Exploring Future Stakeholder Feedback on Performance-Based Design Across the Virtuality Continuum

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Sooji Ha, Neda Mohammadi, L. Sena Soysal, John E. Taylor, Abigail Francisco, Sean Flanagan, and Semra Çomu Yapıcı

Abstract

Communication of building project designs to stakeholders is important for successful implementation, but it is often difficult to get feedback from the future occupants of buildings. Yet, there is a growing trend in development of visualization tools to enhance participation of the public by effectively providing building information to stakeholders. However, we lack research evaluating the effectiveness of different building model visualization tools, and their performance with gathering feedback from future building occupants. This study compares the effectiveness of three visualization tools—360° panorama, virtual reality and augmented reality applications—with eliciting feedback from future occupants of a Living Building Challenge project at the Georgia Tech campus compared to more conventional 2D visualizations. The effectiveness comparison was conducted across the seven performance categories defined by the Living Building certification program. The results indicated that the visualization tools had significant differences in communicating information in the Equity, Energy, Health and Happiness, Place, and Water performance areas. This study provides a quantitative perspective on the effectiveness of visualization technologies across the virtuality continuum, and has implications for pre-occupancy surveys by exploring new feedback mechanisms that encourage users to participate in building design.

Keywords

Visualization • Virtual reality • Augmented reality • Living building challenge • Occupant perception

50.1 Introduction

Occupant satisfaction, comfort and productivity are dependent on the decisions made in a building's design phase and may directly influence the desired sustainability and performance goals [1]. This is especially true for buildings that are designed to very high energy and performance standards, and their successful operation depends on effective interactions with future occupants [2]. However, during a building's design and construction there are rarely opportunities for future building occupants to give feedback on the design [1, 3]. Proactively engaging with future occupants is critical in ensuring that the building best serves people of diverse backgrounds while reducing the risk of costly fixes in the future [4]. This is crucial when a building is expected to achieve high performance goals (i.e., net-zero energy, net-zero water, or certain green building certification programs such as LEED, or the Living Building Challenge). To collect and incorporate this feedback, a proposed building's design must be communicated to future occupants in an effective way despite it being difficult to those not involved in the design process to understand a proposed building design or its operations [1, 3]. In addition, communications must appeal to heterogeneous populations to ensure the feedback loop is accessible and inclusive to a variety of

S. Ha · N. Mohammadi · J. E. Taylor (✉) · A. Francisco · S. Flanagan
Georgia Institute of Technology, Atlanta, GA 30332, USA
e-mail: jet@gatech.edu

L. Sena Soysal · S. Ç. Yapıcı
Boğaziçi University, 34342 Beşiktaş/Istanbul, Turkey

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audiences [5]. An increasing body of research, underlying the need to involve future users into the design process, emphasizes the effectiveness of visualization technologies in communicating design features and plans [6, 7]. However, research has shown that understanding the proposed building design in the pre-construction phase can be challenging for non-expert occupants [3, 8].

In this study, we explore the implications of offering various spatial design representations to future building occupants via a combination of traditional and emerging visualization technologies: 2-dimensional (2D) images, 360° panorama views, virtual reality (VR), and augmented reality (AR). We compare the effectiveness of these tools for information communication and engaging future occupants with respect to the performance areas the building aims to achieve. We have developed this series of visualizations to specifically represent “The Kendeda Building for Innovative and Sustainable Design”—hereafter referred to as KBISD—at the Georgia Institute of Technology (Georgia Tech) campus, being constructed in 2018. The building should be substantially completed in early 2019, with Living Building Challenge (LBC) 3.1 certification expected in 2020.

50.2 Visualization Across the Virtuality Continuum

The concept of the virtuality continuum was first introduced by Milgram and Kishino [9]. It represents the mixture of classes of objects presented in any particular display. The virtuality continuum spans from completely real to completely virtual environments, encompassing various degrees of segmented and virtual reality. The real environment defines environments of solely real objects, and the virtual environment consists solely of virtual objects. The mixed reality (MR) environment, represents an environment where real world and virtual world objects are presented together within a single display, meaning it is anywhere between the two ends of the virtuality continuum [9]. As a subset of MR, AR is a visualization method in which virtual objects are aligned with the real environment, and the viewer can interact with them in real time [10].

