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A Comparative Analysis of Visualization Methods in Architecture: Employing Virtual Reality to Support the Decision-Making Process in the Architecture, Engineering, and Construction Industry

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Abstract: The design process of the built environment relies on the collaborative effort of all parties involved in the project. During the design phase, owners, end users, and their representatives are expected to make the most critical design and budgetary decisions—shaping the essential traits of the project, hence emerge the need and necessity to create and integrate mechanisms to support the decision-making process. Design decisions should not be based on assumptions, past experiences, or imagination. An example of the numerous problems that are a result of uninformed design decisions is "change orders", known as the deviation from the original scope of work, which leads to an increase of the overall cost, and changes to the construction schedule of the project. The long-term aim of this inquiry is to understand the user's behavior, and establish evidence-based control measures, which are actions and processes that can be implemented in practice to decrease the volume and frequency of the occurrence of change orders. The current study developed a foundation for further examination by proposing potential control measures, and testing their efficiency, such as integrating Virtual Reality (VR). The specific aim was to examine the effect of different visualization methods (i.e., VR vs. construction drawings) on, (1) how well the subjects understand the information presented about the future/planned environment; (2) the subjects' perceived confidence in what the future environment will look like; (3) the likelihood of changing the built environment; (4) design review time; and (5) accuracy in reviewing and understanding the design.

Key words: Virtual reality, construction change orders, architectural visualization, decision making process, construction management, construction technology, interior environmental design.

1. Introduction

The modern approach of the Architecture, Engineering, and Construction (AEC) industry is devoted to the technical, functional, and aesthetic aspects of the built environment. Its central focus is not only the building construction, but also the human interaction with the surrounding environment. Architectural projects move from a macroscopic scale to the microscopic scale, from the planning of the built environment in general, to specific settings according to specific disciplines and needs. Architectural design starts with vision, moves to concepts, and then actual spatial formations. Successful architects always rely on the synthesis of theory and practice, in other words, scientific research and practical experience. Each architectural project is unique in concept, design, and construction, and this complexity and uniqueness of architectural projects makes it almost impossible to

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complete any project without change orders. Change orders are the result of a combination of factors triggering a deviation from the original scope, or a change in design during the construction phase. Architectural projects include several phases, from strategic planning to the building commissioning. The main parties involved in a construction project are usually the owner, the design professional, and the contractor. These major players often face situations where they must make critical design decisions. Most of the important design and financial decisions are made prior to completing and issuing the construction documents. Some of these decisions are made based on assumption, personal experiences, and imagination. Regardless of the nature and complexity of construction projects, they typically share a common denominator known as “change orders”. In this study, change orders are defined as any deviation from the original scope of work during the construction phase that may result in an increase of the overall cost and construction schedule of the project. It is of utmost importance for owners and end users to understand the design of their future built environment. In this context, VR (virtual reality) has emerged as new technology that holds great potential to improve and facilitate the building construction delivery process. VR is seen by many experts as the ultimate tool for improving communication between designers and other parties involved in construction projects. The benefit of VR lies in its ability to enhance communication to facilitate the decision-making process in building design. VR provides a great opportunity to facilitate communication during the design process in order to help participants better understand and identify any emerging problems, thereby simplifying and expediting the decision-making process with regard to future environments [1, 2]. Several studies regarding VR applications (e.g. [1-6]) have shown that VR helps parties with different backgrounds and design expertise who are involved in a project to coordinate their perceptions as well as their understanding of the project.

2. Method

2.1 Study Design

The study employed a post-only, control group research design where the control group was exposed to only traditional Construction Documents (CD), whereas the experimental group was exposed to both CD and a VR environment. The study answered the research questions by comparing the responses of 107 participants using multiple quantitative data analysis techniques. A between-group experiment was conducted to explore differences between the CD and the CD+VR groups by examining the effect of the two different Visualization Methods (VM) on:

(1) How well the subjects understand the information presented about the future/planned environment.

(2) The subjects’ perceived confidence in what the future environment will look like.

(3) The likelihood of changing the built environment.

(4) Design review time.

(5) Accuracy in reviewing and understanding the design.

The current study addressed the following questions:

(1) Which of the VMs provide a higher understanding of the future built environment?

- What is the effect of different VMs in terms of understanding the following interior design elements: spatial dimensions; interior finishes; furniture layout; and interior spatial layout?

(2) Which of the VMs has a higher potential to increase the client’s perceptual confidence about making critical design decisions about the interior environment?

- Which of the VMs has a higher potential to increase the client’s perceptual confidence about making critical design decisions regarding the following interior environment components: interior environment spatial dimensions, interior finishes, and furniture layout?

(3) Which of the VMs has a higher potential to decrease the likelihood of design changes during and/or after construction?

(4) What is the effect of VMs on the design review

time?

(5) What is the effect of VMs on accurately reviewing and understanding the proposed design?

It was assumed that the participants' results on the traditional CD, administered before the introduction of the experimental manipulation on the CD and VR group, would be essentially equivalent across both groups due to the random assignment of participants to both conditions.

The experiment adhered to the following conventions/steps: (a) two groups were formed following a random assignment of participants to each group; (b) participants in both groups were exposed to the same set of CDs. VR was administered to the treatment group in addition to the CD; (c) data were collected using a survey questionnaire measuring participants' perceptions, a time recorder, and a MCQ (multiple choices questionnaire) for accuracy; and (d) the collected data were compared between the two groups to identify any significant differences to ensure that the experiment was done with integrity/fidelity. Study variables are presented in Table 1.

2.2 Study Variables

Table 1 Study variables.

