Urban Energy Data Visualization and Management: Evaluating Community-Scale Eco-Feedback Approaches

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Abstract: As energy consumption in urban areas rises to the level of being a global concern, the impact of community behavior becomes critical to assessing and managing energy consumption. Eco-feedback systems are taking advantage of data streams from advanced metering infrastructure and are being widely implemented with the goal of increasing engagement in more sustainable behavior. However, the effectiveness of eco-feedback systems at an urban scale largely depends on how the information is communicated to and visualized by various communities. Advanced visualization technologies, such as virtual reality (VR), have proven to be efficient tools in information communication and visualization in diverse fields and present a promising opportunity in information representation for eco-feedback studies at scales larger than a single building. This paper examines the effectiveness of a VR-integrated community-scale eco-feedback system deployed across 54 buildings on Georgia Tech's campus by integrating 15-min increment energy consumption data into an interactive VR platform of the campus and conducting a user testing experiment on visualization characteristics, such as immersion, presence, involvement, and simulator sickness, along with system usefulness, that play a decisive role in users' preference and perceived energy-saving motivation toward the two systems. Yet, participants indicated polarized preferences for the two types of systems. This finding suggests that to increase the effectiveness of energy feedback at the urban scale as open urban energy data become more available, eco-feedback systems need to incorporate the specific preferences of the communities receiving feedback or be designed capable of displaying energy feedback that meets users' diverse preferences. In doing so, we may capitalize on the increasing data richness of energy consumption information in cities to more effectively encourage energy-saving behavior and meet the sustainability targets set by city governments. **DOI: 10.1061/(ASCE)ME.1943-5479.0000879.**

Introduction

Urban energy consumption has long been a concern for urban scientists, planners, and city managers (Chen and Chen 2015) because it comprises a major part of global energy consumption (Eicker 2019) resulting from intensified human activities. Building energy consumption stands out as a significant contributor to urban energy use (EIA 2019). The ongoing energy crises and the abundance of carbon emission reduction goals being established have stimulated global efforts toward improved building energy efficiency. Public participation has been identified as a fundamental requisite to meet the sustainability and inclusiveness goals of smart cities (Corsini et al. 2019; Liu et al. 2018). Therefore, encouraging citizens to participate in energy-saving behaviors to achieve broader citywide sustainability goals is critical. In recent years, governments around the world have launched a number of open data initiatives and ordinances empowered by advanced smart metering infrastructures with the goal to facilitate government transparency, release social and commercial value, and enable participatory governance (Attard et al. 2015). A key element underlying the success of the initiatives is to transform the data into a more accessible, usable, and understandable form to inform better decision making (Francisco and Taylor 2019).

Eco-feedback systems, which stream information from increasingly pervasive metering infrastructures, have been widely adopted with the goal of motivating sustainable behavioral changes under the assumption that occupants are unaware of the energy consumed as a result of their day-to-day behaviors (Attari et al. 2010). Eco-feedback has been suggested as an effective behavioral intervention strategy (Delmas et al. 2013). Given the decentralization trend in the power grid and the penetration of renewable energy, the importance of energy resilience and sustainability at a community scale has become more important (Bennett et al. 2020). Recent studies on eco-feedback systems have suggested expanding the systems to the community scale (Geelen et al. 2013) and have indicated promising potential of community-scale energy interventions and positive performance indicators, such as increased motivation (Francisco and Taylor 2019; Melville et al. 2017). In contrast, the effectiveness of eco-feedback systems heavily relies on how the information is communicated and visualized to users (Sanguinetti et al. 2018).

Innovations in advanced visualization technologies, such as virtual reality (VR), present new and promising opportunities in information representation in eco-feedback systems at urban scales. VR has been applied in diverse fields as an effective information visualization and communication tool because it provides users with a realistic experience in an interactive and immersive three-dimensional (3D) environment and helps relieve cognitive overloads (Du et al. 2020). In contrast to computer monitor displays

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[two-dimensional (2D) or 3D], in which data visualizations are based on gestalt perceptual principles (i.e., visual elements are grouped according to proximity, similarity, symmetry, and others), VR is developed based on the theory of affordance from perceptual psychology (Gibson 1977), thus providing the user with an extended sensory experience. As a result of the VR perceptual and interactive properties (e.g., spatial perception, shape recognition, color differentiation, movement detection, and others), the user is better equipped to reason and develop insights when interacting with the data (Milgram and Kishino 1994; Stucky et al. 2009). Addressing the spatial and temporal complexities of real-time urban information is also proposed to support smart city decision making and management (Mohammadi and Taylor 2017).