The traditional visualizations used in building design communication are 2D images and drawings. With the advancement of technology and computerized visualizations over the past several decades, there has been a clear shift from using 2D methods to using 3D visualizations [11]. Compared to 2D visualizations, the 3D visualizations are often considered to have more capability to enable communication between user groups [1, 12, 13]. Immersive 3D visualizations create the sensation of being “inside” the visualization and can result in greater spatial understanding for the users [14]. 360° panorama views allow viewers to “look around”, thus providing a sense of telepresence [15]. They are currently widely used as virtual tours, with applications including various historical sites, universities, and museums [16]. In the virtuality continuum, 360° panorama based VR is an extension of computer graphics and VR [17]. Categorized as a desktop VR, this can enable interaction with a smartphone or tablet, allowing non-VR expert end-users to experience virtual environments using familiar devices [18]. While they provide better user control and can be viewed on standard monitors with no high bandwidth requirements [17], 360° panorama views may have limited attributes of immersion or interactivity compared to VR or AR.

VR is a more immersive visualization where head-referenced displays, such as head-mounted displays, are usually worn on a user’s head, so that the user experiences complete immersion in the virtual environment [14]. On the other hand, AR can be displayed on a smartphone or tablet. AR has been shown to improve design perception of computer-aided design (CAD) images [19]. AR and VR can be used to enable collaborative construction processes and performance monitoring [20], that may better engage diverse stakeholders. In addition, visualization tools have been used as a participatory and end-user-centered communication tool [21]. Wergles and Muhar [22] compared user responses to visualizations versus on-site visits and found that visualizations were superior to real site visits, when designed to target certain views.

We have implemented a study that evaluates future occupants’ responses to a building pursuing a rigorous green building standard, using visualization tools including 360° panorama views, AR, and VR, which are compared with responses to traditional 2D image visualizations. This study is designed as follows: First, we developed 360° panorama views, AR, and VR applications along with the traditional 2D images of the KBISD building. Second, we recruited participants from among the Georgia Tech campus community to engage in exploring the building using one of the developed visualization technologies. Lastly, we examined how effective each application performed at communicating the seven building performance areas (i.e., Petals) to future occupants.

50.3 Methods

50.3.1 Kendeda Building for Innovative and Sustainable Design at Georgia Tech

Living Building Certification (LBC) is a green building certification program and sustainable design framework. Considered as the world's most rigorous proven performance standard for buildings, it aims to create buildings that give more to nature than they take, with net positive energy and net zero water as the basis of the challenge. The LBC is comprised of seven performance areas, referred to as "Petals": beauty, equity, energy, health and happiness, material, place, and water. Each Petal is subdivided into a total of 20 imperatives that a project must meet to receive certification. The LBC requires each project to operate for at least 12 consecutive months prior to evaluation, and projects that have met all the assigned imperatives and proven performance during operation earn full program certification—the 'Living' status. The KBISD at Georgia Tech is expected to provide a fully functional building that integrates naturally into the Georgia Tech campus and provides highly flexible academic and community space, becoming the first Living Building in the southeast of the U.S.

50.3.2 Research Design and Hypotheses

For the purpose of this study, we developed four visualizations of the KBISD including a 360° panorama views application, AR application, VR application, and 2D images of the KBISD using the original Revit 3D models provided by the project architect. These were incorporated into the *Unity* 3D platform. The 360° panorama views were used to create the baseline visualization 2D images. The visualization design and experimental setup are described in the following paragraphs.

To develop the 360° panorama views, significant locations in the VR were identified and developed into panorama views. Next, 2D images of the building were generated by taking screen captures in all four directions of each panoramic location. The AR and 360° panorama view applications were installed on an iPad device. The Oculus head-mounted display and control devices were used to provide interactive and immersive user experiences.

Next, participants were recruited by word-of-mouth, distribution of flyers, and online communications to emailing lists to explore the virtual model of the KBISD building and respond to a survey questionnaire approved by the Georgia Tech Institutional Review Board (IRB #H17412). We set up VR experiment kiosks and provided virtual tours in multiple locations on campus, including the Student Center, the Undergraduate Learning Commons, and at an outdoor Earth Day event, in addition to a VR experiment station in our research laboratory. AR participants met at the physical location of the future building, and had a tour of the building site. The survey was designed to investigate how effectively each tool provides information regarding each of the seven Petals. First, we asked respondents about their familiarity with AR/VR technologies and green building certification programs. Next, we asked them to rate their impression of the KBISD, with a 7-point scale ["Inspiration", "Delight", "Interest", "Neutral", "Boredom", "Discomfort", and "Sadness"].