Independent variables	Definition		Measurement
Construction documents Nominal/categorical	Floor plans, elevations, and 3d perspectives that show the relationships between different spaces, spaces, and other physical features of the environment. Plans and elevations included dimensions to specify room sizes. Floor plans also included details of furniture, fixtures, and equipment.		0/1
VR Nominal/categorical	An environment that is produced by a computer based on the architectural plans and seems very like reality to the person experiencing it through an immersive HMD (head mounted display).		0/1
Dependent variables			
Design decision perceptual confidence Ordinal	Theoretical: Someone's level of confidence placed in his or her impression about making critical design decisions about something or someone. Operational: Participant's level of confidence placed in his or her impression about making critical design decisions about their future space and especially about: spatial dimensions, interior spatial layout, furniture layout, and interior finishes.		0 to 10 with 0 being least confident and 10 most confident.
Level of understanding Ordinal	Theoretical: extract meaningful information from the visual display, process information, and integrate these elements into a comprehensible mental representation. Operational: participant's level of understanding of spatial dimensions, interior spatial layout, furniture layout, and interior finishes.		Ranking and 3-point Likert scale
Perceived likelihood of change Ordinal	Theoretical: Perceived likelihood of change orders. Operational: The participant's perceived probability level that he or she will change one or more of the built environment's design properties during or after construction.		Ranking of the VM and 0 to 10 range.
Task performance accuracy Continuous/ratio	Theoretical: Exactness or precision of the performed task. Operational: Out of the five design element identification questions, how many are correct/accurate/exact?		
Time Continuous/ratio	Theoretical: The measured period during which an action, process, or condition exists or continues. Operational: Time period in minutes during which each participant is tested for responding to the interior environment components questions with one of the VMs.		
Demographic variables			
Gender	Age		Education level
Descriptive and "covariate" variables			
Professional background	Experience in using VR	VAs (visualization abilities)	Proficiency in reading and understanding architectural plans
AEC	0-10	5-point Likert scale	5-point Likert scale
Do the users have any background in Architecture, Engineering, and Construction?	Exposure to VR prior to the experiment	The ability to visualize and imagine the real environment just by studying the Construction Documents	Degree of understanding architectural and engineering plans and symbols

2.3 Subjects

Participants were recruited through a convenience sampling strategy. Students, faculty, and staff from an R1 large public University, located in the southwest region of the United States were approached for participation through electronic communication in daily news announcements. Volunteering subjects were contacted for the experiment time and location. Those with vision impairment were excluded. An agreed upon time was scheduled for the selected participants to come to the lab and undergo consent, and then undertake scripted tasks. Participation was voluntary, and subjects were free to withdraw at any time. The final sample size was 107. Participants ranged in age from 18 to 74. There were 60 participants in the

CD+VR group, and 47 participants in the CD group. Participants in the CD+VR group were 58% males and 42% females. Of the participants, 50% indicated that they were exposed to VR, but only 13% had used VR during the design phase of a construction project. Additionally, 17% of the participants were high school graduates, 48% were undergraduate students, 32% were graduate students, and 3% reported having a professional degree. Their mean age was 37. Participants in the CD group were 33% males and 67% females. Of the total number of participants, 56% indicated that they were exposed to VR, and 59% had experience with architectural plans during the design phase of a construction project. In addition, 10% of the participants were high school graduates, 53% were undergraduates, 27% graduates, and 10% with professional degrees. Their mean age is 32.

2.4 Instruments

2.4.1 VR Model

The VR Model was developed based on the architectural plans of the University Health Sciences Center new and expansion buildings. The project was under construction at the time of data collection and scheduled for substantial completion in the same year. Design diagrams and massing models that depict the basic design concept for the project were presented to the participants, including plans, elevations, and 3D models. The proposed project sites for the construction are identified in Fig. 1 below as the Conference Center. The Health Sciences Center is located west of the campus, and it consists of several buildings, including a library, an academic classroom building, and a medical pavilion for physicians, among others.

The Conference Center, represented in Fig. 2, is located north of the academic classroom building. The Conference Center is intended to provide meeting and event space for the Health Sciences Center. The building's conceptual design intent was to be welcoming and inviting donors and visitors by providing upper end finishes. Within the building the design intent was to provide an ease of flow for guests entering the pre-function area directly from the main lobby. The pre-function area was designed to provide an easy transition to the main event space, with the support spaces being located out of the public/guests' view.

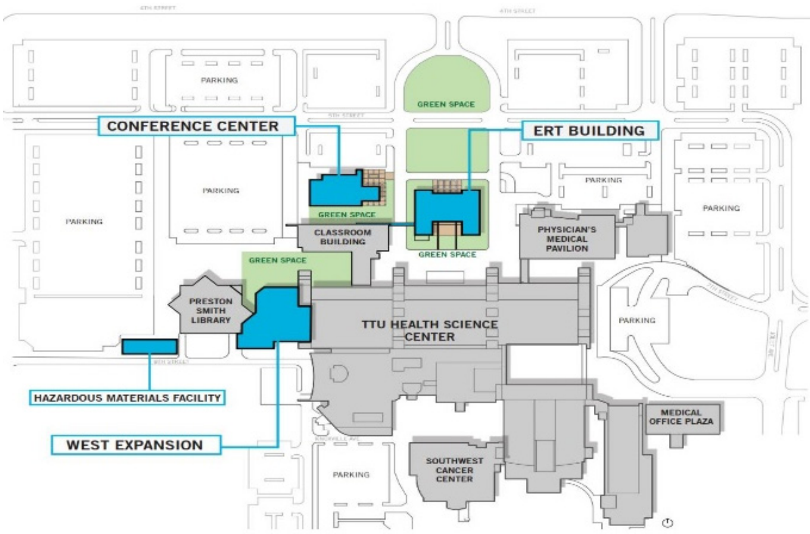

Fig. 1 University medical center and academic event complex.