In this paper, VR technology is leveraged and used to create a community-scale eco-feedback system to examine how users perceive and evaluate this system and its potential for driving sustainable behavioral changes.

Background

Eco-feedback is an information technology that provides resource consumption feedback about individual or group behaviors with the goal of promoting more sustainable behaviors (Froehlich et al. 2010). Eco-feedback systems have been widely adopted to communicate energy consumption information with building occupants to engage users and encourage more energy-saving behaviors. For example, the UK government has implemented the Smart Meter Implementation (SMI) Programme mostly driven by the European Union Energy Efficiency Directive, which involves integrating smart meters and in-home displays to provide consumers real-time feedback on their energy consumption (Pullinger et al. 2014). Eco-feedback has indicated promising outcomes in encouraging energy savings and behavioral changes in both residential and commercial sectors. A meta-analysis of more than 156 published feedback studies from 1975 to 2012 found that such information strategies providing occupants with feedback on their electricity consumption contributed to a 7.4% average reduction in electricity use in residential buildings (Delmas et al. 2013). The analysis also indicated positive outcomes for energy reduction in the commercial sectors (Gulbinas et al. 2014; Gulbinas and Taylor 2014; Kamilaris et al. 2015).

In addition, millions of smart meters are being installed in the United States by both electric utilities and the government to engage consumers in energy-efficient grid operations, such as demand response (Uribe-Pérez et al. 2016). This effort has led to millions of data records being generated by metering infrastructure in urban areas, often in near real-time, empowering information communication of eco-feedback systems at scales larger than a single building. Geelen et al. (2013) called for eco-feedback systems at the community scale due to the decentralization brought by smart grids and argued the proven effectiveness of comparative eco-feedback between related individual units. The findings of an interview with participants in a community demand response trial carried out by Melville et al. (2017) suggested that a sense of community is motivating to engage them in community-based energy management. A community scale eco-feedback study was carried out by Burchell et al. (2016) to explore the potential of community action in a two-year Smart Communities project. Information communicated within the context of the community was found to support longer-term engagement compared with conventional eco-feedback systems, adherence to which is often short term. Following this, more studies elevated the scale in broader social settings to community groups (Gupta et al. 2018; Peacock et al. 2017). A study of citizen perspectives on a mobile-based community-scale energy eco-feedback system suggested that users had a strong interest in accessing the eco-feedback information at multiple spatial scales (Francisco and Taylor 2019).

However, not all eco-feedback systems work effectively in persuading users to adopt energy-saving behaviors. Jain et al. (2012) found variability in observed savings and corresponding interface elements across eco-feedback studies. Sanguinetti et al. (2018) suggested that the effectiveness of eco-feedback systems is largely impacted by an in-depth understanding of the key design dimensions: information, timing, and display. Thus, how the information is communicated to users in eco-feedback systems plays a decisive role in system performance. Information representation has been indicated to impact user energy consumption behavior. In the experiment in Jain et al. (2013), energy consumption information was represented in different units—direct kWh use and environmental externality CO_2 emissions—and the results indicated feedback with CO_2 emissions drove greater reductions in energy consumption. Jain et al. (2012) also indicated that the user interface design had a significant impact on user engagement and energy-saving behaviors: in their study, historical comparison and incentives ranked at the top in encouraging user engagement and energy conservation.

Eco-feedback systems have long been promoted by technological advancements in information visualization to more effectively convey information and encourage users to curtail resource consumption. Moving beyond early paper-based eco-feedback, computerized digital displays now prevail in eco-feedback systems ranging from desktop computers to appliance-embedded monitors (Sanguinetti et al. 2018). Francisco et al. (2018) further explored the impacts of information representation by comparing the building information model (BIM)-based eco-feedback with conventional bar chart-based eco-feedback and found that the BIM-integrated building energy information representation outperformed the traditional bar char visualization for eco-feedback systems. Along these lines, advanced visualization, such as VR, offers a relatively unexplored yet promising opportunity in the information representation of eco-feedback systems.