Following general familiarity questions, four questions for each Petal were included, designed to closely address the Petal descriptions suggested by the International Living Future Institute [23], making a total of 28 questions. Within these questions, we asked respondents to report to what degree they thought each Petal was achieved. For example, for the Health and Happiness Petal participants were asked, "To what extent do you agree or disagree with the following statements? (1) The design of the interior spaces nurtures a connection with nature, (2) The design of the exterior spaces nurtures a connection with nature, (3) The number of windows allows adequate access to sunlight in the building, and (4) The design of the Living Building promotes good indoor air quality". Responses were restricted to 6-point Likert scale format, with the following options: strongly disagree, somewhat disagree, neither agree nor disagree, somewhat agree, strongly agree, and this tool does not provide me enough information to form an opinion. The final response option (i.e., no opinion) aligns with the response option in [24]. "No opinion" responses versus other responses (i.e., opinion formed) were evaluated to test our hypotheses.

Finally, demographics questions were asked to compare the sample population to the broader Georgia Tech community population. This question included: affiliation/relationship with Georgia Tech, age, gender, ethnicity, and average hours spent on campus. At the end of the survey, participants could optionally complete an open-ended response about their overall participation experience.

To quantify tool effectiveness, the following hypothesis was tested:

Hypothesis. There is a significant difference in the distribution of opinion formation enabled about the [H1–7] Petal Performance Areas between 2D images, 360° panorama views, AR, and VR visualization tools [a–f].

Table 50.1 Hypothesis development across the seven petals

Hypothesis	
a. 360° panorama views > 2D images b. AR > 2D images c. AR > 360° panorama views	d. VR > 2D images e. VR > 360° panorama views f. VR > AR

To statistically test the seven hypotheses, a non-parametric the chi-square (χ^2) test (significance level $\alpha = 0.05$) was used, to detect if a difference exists between the visualization tools. Because the chi-square test does not specify which combination of categories contributes to statistical significance, if a statistically significant difference is detected for each hypothesis we move forward to conduct post hoc tests using the standardized residual method [25] to determine which combination of visualization tools contribute to statistical significance (i.e., when a standardized residual is greater than 2.0 in absolute value). To adjust for Type I error rate, we use modified significance levels of $\alpha = 0.0131$(*) and $\alpha = 0.068$ (**), corresponding to $\alpha = 0.1$ and $\alpha = 0.05$, respectively [26]. Table 50.1 details the hypotheses developed comparing the effectiveness of each combination of visualization tool for each Petal category.

50.4 Results

A total of 129 responses were collected for the analysis, with a distribution of 34, 38, 41, and 16 participants in 2D, 360° panorama views, AR and VR study groups, respectively. Representative of the Georgia Tech community population, the demographic makeup of survey respondents includes a gender distribution of 56.6% male and 43.4% female, ethnicity distribution of 33.6% Asian, 42.5% white, 11.5% black or African American, 4.4% Hispanic or Latino, 2.7% white–Asian interracial, and 5.3% no response or other. The age distribution was 63.7, 23, 7.1, 4.4, and 1.8% for ages between 18–24, 25–34, 35–44, 45–54, and 55–64, respectively. More than half (54.9%) of the respondents were undergraduate students, 15.9% were PhD students, and 11.5% were masters students. Staff made up 14.2% of the respondents, while 1.3% were faculty members of Georgia Tech. More than 70% of the respondents spent more than 8 h on campus, while less than 10% of the respondents spent less than 5 h on campus on a daily basis. A total of 56.6% were either "Not familiar at all" or "Slightly familiar" with green building certificate programs, and only 13.3% responded they were more than "Very familiar" with such programs.

Table 50.2 shows the results of chi-square test of independence in opinion formation for each Petal across the four visualization tools.