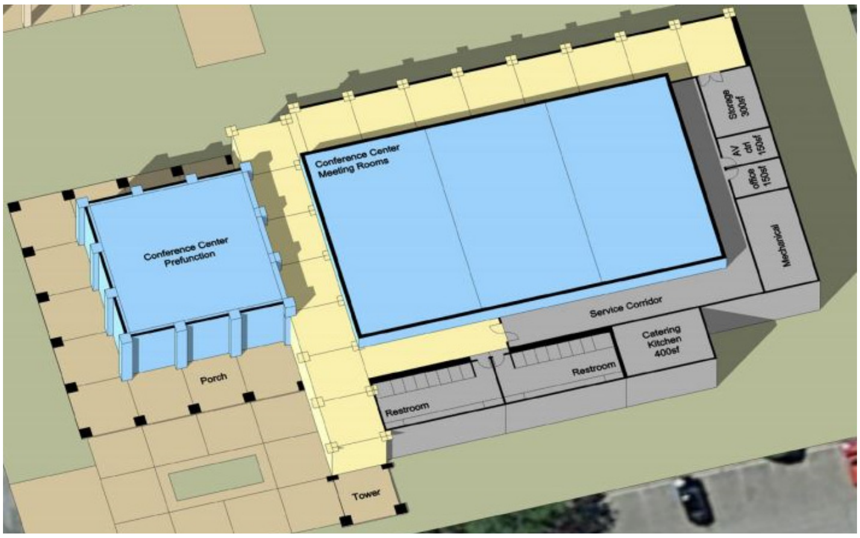

Fig. 2 Expanded view of the Conference Center.

2.4.2 VR Stations

The virtual model was displayed on an OLED Oculus Rift station with a 2,160×1,200 pixels resolution, a 110° field of view, and three 8×8 tracking area sensors, with a manual motion controller. All Head Mounted Displays were connected to the computers with the following characteristics: NVIDA GeForce GTX 960, Intel Core i3-6100, and 8GB RAM. Some of the VR renderings are shown below in Figs. 3 and 4.

2.4.3 CD

The CDs along with 3D massing models and perspectives were presented on an ANSI E 34”×44” hard copy as shown in Fig. 5.

2.4.4 Perception Survey Instrument

The survey was comprised of five different sections to assess understanding of the design, confidence in making design decisions, likelihood of change to the built environment, design review time and accuracy, and finally participants’ demographic information. The survey was developed based on the literature review findings, industry professionals’ input, and decision makers in professional entities. The survey was reviewed and checked for clarity by AEC and non-AEC professionals as part of the general research validity verification. Qualtrics was used as a data collection tool.

Fig. 3 VR rendering of the Conference Center interior guest space.

Fig. 4 Rendering of Conference Center interior support spaces.

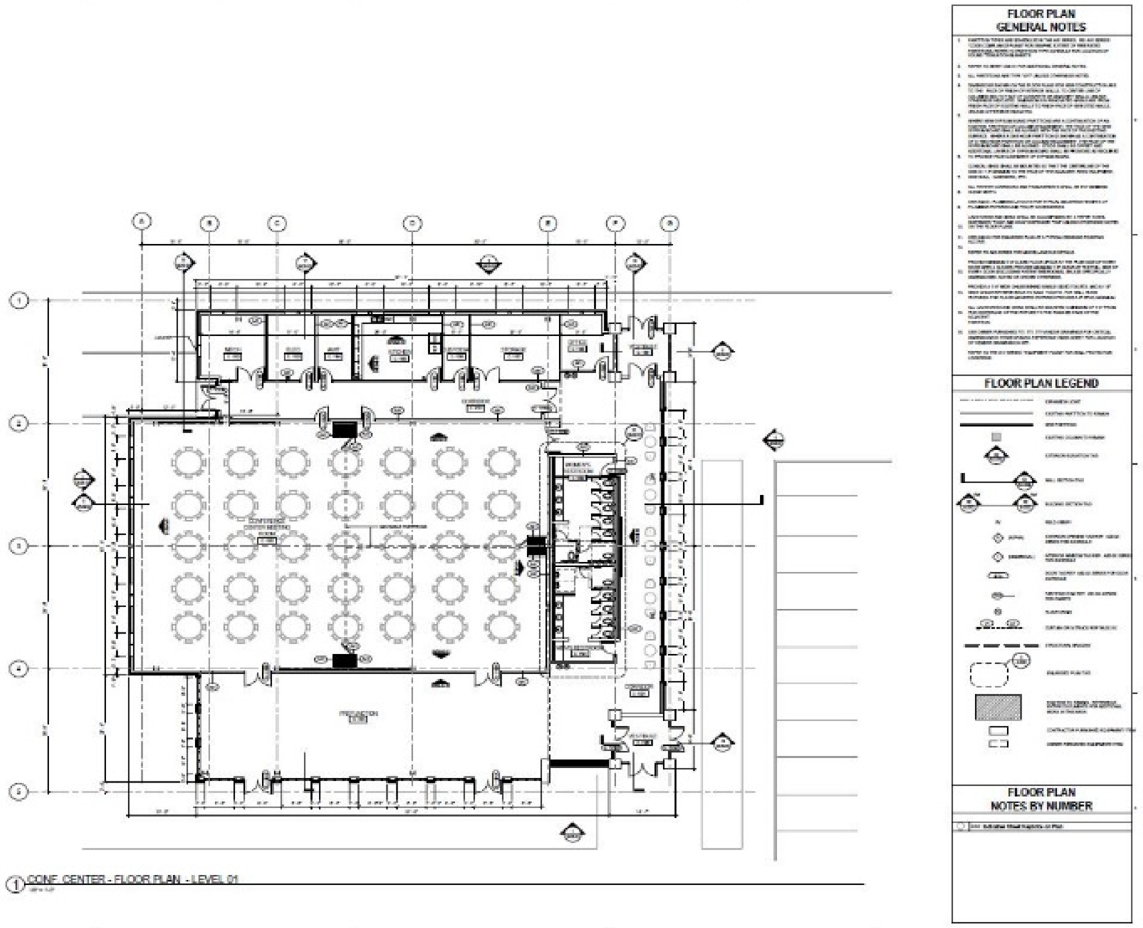

Fig. 5 Conference Center CD.