VR enables a computer-generated three-dimensional world in which users can interact with the virtual environment with a strong sense of presence (Bryson 1996). This technology has been widely used in various fields as an efficient tool in information communication, such as training, education, and psychological therapy applications. The architecture, engineering, and construction (AEC) industry, which heavily relies on visual communication (Heydarian et al. 2015b), has also implemented virtual environments in various applications, although it has been primarily applied as a marketing tool for customer visualization (Wojciechowski et al. 2004) or education and training for the workforce (Pour Rahimian et al. 2014). Innovative computerized visualization technology is now being expanded to the entire building life cycle. For instance, VR is being used in the building design stage to inform the collaborative design and promote a comprehensive understanding of the proposed design among designers, constructors, and other stakeholders at an early stage, which offers more flexibility and cost-saving benefits (Dunston et al. 2007; Frost and Warren 2002). During the building construction phase, VR has been implemented to assist with education (Messner et al. 2003), management, and planning (Goulding et al. 2014; Waly and Thabet 2003). For use during the facility management stage, VR has been integrated with the building's BIM model to enhance communication and collaboration between facility managers and other stakeholders with the goal of promoting sustainability (Ammari and Hammad 2014; Shi et al. 2016).

A limited number of studies examined the potential of occupant or user engagement in promoting building energy sustainability by leveraging VR technology. Kuliga et al. (2015) suggested that VR provides strong potential to engage occupants in building usability studies and pre-and-post occupancy evaluations in both studies. Comparing VR with a real-life physical environment, Heydarian et al. (2015b) measured participants' performance in immersive indoor environments with regard to office-related tasks and sense of presence and found similar outcomes between the virtual and real-world environments. They suggested that immersive environments can effectively help assess occupant behaviors in real-life settings. In another study, Heydarian et al. (2015a) examined lighting use behaviors of users in virtual environments under different lighting control strategies to identify the most energy-efficient control strategy. Urban planning involving public participation has also implemented VR to engage users in an interactive virtual environment simulating real-life scenes (Al-Kodmany 2002). These studies often focus on engaging occupants during earlier stages of the building life cycle to inform a better design; however, more recent work sought to assess the potential for urban-scale building energy analytics (Francisco et al. 2020). How occupants respond to building operational information visualization in virtual environments and how that compares with 2D representations typical of existing eco-feedback studies remain unknown. Meanwhile, the characteristics of VR offer a promising opportunity as a novel type of information representation in eco-feedback systems.

Compared with the traditional monitor display (2D and 3D), visualizing information in VR has been suggested to enhance intuitiveness and information comprehension. Huang and Lin (1999) developed a tool that transforms previous 2D GIS data to VR-based representation, which was suggested to assist better city planning and management. Ware and Franck (1994) designed an experiment to compare the effectiveness of information display in 2D, 3D, and VR, in which VR outperformed both 2D and 3D information display. The realistic experience generated by VR plays a key role in its potential as a visualization approach for eco-feedback systems. The sense of immersion that VR exhibits is found to contribute to a more intuitive understanding of the data and better perception of data relationships (Donalek et al. 2014). Intuitiveness plays a decisive role in determining the performance of eco-feedback systems (Francisco et al. 2018). In addition, visualizing information in a VR environment has been suggested as an effective approach for providing an immersive and interactive environment that reduces information clutter, alleviating cognition load and improving an overall understanding of the dataset, especially with spatially diverse and multidimensional data (Bowman and McMahan 2007; Park et al. 2000), which is especially encouraging for community-scale eco-feedback systems due to the increasing amount of information resulting from enlarged spatial complexity. Game-like interactions in VR are likely to interest users through strategies such as gamification, which has been extensively employed in eco-feedback studies (Gandhi and Brager 2016; Johnson et al. 2017) to enhance cognition, learning, and behavioral changes. Hence, the unique characteristics provided by VR are likely to positively impact information delivery.