Results indicate that responses to opinion formation for the four visualization tools are independently distributed, meaning that a statistically significant difference exists in the distribution of opinion formation for about all but the Beauty and Material Petals, between 2D images, 360° panorama views, AR, and VR visualization tools. Therefore, the null hypotheses H2 (Equity), H3 (Energy), H4 (Health), H6 (Place), and H7 (Water) are rejected, allowing us to move forward to post hoc tests. Failing to reject the null hypotheses H1 (Beauty) and H5 (Material), we conclude that the four visualization tools do not differ in providing information that may enable opinion formation in these Petals.

The standardized residual test was performed on hypotheses H2 (Equity), H3 (Energy), H4 (Health), H6 (Place), and H7 (Water), to test hypotheses (a) through (f) to interpret which tool contributed to the statistically significant difference of the four groups. Table 50.3 shows the standard residuals of the contingency tables for each hypothesis. Positive z-score represents that the visualization tool contributed to respondents being able to form opinions with the information they were

Table 50.2 Hypothesis test results of all visualization tools using chi-square test

Hypothesis	χ^2	df	p-Value
H1. Beauty	0.341504	3	0.96220378
H2. Equity	16.9335	3	5.000E–04*
H3. Energy	14.87556	3	0.00209979*
H4. Health	23.7192	3	2.000E–04*
H5. Material	4.038094	3	0.25787421
H6. Place	16.90154	3	7.999E–04*
H7. Water	15.93878	3	0.00139986*

$^*p < 0.05$

Table 50.3 Standardized residuals and corresponding *p*-values for opinion formed responses

Hypothesis	2D *z*-Score *p*-Value	360° *z*-Score *p*-Value	AR *z*-Score *p*-Value	VR *z*-Score *p*-Value
H2. Equity	−1.97 0.049245	−2.37 0.017608	0.54 0.587492	3.8 0.000144‡
H3. Energy	−2.11 0.035206	1.94 0.052288	−2.67 0.007497‡	1.99 0.047091
H4. Health	−3.88 0.000103‡	2.04 0.041413	−1.94 0.051968	3.05 0.002254‡
H6. Place	−2.64 0.008202†	−0.72 0.469492	−1.01 0.313691	3.92 8.75889E–05‡
H7. Water	−1.44 0.150728	−2.88 0.00401‡	1.78 0.075115	2.92 0.003538187‡

† $p < 0.0131$, ‡ $p < 0.0068$

provided by the tool. A negative *z*-score indicates that the visualization tool contributed to respondents being unable to form opinions with the information they were provided, meaning the tool failed to communicate enough information to users to form an opinion about the Petal. 2D images showed negative *z*-scores with significance for the Health and Happiness and Place Petals. 360° panorama views had negative *z*-score with significance at the Water Petal. AR showed significant *z*-score at the Energy Petal, with a negative *z*-score. VR showed significant positive *z*-score for all four tested hypotheses.

As shown in Table 50.3, VR has significantly contributed to opinion formation of all tested Petals, except for Energy. On the other hand, 2D images contributed significantly to no opinion formation for the two Health and Happiness and Place Petals. In H2 (Equity), VR significantly contributed to opinion forming responses, allowing us to accept hypotheses (b), (d), (f), and conclude that VR is more effective than other three visualizations in assessing the Equity Petal. However, since no other visualization tool has a significant *z*-score, there is not enough evidence to accept (a), (c), and (e), and therefore we did not find a relationship across any of the tools.

In H3 (Energy), only hypothesis (f) is accepted at *p*-value of 0.0131 level, since AR significantly contributed to no opinion forming of respondents, which means AR performed the worst among the visualizations. VR and 2D visualizations showed significant results in the Health and Happiness Petal; VR significantly contributed to opinion responses in the Health and Happiness Petal, while 2D has contributed to no opinion responses. Therefore, we accept H4 (a), (b), (c), (d), and (f): 2D performs worse than all the other three visualizations, and VR performs better than all the other visualizations. However, the results do not provide statistical evidence that AR performed better than panorama views, therefore, H4 (e) is rejected. Similarly, the standardized residual method's results for the Place Petal allows us to accept H6 (a), (b), (c), (d), and (f) and reject (e). However, this conclusion is made at a less significant level, since the negative *z*-score of 2D is significant at a 0.0131 *p*-value. Interestingly, in the Water Petal, the panorama view performed significantly worse than the other three tools, while VR was also the most effective visualization. Therefore, we accept H7 (b), (d), and (f). H7 (e) is also accepted for AR since it performed better than the 360° panorama views.