2.5 Procedure

The experiment took place at a university library. The VR/AR (Virtual and Augmented Reality) Lab at the University was provided through a generous federal grant. The VR/AR lab includes six OLED Oculus Rift stations with 2,160×1,200 pixels resolution, a 110° field of view, and three 8×8 tracking area sensors for each station, with a manual motion controller. Head Mounted Displays were connected to the computers. The lab is available to all students, faculty, and staff to conduct research using this emerging technology. The VR/AR Lab is located on the second floor of the University library, its adjacency to the 3D lab makes it strategically located for convenience and ease of use, especially for students and researchers so they can simultaneously work on their 3D models and visualize them in the same vicinity. After setting up the VR station and the CD, a pilot test was run to ensure proper functioning of the instruments. On the experiment day, and upon arrival at the lab, each participant read and signed the consent form. Participants were given a detailed description of the experiment and with what they would be tasked. After they were familiarized with the equipment and procedure, each subject was assigned a participation number that was used for tagging all data. Each participant in the control group was asked to examine the CD and give a confirmation sign when they reached a good level of understanding of the design. The control group participants were then asked to answer the questionnaire. Time was recorded through Qualtrics as an integrated part of the questionnaire and attached to each participant's response. The same procedure was followed with the treatment group. The survey started with a detailed description of the experiment's procedure along with the consent for voluntary participation. Participants were informed that the research investigates the use of different VMs and their implication in the decision-making process during the design phase of architectural projects. They were asked to evaluate different VMs (VR and CD), and told that the evaluation would be completed through a short survey. Participants had the choice to stop answering questions or mapping at any time. Participants were also informed of the potential risks associated with VR environments such as dizziness, seizures, eye or muscle twitching, or blackouts triggered by light flashes or patterns, and that this may occur while they are watching TV, playing video games or experiencing VR, even if they have never had a seizure or blackout before, or have no history of seizures or epilepsy. Such seizures are more common in children and young people. In the case of experiencing any of these symptoms they were urged to discontinue use of the headset and notify the researcher. No personally identifiable information was collected. Participation was completely voluntary. All information gathered in the survey remained confidential and anonymous, and neither identity nor contact information were retained for any publication. Upon completion of the experiment, each participant was thanked and rewarded with a $5 Starbucks card.

2.6 Limitation

The population of interest for this study was the "owners" and/or the "end users" of the building, because they are the ultimate design decision makers, and the primary party responsible for change orders. However, due to limited time and resources, it was decided to hire participants from a conveniently accessible population, which was comprised of students, staff, and faculty from the University. This research scope is limited to the interior architecture discipline; all the research variables were related to the interior environment as shown in Table 1.

2.7 Statistical Analysis

The statistical analysis results followed the sequence of the research questions, and each question was targeted with the most appropriate analytical technique for examination. Analytical techniques included non-parametric tests, ANOVA (analysis of variance), and regression models, as appropriate.

2.7.1 Contribution of VM to Overall Understanding of the Design

Understanding of the design was conceptualized as the combined measure of the following survey questions:

- Construction Documents Group Q8: To what extent did you feel the architectural plans help you understand how the real interior environment will look?
- VR + Constriction Documents Group Q11: To what extent did the use of both the VR model and the architectural plans help you understand how the real interior environment will look?

In order to determine the contribution of the VMs to the overall understanding of the presented interior environment, a series of statistical tests were conducted. First, a Chi Square was used to detect any significant association between the two groups regarding their understanding of the presented interior environment. Second, a Kruskal-Wallis test was used to assess significant differences between the two groups in terms of their understanding of the presented interior environment. Third, Ordered Logistic Regression was performed to predict the level of understanding of the interior environment with a set of other independent variables, such as the AEC background.

2.7.2 Contribution of VM on Ranking a Building's Interior Environment Components by Perceived Importance

In order to test the effect of VM on ranking a building's interior environment components by perceived importance, a Chi Square test was performed to test for any significant associations between the type of VM and the rank of each interior environment component. The building interior environment components are: Spatial Dimentions, Interior Finishes, Furniture Layout, and Interior Spatial Layout, and are ranked from most to least important, with four being the most important and one being the least important.

2.7.3 Contribution of VM to the Perceived Confidence Levels when Making Critical Design Decisions

Perceived confidence in making critical design decisions was conceptualized as the combined measure of two survey questions:

- Construction Documents Group Q10: In general, how confident would you be about making critical design decisions after being exposed to the architectural plans of the space during early design stages?
- Construction Documents + VR Group Q17: In general, how confident would you be about making critical design decisions after being exposed to both the architectural plans and the VR model of the space during the early design stages?

In order to determine the contribution of the VM to the perceived confidence levels in making critical design decisions about the interior environment, a univariate analysis of variance (Factorial ANOVA) was conducted. The Factorial ANOVA had two independent variables, the first independent variable was the VM, with two levels: CD+VR or just CD. The second independent variable was the VAs of the participants with three levels: below average, average, and above average. The VA was selected as an independent variable as they emerged as a statistically significant contributor to the perceived confidence levels in pre-data analysis. The Factorial ANOVA permitted testing for any significant differences between the two levels of the main predictor variable (VM), while controlling for the secondary predictor variable (VA). It also allowed measurement of the contribution, or the effect size of each predictor variable in the overall model. The Factorial ANOVA was followed by a Tukey's post hoc test to report any significant differences between the different levels of the VAs regarding the measured levels of confidence.

2.7.4 Contribution of VM to the Participants' Perceived Confidence Levels in Making Critical Design Decisions about the Interior Environment Components

In order to determine the contribution of the VM to the participants' perceived confidence levels in making critical design decisions about the following interior environment components—interior environment spatial dimensions, interior finishes, and furniture layout—a univariate analysis of variance was conducted. The Factorial ANOVA had two independent variables: the first is the VM with two levels: CD+VR or just CD. The second was the AEC background with two levels: those with AEC background or those with no AEC background. The AEC background was selected as an independent variable as it emerged to be a statistically significant contributor to the perceived confidence levels in pre-data analysis.