The recent proliferation in advanced visualization technologies such as VR offers a relatively unexplored but promising opportunity in information representation for eco-feedback systems. However, the performance of such innovative information representation in eco-feedback studies remains unknown. To address this gap, this study developed a VR-integrated community scale eco-feedback system with the goal of leveraging the unique characteristics of VR to enhance the representation of community energy-use information. After achieving this, a user testing procedure was implemented to evaluate the system's effectiveness using a 2D eco-feedback system as the control group. Four different aspects of the proposed VR system compared with the 2D system were assessed: usability, utility, visualization characteristics identification, and motivation.

Usability

Usability testing is a crucial component in any human-centered design process and helps ensure that the system meets the user's needs and minimizes the possible negative impacts from using the system (Bastien 2010). Generally, usability testing assesses how easy it is to use a user interface and the corresponding functionality. As defined by Nielsen (Billinghurst 2008), usability is comprised of five quality components: learnability, efficiency, memorability, errors, and satisfaction. In this study, Likert-type questions from IBM's Post-Study System Usability Questionnaire (PSSUQ) (Lewis 1995) were adopted in the survey. In addition, questions adapted from Francisco et al. (2018) and Bonino et al. (2012) that asked about a user's understanding of the color-coding scheme were added to evaluate the efficiency and errors perspectives. Beyond the survey questions, observational data about how the participants interacted with both systems and their performance (i.e., time and accuracy) in completing the tasks were used to complement the survey results. Observation is a critical measure to accurately understand human actions in usability testing. Observational outcomes can help eliminate the bias introduced by an over-reliance on self-report data (Adams et al. 1999; Campbell and Fiske 1959) and enhance the validity of the research.

Utility

Utility is an attribute that measures whether the system design meets the user's needs and works together with system usability to form "usefulness" (Nielsen 2012). Utility is as important as usability because an easy-to-use system does not guarantee the provision of needed information or functionalities. Therefore, questions to assess system utility were incorporated into the survey.

Visualization Characteristics Identification

Conventional usability testing cannot satisfy the evaluation of systems with virtual environments. Kalawsky (1999) developed a tool to measure the usability of virtual environment systems and identified diagnostic factors assigned to each question. The characteristics of virtual reality, as identified by previous research are a sense of presence, immersion, involvement, and simulator sickness (Kalawsky 1999; Schuemie et al. 2001; Witmer and Singer 1998). Witmer and Singer (1998) suggested that a sense of presence is closely correlated with performance in a virtual environment. They also proposed four underlying factors (i.e., control, sensory, distraction, and realism) that contribute to the sense of presence and designed a presence questionnaire (PQ) to quantitatively measure users' sense of presence. The clustering results of the PQ data indicate the PQ subscales can be divided into *Natural*, *Interface Quality*, and *Involved/Control*. Likert-type questions designed to quantitatively measure the visualization characteristics of VR were selected and adapted from previous studies.

Motivation

As an eco-feedback system, the main goal is to help users better understand building energy performance across the community and ultimately motivate them to adopt behavioral changes. Thus, questions regarding perceived motivation to adopt sustainable behavior were constructed and added to the survey. Thus, the objectives of this study are as follows:

1. Understand the usefulness of the proposed system as an eco-feedback tool, which incorporates system usability, utility, visualization characteristics identification, and perceived motivation; and
2. Examine the system which participants prefer or feel more motivated to adopt sustainable behaviors and the system characteristics that are decisive in user selection.

Detailed information about the front- and back-end designs of the eco-feedback system and testing design and results are discussed in the following sections.

Methodology

In this study, the term "community" refers to its territorial and geographical notion, as suggested by Gusfield (1975). No globally accepted definition exists about what constitutes a territory-based community other than mostly recognized components: shared territory, common life, collective actions, and mutual identity (Theodori 2005). Thus, this study proposes that a community's size is flexible, which can be scaled up or down to various geographical boundaries. Based on the aforementioned objectives, the method for this study is mainly composed of two parts. First, a VR-integrated community scale eco-feedback system was developed to visualize building energy performance across Georgia Tech's campus as our testbed community in an immersive environment using the Unity (Unity Technology 2018) platform. The aim is to improve information communication by taking advantage of VR characteristics. Second, to examine the effectiveness of the proposed system, user testing was performed to collect both self-report and observational data on how participants responded to the VR system, and a 2D eco-feedback system of the same data and similar functionality served as the control group. In the following subsections, the main methodology steps implemented and rationales behind each step are explained in detail.