Table 50.4 provides a summary of the hypothesis test results. Overall, we can conclude that VR is a more effective visualization tool than the other three in communicating performance-based building design for Equity, Health and Happiness, Place, and Water Petals. 2D images generally contributed to "no opinion" responses.

Table 50.4 Overall hypotheses testing results

Hypothesis	Four tools are different	360°>	AR>		VR>		
		2D	2D	360°	2D	360°	AR
H1. Beauty	✖						
H2. Equity	✓*				✓‡	✓‡	✓‡
H3. Energy	✓*						✓†
H4. Health	✓*	✓‡	✓‡		✓‡	✓‡	✓‡
H5. Material	✖						
H6. Place	✓*	✓†	✓†		✓†	✓‡	✓‡
H7. Water	✓*			✓‡	✓‡	✓‡	✓‡

* $p < 0.05$, † $p < 0.0131$, ‡ $p < 0.0068$

50.5 Discussion

Our findings that VR enabled users to better form opinions about the design are supported by qualitative comments collected at the end of the survey. For example, one user who viewed the 2D building images said the “Building looks nice but the pictures allow no context for making informed judgements”. Another user stated they, “Want to see what it’d actually look like”. Response rates for “Neutral”, “Boredom”, and “Discomfort” were larger in 2D than other groups: 21% of 2D group respondents selected one or two of these impressions for the building, while other groups’ percentage for such neutral and negative impressions were relatively low, having 11, 5, and 13% from 360° panorama views, VR and AR groups, respectively. In addition, users who viewed the building in VR provided more positive comments. One user stated, “This is a great idea for using VR to show the building”. Another user said, “I loved it! Cool space, excited for its construction”, and “I appreciated the rooftop garden/space”. Although the panorama view did not show significant contributions to either opinion or no opinion responses, the general comments collected from the application provides some interpretation of its use: more comments were provided for this application, and many of them were simple, complimentary comments, perhaps indicating that participants felt more comfortable providing comments using the visualization. However, AR seems to be a less user-friendly and effective tool for visualizing Petals, with one user saying, “The iPad was a bit cumbersome” and another reporting that it “was not a great choice for conveying information about the building. You spend a lot of time looking at the iPad, and don’t really get a feeling for the size and layout of the building”.

This study can be improved by enhancing the visualization tools such that additional details about each Petal can be communicated to users. Especially those that are often relatively harder to intuitively experience. For example, simulating sunlight and air circulation inside the building (Health and Happiness), labels of materials (Materials), and visible water collection and cleaning mechanical systems (Water) may significantly improve the level of information provided to users.

This study provides qualitative and quantitative evaluations of the effectiveness of visualization technologies across the virtuality continuum, among the seven Petals of the KBISD at Georgia Tech. However, the LBC is just one example of the many sustainable rating systems for buildings of the future that aim to address challenges and complex performance measures such as energy efficiency and human wellbeing. This study can provide guidance for pre-occupancy surveys, leveraging in situ feedback mechanisms to encourage users to participate in a building’s design through utilization of advanced visualization technologies, namely AR, VR, and 360° panorama views. This approach can also inform future sustainable and high-performance building studies on how to maximize engagement of stakeholders into the performance-based design phase of the project to ensure the building functions best serve those who will use it.

50.6 Conclusion

This study compared the effectiveness of four visualizations in communicating building design information to future building occupants, through a case study of a building seeking LBC certification at the Georgia Tech campus. Three interactive visualization tools along with 2D images were developed. After virtually exploring the building using these visualization tools, participants’ ability to form an opinion about the building Petals (performance areas) was examined via a survey questionnaire and used to measure the visualization tools’ ability to provide enough information about each Petal. The results indicate that the four visualization tools differ in communicating design information about all but the Beauty and Material Petals. In particular, VR was the most effective communication and visualization tool, except for in the case of the Energy Petal. On the other hand, 2D images failed to communicate enough information to users, relative to the other visualization tools. 360° panorama and AR did not seem to have consistent contributions to either opinion or no opinion responses. These findings can inform design and construction firms on the most impactful approaches to providing design visualizations to stakeholders.

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