The Factorial ANOVA permitted testing for any significant differences between the two levels of the main predictor variable VM, while controlling for the secondary predictor variable AEC. This technique also allowed measurement of the contribution, or the effect size of each predictor variable in the overall model. A

Factorial ANOVA was conducted to compare the main effect of VM and the interactive effect between VM the AEC background variable on perceived confidence levels in making critical design decisions about interior environment components. The VM included two levels, CD+VR and CD only, and the AEC background consisted of two levels: those with AEC background or those with no AEC background.

2.7.5 Effect of VM on the Likelihood of Change to the Built Environment

The likelihood of change was conceptualized as the combined measure of two survey questions: To examine the effect of VM on the reported likelihood of changes to the built environment after or during construction after being exposed to one of the VM methods, ANOVA was conducted between the two groups of participants. The independent variable was VM with two levels: CD+VR, or CD only. The dependent variable was the likelihood of change, measured from 0 to 10, with 0 being extremely unlikely and 10 being extremely likely.

2.7.6 Effect of VM on Design Review Time

The questions for this variable appeared as follows in the surveys:

Q1. How many exit signs are there in the meeting room: 2, 4, or 5?

Q2. What is located on the opposite wall of the accessible toilet fixture in the men's restroom: lockers, urinals, or hangers?

Q3. How many double doors are there in the meeting room: 1, 3, or 5?

Q4. Are the double doors in the meeting room: fully glazed, or solid?

Q5. How many ceiling mounted projectors are there in the meeting room: 4, 6, or 1?

Q6. What type of floor finish is used in the meeting room: carpet, ceramic tile, or polished concrete?

Q7. Does the operable partition in the meeting room go all the way to the ceiling: yes, or no?

2.7.7 Effect of VM on Design Review Accuracy

The questions for this variable appeared as follows in the surveys:

Q1. How many exit signs are there in the meeting room: 2, 4, or 5?

Q2. What is located on the opposite wall of the ADA toilet fixture in the men's restroom: lockers, urinals, or hangers?

Q3. How many double doors are there in the meeting room: 1, 3, or 5?

Q4. Are the double doors in the meeting room: fully glazed, or solid?

Q5. How many ceiling mounted projectors are there in the meeting room: 4, 6, or 1?

Q6. What type of floor finish is used in the meeting room: carpet, ceramic tile, or polished concrete?

Q7. Does the operable partition in the meeting room go all the way to the ceiling: yes, or no?

3. Results

3.1 Contribution of VM to the Overall Understanding of the Design

Results indicate that there is a significant association between the type of VM used in the experiment and the level of understanding of the interior environment, χ^2 $(2, N = 107) = 27.76$, $p < 0.05$. The Cramer's V effect size result indicated a strong association between the type of VM and the level of understanding of the interior environment: $V > 0.5$.

Results also show that 44.9% of all participants find the use of both of these VMs very helpful in understanding the interior environment, as opposed to only 14% who find the use of CD to be very helpful in the overall understanding of the interior environment. These results suggest that the use of both Construction Documents and VR is perceived to be more helpful in understanding how the real interior environment will look.

The cumulative odds ratio is exp(2.004) = 7.41, which means when passing from CD to CD+VR there is an increase of 7.41 times in the perceived helpfulness of understanding the interior environment. The 95% confidence interval for this cumulative odds ratio shows that this increase is between 9.5 and 5.8 times exp(2.004±1.96×0.129) = exp(2.252; 1.757) = (9.51; 5.76).

The model fit to the data, test $G^2 = 4.5$ and $\chi^2 = 5.4$, with $df = 4$ and $sig = 0.24$. The adjustment of goodness of fit is found for all observations as the Pearson residuals are lower module at 1.96.

The explanatory variable VM improves the model, because the unexplained variation decreases from 59.088 in the model with only a constant to 23.854, a difference of 35.234, which is statistically significant ($p < 0.05$).

There is strong evidence of association between the two variables. The Wald test is equal to 5.15 with $sig = 0.001$, which also denotes the relevance of VMs.

3.2 Contribution of VMs on Ranking a Building's Interior Environment Components by Perceived Importance

The use of both VR and CD was the most helpful in understanding the interior environment components in the following order: (1) Interior Spatial Layout, (2) Interior Finishes, (3) Spatial Dimensions, and (4) Furniture Layout.

The use of CD only was the most helpful in understanding the interior environment components in the following order: (1) Spatial Dimensions, (2) Interior Spatial Layout, (3) Furniture Layout, and (4) Interior Finishes.

3.3 Contribution of VM to Perceived Confidence Levels when Making Critical Design Decisions

A Factorial ANOVA was conducted to compare the main effect of VM and the interaction effect between VAs on the perceived confidence level. The VM included two levels, CD and CD+VR, and the VA consisted of three levels: below average, average, and above average.

All effects were statistically significant at the 0.05 significance level. The main effect for VM yielded an F ratio of $F(1, 101) = 74.3$, $p < 0.001$, indicating a significant difference between participants exposed to both VR and construction documents ($M = 8.35$, SD = 1.92), and participants exposed to construction documents only ($M = 4.08$, SD = 2.75), with a large effect size of $\eta^2 = 0.42$; meaning that 42% of the change in the measured perceived confidence was accounted for by the type of VM used.

The effect of VA yielded an F ratio of $F(2, 101) = 5.25$, $p < 0.05$, indicating significant differences between participants with below average VA ($M = 4.61$, SD = 3.43), participants with average VA ($M = 6.96$, SD = 2.90), and participants with above average VA ($M = 8.07$, SD = 2.26), with a moderate or medium effect size of $\eta^2 = 0.09$; meaning that 9% of the change in the measured perceived confidence was accounted for by the participant's levels of VA. The interaction effect was statistically significant, $F(2, 101) = 4$, $p < 0.05$.

These results suggest that the use of both construction documents and VR is more effective at increasing confidence in making critical design decisions about the interior environment by 42%.