VR and 2D Community Eco-Feedback System Development

Energy Data Collection

The Georgia Tech campus was selected as a testbed community for the design and development of the prototype community-scale eco-feedback system. Whole building-level electricity consumption data on 54 buildings recorded at 15-min intervals, which is a widely accepted time interval for electricity monitoring, modeling, and predicting, was provided by Georgia Tech Facility Management. The duration of the energy feedback displayed in both the VR and 2D eco-feedback systems was one year.

VR Eco-Feedback System Design

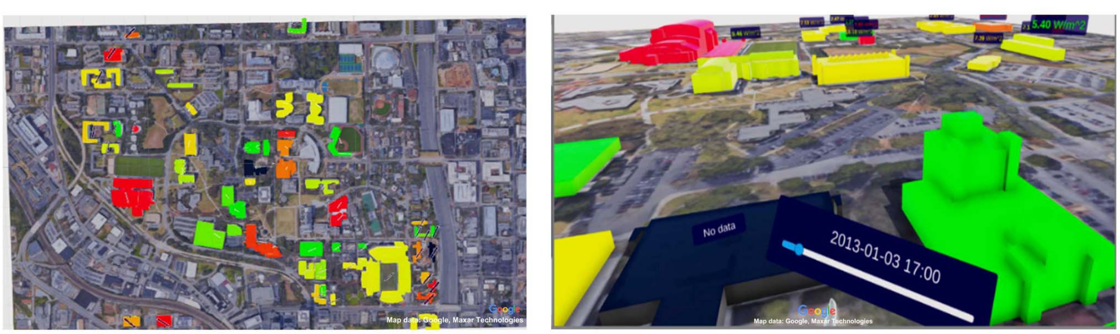
Users can access the interactive VR-integrated eco-feedback system through a head-mounted display (HMD), a pair of touch controllers, and two sensors that provide a stereoscopic view of the virtual Georgia Tech campus by tracking the user's position and orientation. Interactivity within eco-feedback systems has been demonstrated as a significant measure to motivate users to adopt sustainable behaviors by enabling them to become familiar with their energy usage (McCalley et al. 2005; Weiss et al. 2012). Users can interact with the VR system through navigation that enables scalability and teleportation within the virtual environment. Visualization of building energy usage data is realized by hovering text tags that display the energy use intensity (EUI, W/m^2) and the corresponding performance information represented by color-coded 3D models. Users can access 15-min energy consumption data by interacting with the time slider drifting above their virtual left hand. In the default state, when users do not interact with the timestamp slider, the timestamp automatically moves forward.

Color coding has been suggested as a useful technique to address information visualization problems in 3D environments (Shneiderman 2003). It has also been implemented in eco-feedback studies and suggested promoting user understanding of building energy performance (Bonino et al. 2012). Thus, color coding was applied to the 3D building models to represent the energy performance of individual buildings across the campus. The color coding of each building model at every 15-min interval is determined by a normative EUI comparison.

The back-end development of the prototype system was configured using Unity version 2017.1. Three-dimensional building models were produced according to each building's footprint information from Mapzen (2019), which were streamed and mapped into the virtual environment. Fig. 1 indicates a bird's-eye view and a ground view in the VR-integrated community scale eco-feedback system. Additional detailed information on design principles and the front- and back-end development of the VR-integrated eco-feedback system can be referred to in Xu et al. (2019).

2D Eco-Feedback System Design

The digitalization of information empowers researchers to transfer the previously paper-based eco-feedback to computerized digital devices, such as desktops, laptops, and mobile devices. Most digital representations of eco-feedback are still 2D-based: bar/line graph, pie chart, and floor/room plan (Bonino et al. 2012). Therefore, a 2D eco-feedback system was built (Fig. 2) with similar functions for



(a) (b)

Fig. 1. VR-integrated community scale eco-feedback system: (a) bird's-eye view of campus buildings' relative energy performance; and (b) immersive view of buildings' relative energy performance with timestamp slider visible. (Map data Google, Maxar Technologies.)

