

II. Location Finding

One of the tasks assigned to the each subject was to find a specific location in the wood-frame house model (e.g. go to the garage, the bathroom, the living room etc). Subjects were given a 2D plan as a reference. Subjects were asked regarding the ease of finding the specified location in the VR environment.

Figure 11 shows the mean and standard error of the subject's responses regarding the finding of specific locations using the three VR displays. In this category, the mean responses were CAVE™ = 4.80, HMD = 4.65 and IWB = 4.68 (see Figure 11).

However, although that there was no statistical difference amongst the VR displays, some subjects indicated that in the CAVE™, they were able to find the designated locations with less difficulty because of the life-sized display, larger FOV and ease of use of the navigation device. Meanwhile in the IWB, it was also easy to find the locations because of the bird-eye-view perspective (or outside-in view) of a smaller scaled 3D model. In the IWB and with the wood-frame-house model being displayed, instead of navigating through the 3D model, subjects can just reached out and directly pointed to the specified location. In the HMD, with a limited FOV and the feeling of confinement, some subjects expressed that it was somewhat less easy to find the locations.

III. Interaction Experience

This section described the overall interaction experience in the VR environment. The main focus of this was the sense of spatial presence ("being there") and involvement (concentration on the models and the given tasks). Figure 12 shows the mean and standard error of the subjects' responses in relation to the suitability of each VR displays to display the

3D models. The squares and triangles represent the means for the WFH and ACC model respectively.

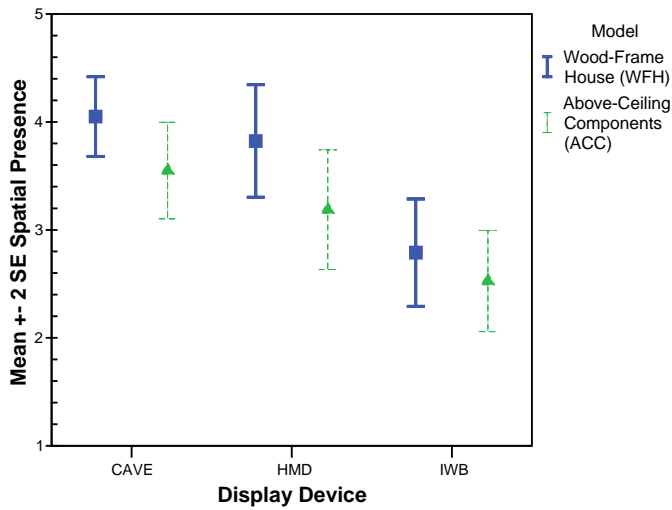


FIGURE 12
SPATIAL PRESENCE
MEANS AND STANDARD ERRORS

It can be observed in Figure 12 that the means and standard errors are very similar for the CAVE™ and HMD. However, the IWB has lower means for both 3D models. Furthermore, Table 5 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.

The CAVE™ was able to provide the best sense of presence, where subjects felt that they were actually part of the VR environment, and also ensured that the perceived experience was interpreted as being real. The CAVE™’s characteristics of having a larger FOV, better navigation interface and larger physical space for subjects to move around (10’x10’x10’) were the contributing factors why most subjects preferred the CAVE™. Subjects were also able to focus best in the CAVE™. Focusing allowed subjects to interact more efficiently with regards to the tasks given in VR environment and hence instigated the sense of presence.

It can be observed in Figure 13 that all the means and standard errors for involvement are very similar. Furthermore, Table 6 show a significance value of the Levene’s test of 0.986 which is greater than 0.10. Therefore, there is no statistical significant different amongst the VR displays and the small difference observed was due to random variation.

TABLE 5
MULTIPLE COMPARISONS
REGARDING SUITABILITY OF VR DISPLAYS

Dependent Variable: Spatial Presence					
	(I)	(J)	Mean	Std.	
LSD	Display	Display	Difference (I-J)	Error	Sig.
	CAVE	HMD	.28	.24	.237

	IWB	1.14(*)	.23	.000	
HMD	CAVE	-.28	.24	.237	
	IWB	.86(*)	.24	.001	
IWB	CAVE	-1.14(*)	.23	.000	
	HMD	-.86(*)	.24	.001	
Tamhane	CAVE	HMD	.28	.25	.578
	IWB	1.14(*)	.23	.000	
HMD	CAVE	-.28	.25	.578	
	IWB	.86(*)	.26	.004	
IWB	CAVE	-1.14(*)	.23	.000	
	HMD	-.86(*)	.26	.004	

Based on the observed means.

* The mean difference is significant at the 0.05 level.

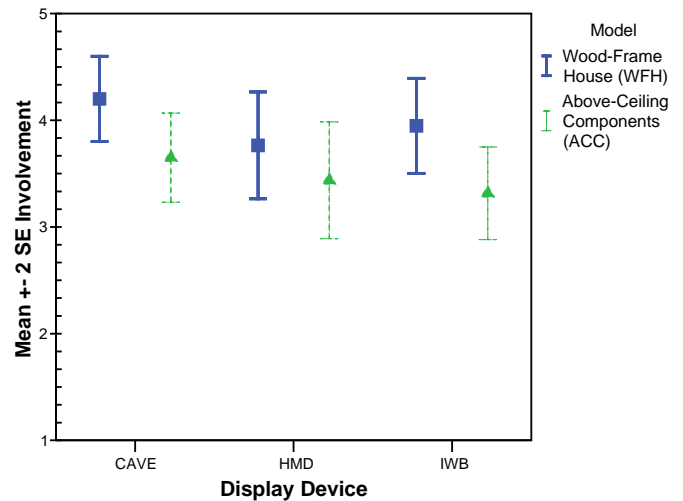


FIGURE 13
INVOLVEMENT
MEANS AND STANDARD ERRORS

TABLE 6
LEVENE’S TEST OF EQUALITY OF ERROR VARIANCES(A)
REGARDING INVOLVEMENT

Dependent Variable: Involvement			
F	df1	df2	Sig.
.126	5	105	.986

Tests the null hypothesis that the error variance of the dependent variable is equal across groups

The state of involvement was actually the subjects’ own psychological state of experience resulting from a direct focus and attention in the VR environment. Subjects, who gave more attention, found that they were more involved in the VR environment and hence increased their sense of presence.

Although there was no statistical difference amongst the VR displays, some subjects indicated that the IWB produced better involvement ratings than the HMD. This could be possible because subjects experienced the sense of being in control of the 3D models. Since subjects them had either architecture or construction background, they were used to ‘doll-house’ type models, hence the 3D models shown on the IWB produced a very similar experience.

CONCLUSIONS

This preliminary evaluation provided worthy of noting information regarding the VR displays for Construction Training and Education. It was found that the suitability for training and education of CAVE™, HMD and IWB were not statistically significantly different. The small difference among the means of CAVE™, HMD and IWB is attributed to random variations. Similarly, it was found that there is no statistical difference among the CAVE™, HMD and IWB for finding locations within the VR environment. Finally, it was found that the CAVE™ and the HMD were better than the IWB to create the sense of spatial presence.

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