3.4 Contribution of VM to Participants' Perceived Confidence Levels in Making Critical Design Decisions about the Interior Environment Components

3.4.1 Interior Environment Spatial Dimensions

The main effect for VM yielded an F ratio of $F(1, 103) = 9.21$, $p < 0.05$, indicating a significant difference between participants exposed to both construction documents and VR ($M = 7.14$, SD = 2.20), and participants exposed to construction documents only ($M = 4.29$, SD = 2.68), with a medium effect size of $\eta^2 = 0.08$; meaning that 8% of the change in the measured perceived confidence with regard to making critical design decisions about the interior spatial dimensions was accounted for by the type of VM used.

The effect of AEC yielded an F ratio of $F(1, 103) = 5.02$, $p < 0.05$, indicating significant differences between participants with an AEC background ($M = 4.61$, SD = 3.43), participants with average VA ($M = 7.14$, SD = 2.20), and participants without an AEC background (M

= 4.29, SD = 2.68), with a small effect size of $\eta^2 = 0.04$; meaning that up to 4% of the change in measured perceived confidence with regard to making critical design decisions about the interior spatial dimensions was accounted for by a background in AEC.

3.4.2 Interior Finishes

The main effect for VM yielded an *F* ratio of $F(1, 103) = 19.52$, $p < 0.001$, indicating a significant difference between participants exposed to both VR and construction documents (*M* = 7.90, SD = 2.13), and participants exposed to construction documents only (*M* = 3.77, SD = 2.83), with a large effect size of $\eta^2 = 0.16$; meaning that 16% of the change in the measured perceived confidence with regard to making critical design decisions about the interior finishes was accounted for by the type of VM used.

3.4.3 Furniture Layout

The main effect for VM yielded an *F* ratio of $F(1, 103) = 14.53$, $p < 0.001$, indicating a significant difference between participants exposed to both VR and construction documents (*M* = 8.20, SD = 1.94), and participants exposed to construction documents only (*M* = 5, SD = 2.80), with a medium effect size of $\eta^2 = 0.12$; meaning that 12% of the change in the measured perceived confidence with regard to making critical design decisions about furniture layout was accounted for by the type of VM used.

These results indicate that the use of VR increased the participants' perceived confidence about making critical design decisions regarding the interior environment components. The increase in confidence varied from 8% for the interior spatial dimension, to 12% for furniture layout, and 16% for the interior finishes.

3.5 Effect of VM on Likelihood of Change to the Built Environment

The one-way ANOVA between the two groups was statistically insignificant, $F(1, 105) = 1.44$, $p = 0.233$, indicating no significant difference between participants exposed to both construction documents and VR (*M* = 4.68, SD = 3.53), and participants exposed to construction documents only (*M* = 3.92, SD = 2.90).

To examine the effect of VM on the reported likelihood of changes to the built environment in the CD+VR group, ANOVA was conducted between the means of their responses of likelihood of changes when exposed to CD+VR, as opposed to CD only. The independent variable was VM with two levels: CD+VR or CD only. The dependent variable was the likelihood of change, measured from 0 to 10, with 0 being extremely unlikely and 10 being extremely likely.

The main effect for VM yielded an *F* ratio of $F(1, 105) = 4.65$, $p < 0.05$, indicating a significant difference between participants' responses if they were exposed to both construction documents and VR (*M* = 4.67, SD = 3.53), and participants responses if they were only exposed to construction documents (*M* = 5.95, SD = 2.33).

In comparing the results of the two analyses, the CD+VR group reported a much lower likelihood of changes to the built environment when using CD+VR, which was less than using CD only. These results suggest that the use of VR is perceived to decrease the likelihood of changes to the built environment during or after construction.

3.6 Effect of VM on Design Review Time

The main effect of VM yielded an *F* ratio of: $F(1, 105) = 14.73$, $p < 0.001$, indicating a significant difference between participants exposed to both construction documents and VR (*M* = 18.72, SD = 15.87), and participants exposed to construction documents only (*M* = 82.29, SD = 126.12), with a medium effect size $\eta^2 = 0.12$, meaning that 12% of the change in the review time between participants is accounted for by the type of VM used.

These results suggest that the use of VR can decrease the review time of the interior environment design by 62% as presented in Fig. 6.

3.7 Effect of VM on Design Review Accuracy

The main effect for VM yielded an *F* ratio of: $F(1, 105) = 155.25$, $p < 0.001$, indicating a significant difference between participants exposed to both construction documents and VR ($M = 0.93$, SD = 0.1), and participants exposed to construction documents only ($M = 0.56$, SD = 0.1), with a very large effect size $\eta^2 = 0.6$, meaning that 60% of the variance between participants is due to the type of VM used.

These results suggest that the use of VR can increase the accuracy of reviewing and understanding the interior environment design by 37% as presented in Fig. 7.