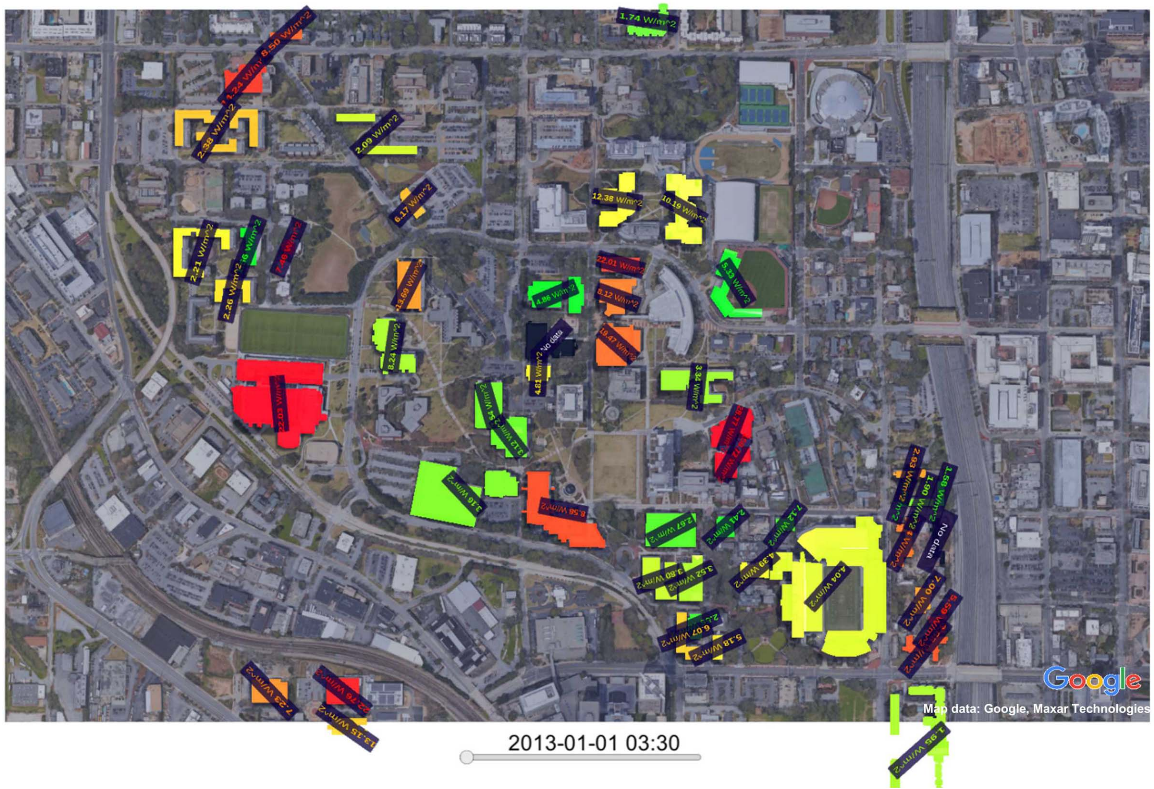


Fig. 2. 2D version of community scale eco-feedback system. (Map data Google, Maxar Technologies.)

comparison purposes, for which users can visualize building energy performance across Georgia Tech's campus scene on a 2D plane from a bird's-eye view.

Individual building energy performance is represented the same way as the VR version through color-coded building models and text tags with EUI values hovering above each model. External scenes are built on the same aerial image. Users can interact with the time slider located below the campus map and access energy performance information at each 15-min interval. The 2D eco-feedback system provides users with building energy performance across Georgia Tech's campus in a different year to reduce carry-over effects. Carryover effects are likely to be introduced in within-subject designs in which participants are exposed to more than one treatment, and the effect of one treatment may carry on during the measurement of another treatment (Greenwald 1976). For example, participants may carry over their memory of answers in one system to the other.

Experimental Design

User testing is a crucial step in evaluating whether our proposed community-scale eco-feedback system can work effectively as a learning tool to ultimately motivate energy-saving behavior. The main goal of user testing is to address our objectives of this study by introducing a 2D eco-feedback system as a control group.

Within-subject user testing was implemented in this study because, compared with a between-subject experiment, it requires a smaller sample size and minimizes random noise resulting from different personal histories or contexts. During the user testing, each participant experienced either of the eco-feedback systems in random order when completing the given tasks and was required to fill out a survey on their perceptions and attitudes toward the system that they just experienced. Then, they went through the same process using the other system. A tutorial was given before the formal user testing process that enabled participants to become familiar with the basic operations and functionalities of both systems to minimize the impacts of using a new technology. The survey was generated using Qualtrics. The experiment took approximately 30 min per participant and was approved by Georgia Tech's Institutional Review Board (IRB #19133). Participants were recruited through campuswide emails and flyers to reach as diverse groups as possible. Each participant was compensated with $10.

System Design Evaluation

Due to the limited knowledge of VR performance in information communication for eco-feedback systems, evaluating the system's usefulness is necessary. Only if the system is regarded as a useful eco-feedback tool are further design iterations carried out. To address this issue, user testing was designed to assess four different aspects of the proposed VR system compared with the 2D system: usability, utility, visualization characteristics identification, and motivation.

Using the data collected through user testing, these four aspects were quantitatively evaluated through a series of hypothesis tests. The hypotheses are listed as follows and tested to evaluate the system's usefulness by understanding user experiences and perceptions toward the two systems.

Hypothesis 1: A difference exists between the usability of VR and 2D eco-feedback systems.

Hypothesis 2: A difference exists between the utility of VR and 2D eco-feedback systems.

Hypothesis 3: A difference exists between user identification of the visualization characteristics in 2D and VR eco-feedback systems.

Hypothesis 4: A difference exists between the perceived energy-saving motivation of VR and 2D eco-feedback systems.

Table 1. Summary of evaluation aspects excluding demographic section

Evaluation method	Evaluation aspects	Measures
System design evaluation	**Usability**: *Understanding of color coding*	Single choice
	Usability **Utility** **Visualization characteristics identification** **Motivation**: *this system is likely to motivate me to reduce energy*	Likert scale (1 = strongly disagree, 5 = strongly agree)
System comparison	**Motivation**: *which system is more likely to motivate you to reduce energy and why* **Preference**: *which system do you prefer and why*	Single choice, open ended

Note: Names of evaluation aspects are in bold texts; examples of questions or descriptions of certain evaluation aspects are in italic texts.

Because usability and visualization characteristics are composed of multiple elements, for Hypothesis 1 and 3, if any significant difference was identified, the underlying constructs of system usability and VR characteristics were further analyzed to understand the constructs that contribute to the differences.

Driving Factors for System Preference and Perceived Motivation

In the last section of the survey, after experiencing both systems, participants were asked to select and explain the system they prefer and which is more likely to motivate them to adopt energy-saving behavior. Based on the qualitative information collected in this part and the data obtained in previous sections, the underlying factors that are decisive in participants' choices were further investigated. Thus, we obtain insights into the future design directions of eco-feedback systems at the community/urban scale.

Demographic information was collected at the end of the survey to help us understand how representative our sample was compared with the entire campus population. Participants were also asked about their previous experience using VR and knowledge about campus energy.

A summary of the evaluation perspectives of the survey (demographic information excluded) is listed in Table 1. The five-point Likert rating scale was applied in the survey. To avoid acquiescence bias through which respondents tend to agree rather than disagree with the question (Schriesheim and Hill 1981), three questions were phrased in reversed directions.

In addition to the survey results, observational data were recorded to complement self-report data with the goal of ensuring the study's validity. The time required to complete given tasks—often applied to compare system usability—using both systems was compared to understand whether the proposed system can support users locating a building within the virtual community and identify any inefficiency in a timely manner. During the user testing process, users were asked to repeatedly locate a building with a certain color (i.e., red, green, and black) at a given date. The time taken to complete a task and the corresponding accuracy were recorded to help with system usability evaluations. The experimental procedure is provided in Fig. 3.

When analyzing the quantitative data, a nonparametric Wilcoxon Rank Sum Test (Mann and Whitney 1947) was employed to analyze continuous, semicontinuous, and ordinal (e.g., Likert-type data) variables. The p-value threshold was set to be less than 0.05 to indicate a statistically significant difference (Fisher 1992). The results based on the collected data are summarized and discussed in the following sections.