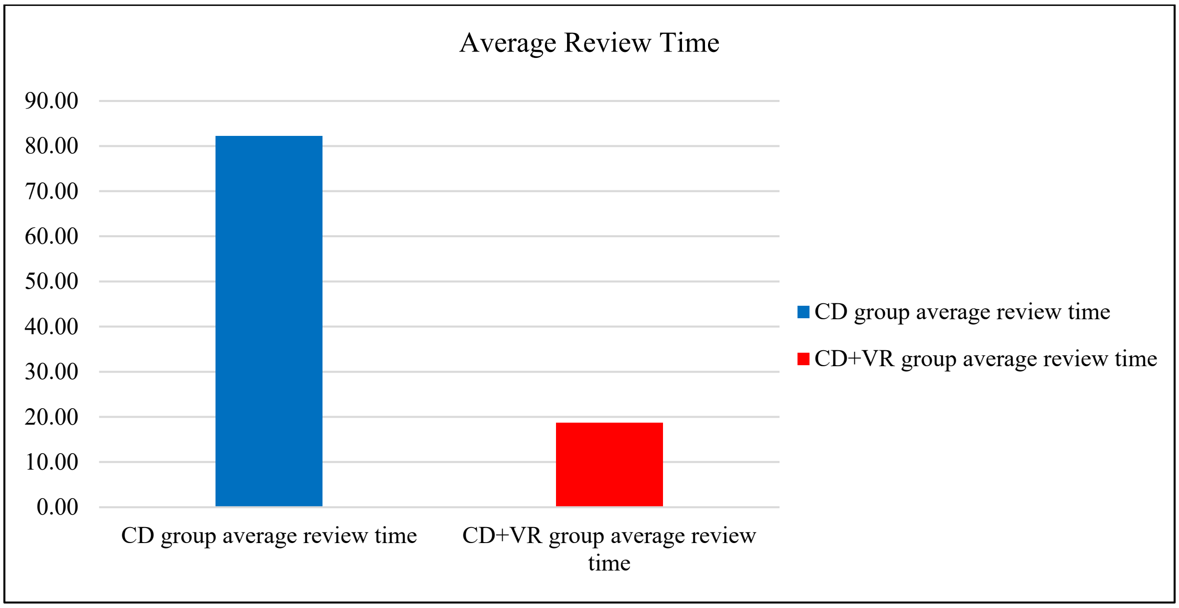

Fig. 6 Average design review time.

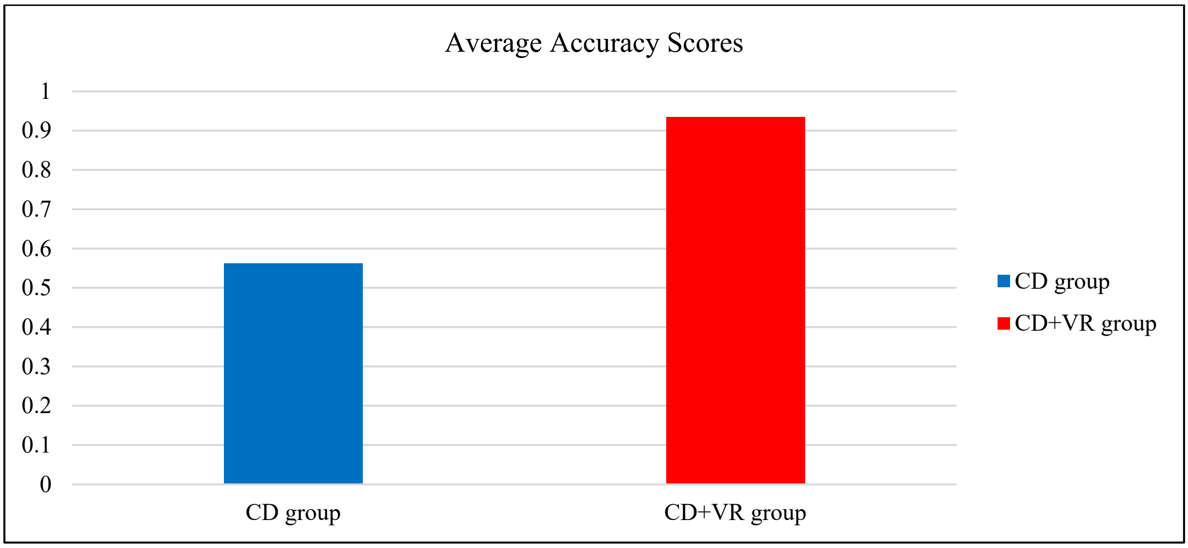

Fig. 7 Average design accuracy scores.

4. Discussion

The purpose of this study was to study and understand the user's behavior under certain VMs, and propose evidence-based control measures that can be implemented to decrease the volume and frequency of change orders. This objective was addressed by identifying change order causes, proposing their potential control measures, and testing the efficiency of the proposed control measures, which is integrating VR as a design VM at an early design stage. The specific aim was to examine the effect of different VMs (i.e., VR vs. construction drawings) on, (1) how well the owners understand the information presented about the future/planned environment; (2) the owner's perceived confidence on what the future environment will look like; (3) the likelihood of changing the built environment associated with each VM; (4) design review time; and (5) accuracy in reviewing and understanding the design. The results are interpreted in light of the full set of results, the applicable literature, the theoretical foundation, and the limitations of the study and literature.

4.1 Interpretation of the Findings

4.1.1 Contribution of VM to Overall Understanding of the Presented Interior Environment

The results indicate that there is a significant association between the type of VM used in the experiment and the level of understanding of the interior environment. Results show that 44.9% of all participants found the use of both VMs very helpful in understanding the interior environment, as opposed to only 14% who found the use of CD to be very helpful in the overall understanding of the interior environment. These results suggest that the use of both CD and VR is perceived to be more helpful in understanding how the real interior environment will look. Furthermore, the data analysis showed that the use of both CD and VR was most helpful in understanding the interior environment components in the following order: (1) Interior Spatial Layout, (2) Interior Finishes, (3) Spatial Dimensions, and (4) Furniture Layout.

4.1.2 Contribution of VM to Perceived Confidence Levels in Making Critical Design Decisions about the Interior Environment

These results suggest that the use of both construction documents and VR holds a potential to increase confidence in making critical design decisions about the interior environment by 42%, as opposed to only using the construction documents, which was not significant.

4.1.3 Contribution of VM to the Participants' Perceived Confidence Levels in Making Critical Design Decisions about the Interior Components

The results indicate that the use of VR increased the participants' perceived confidence about making critical design decisions regarding the interior environment components. The increase in confidence varied from 8% for the interior spatial dimension, to 12% for furniture layout, and 16% for the interior finishes. This is an indication that the use of VR is most helpful in increasing confidence about making critical design decisions about interior finishes, furniture layout, and interior spatial dimensions respectively.

4.1.4 Effect of VM on Reported Likelihood of Changes to the Built Environment after or during Construction

The results indicate that the CD+VR group reported a much lower likelihood of changes to the built environment when using CD+VR as opposed to using CD only. These results suggest that the use of VR is perceived to decrease the likelihood of changes to the built environment during or after construction, which leads to a decrease in the volume and frequency of design and construction change orders.

4.1.5 Effect of VM on Design Review Time

The results suggest that the use of VR can decrease the design review time by 62%, which has a positive impact on the overall project schedule, and is a good indicator that the reviewers understand the design more easily and quickly as opposed to using only the construction documents.

4.1.6 Effect of VM on Accuracy of Understanding the Design

The results indicated a significant difference between participants exposed to both VR and construction documents, and those exposed to construction documents only in responding accurately to the design related questions. These results suggest that the use of VR can increase the accuracy of reviewing the design by 37%.

The findings of this study suggest that the implementation of VR in the design process could have a significant positive impact on the future of building design and construction industry, because a successful building design requires a mutual understanding between all parties involved in the project. Three-dimensional visualization techniques, such as VR, can facilitate mutual understanding, explore design options, and simulate different construction stages. Furthermore, this results in an increased understanding of both qualitative and quantitative aspects of the designed space. The findings of this study confirm the improved spatial comprehension associated with the implementation of VR in the design process as outlined in other studies. Several studies promoting computer VMs argue that it is easier for both architects and their clients to understand and assess their proposed designs through computer VMs. Langdorf [7] supports this point of view, and justifies it using the following reasons: (1) Understanding complex information about design may be greatly extended if the information is visualized; (2) To understand nearly any subject of consequence it is necessary to consider it from multiple viewpoints, using a variety of information; (3) Visualization aids communication with others. Furthermore, Pietch [8] states that computer generated representations are taking over the traditional VMs because traditional means have failed in the attempt to communicate design effectively. The results of this research are good indicators of how VR can enhance design comprehension for users with no AEC background, and therefore decrease the chances of design changes during or after construction. VR also has the apparent benefit of reducing the design review time and increasing the user's ability to rapidly and accurately review the plans and respond to design related questions. In this context of traditional VMs, Daniel and Meitner [9] point out that while computer models can be completely accurate in portraying the physical conditions of an environment, the perceptions, interpretations, and value judgments made by the individual viewer may not be consistent with those that would be produced by actual interaction with the environment. Therefore, the consequence of a poor understanding of the proposed design may result in uninformed decisions. The transition from traditional VMs to VR could fundamentally transform the future of the design and construction processes. Being able to review the design, while spatially immersed in it, can facilitate and enhance the decision-making process by increasing the overall design comprehension and the user's perceived confidence in making critical design decisions. Numerous studies agree that architectural representations play a crucial role in the design process [10]. Architectural representations facilitate the design decision making process by providing the necessary visual information for understanding of the future environment. Brkljac [11] stated that the evaluation of architectural design through visualization is a subjective process, and therefore evaluators do not make similar judgments on the same proposed design. Users should be able to make the appropriate decisions on whether a proposed architectural design is "good" or "bad", and whether they "like it" or "not" just by looking at the proposed design. The results of this research suggest that the use of both construction documents and VR holds the potential to increase user's perceived confidence in making critical design decisions by 42%. This is a significant finding that supports findings in other studies stating that the decision-making process is very complex, especially when it comes to building design and construction.

Wenger [12] states that the design decision making process is "the dance" between the implicit and the explicit knowledge. It requires architects to convey the design, and users to interpret the design in a way that gives it meaning in real life. The results of this study outline the importance of VR as a design communication tool to better understand the design and identify any problems, thereby simplifying and expediting the decision-making process regarding future environments prior to construction.

4.2 Limitations

Although virtual environments have many benefits, they also have some adverse side effects for users such as, dizziness, seizures, eye or muscle twitching or blackouts triggered by light flashes. These side effects need to be reviewed and taken into consideration in future research. This is especially important because the design and implementation of virtual environments contribute to the overall reliability of the study, as well as the health and safety of the participants. While VR enables users to better understand the design and enhance the decision-making process, additional research is needed to assess if this benefit is confirmed. Moreover, the tools utilized in this study would only be suitable for smaller interior environments. Additional research needs to be conducted to assess the effectiveness of different types of VR software and hardware on larger projects with larger groups of participants, and different types of architectural projects with different levels of complexity. Furthermore, the VR simulation evaluation exercise used in this study shows some navigation obstacles to the users in the age range of 55-74. Adverse side effects are common, and can restrict the use of this technology [13, 14]. More than 80% of individuals exposed to VR may experience the following adverse side effects: dizziness, disorientation, drowsiness, nausea, vomiting, loss of balance, fatigue, headache, and eyestrain. The dropout rate on a VR experiment can reach 25% within the first 20 min [15]. The known factors contributing to adverse side effects include, but are not limited to: system lags, large fields of view, sensory conflicts, and relatively more degrees of movement control [13, 14]. As mentioned before, individual differences may affect the way people experience the virtual environments. Delucia and Harold [15] states that people who may be affected the most by VR are people prone to motion sickness, women are often more affected, and people over the age of 40 years. Although VR has already been implemented extensively in gaming, retail, and other domains, its use in the AEC industry remains very limited. This might be due to the fact that the use of a HMD (head-mounted display) can cause problems, such as discomfort and poor depth perception, which was reported by some users in this research. In addition, this research revealed that there are many technical challenges in utilizing VR, which requires some technical proficiency to set up, operate, calibrate, and troubleshoot the system.

5. Conclusion and Future Research

This research is exploratory in nature; it does not claim causation. The objective was to identify and propose potential control measures for change orders, and test the efficiency of the proposed control measures, specifically VR as a design VM. The results of this research were an increased understanding of both qualitative and quantitative aspects of the designed space. We recommend more studies to concentrate on the owner's design understanding as it is the most important and most frequent reason for change orders. New technologies should be implemented to help the owner better understand the design at an early stage of the project to avoid potential changes during or after construction. Despite the rapid development of VR and other visualization enabling technologies, there have been gaps in the literature and the overall body of knowledge regarding the development and its implementation of these technologies in the AEC field. Future research should provide a comparative analysis between the different VR systems suitable for different environments, and different types of architectural projects in supporting and facilitating the design review process. Finally, research is needed to assess the "true" impact of VR on design and building construction in real life related, but not limited to, design quality outcome, project schedule, project budget and cost, and the volume and frequency of change orders.

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