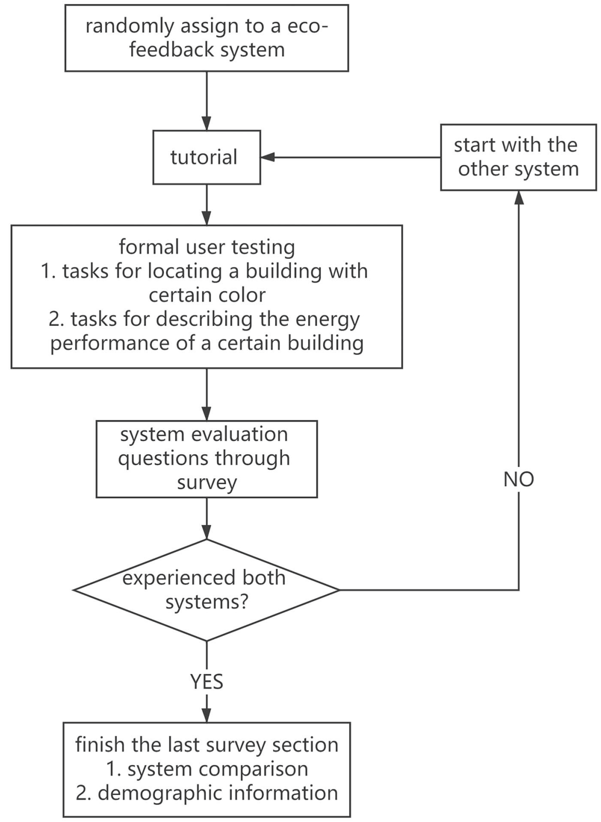


Fig. 3. Flowchart of experiment procedure.

Results

Participants Information

Forty participants were recruited in this study. Table 2 provides an overview of the collected demographic information. Whereas the majority (75%) of the participants reported previous experience with VR, most of them (N = 36, 90%) used VR less than three times during the past three months. More than half of (55%) the participants had knowledge about building energy information at Georgia Tech and accessed the energy information through the Energy Watch system of Georgia Tech or through digital screens installed within buildings. Previous energy-related activities were also reported, as indicated in Fig. 4. As is indicated, most participants (87%) participated in energy-related activities. The "talked to a friend or family member about an energy issue" and "read an article about a topic involving energy" responses ranked the most frequent among all activities. Only three participants mentioned previous experience with commercially available eco-feedback tools.

Evaluation Results of System Design

The results of the system design evaluation are organized by the aforementioned four aspects: usability, utility, visualization characteristics identification, and motivation. Both self-report and observational data are used to ensure the validity of this study.

Table 2. Demographics of participants

Variables	Frequency (Percentage) Total No. of participants = 40
Age	
18–20	6 (15%)
21–29	30 (75%)
30–39	2 (5%)
50–59	1 (3%)
60 or older	1 (3%)
Gender	
Male	13 (33%)
Female	27 (68%)
Academic degree received	
Some college but no degree	8 (20%)
Bachelor's degree	18 (45%)
Master's degree	13 (33%)
Doctoral degree	1 (3%)
Georgia Tech affiliation	
Undergraduate/Graduate student	38 (95%)
Facility manager	2 (5%)
Previous experience with VR	
Yes	30 (75%)
No	10 (25%)
Previous knowledge of campus energy	
Yes	22 (55%)
No	18 (45%)
Previous experience with eco-feedback system	
Yes	3 (8%)
No	34 (85%)
Don't know	3 (8%)

Because the possible carryover bias might have been introduced in the within-subject experiment, the carryover effects in the experiment were first examined. Participants were asked about their understanding of color coding in the survey after experiencing each system. These data are applied to verify the carryover effects and their impact on respondents' accuracy. The accuracy of either experimental condition under different experimental orders was compared using a Wilcoxon Rank Sum Test. The results of the Wilcoxon Rank Sum Test indicate that p-values are higher than the 0.05 threshold, allowing us to accept the null hypothesis. No significant difference was found between the accuracy under different experimental orders. This finding indicates that no significant carryover effects are imposed by the treatment order.

Thus, the four evaluation aspects of the system design were further examined to investigate whether the proposed VR eco-feedback system is regarded as a useful eco-feedback tool in motivating sustainable behavior. Statistics on the four aspects from the Likert-scale questions are indicated in Table 3, including the means and standard deviations (SD) of the variables measured in the survey. Table 4 indicates the results of the hypothesis test with respect to the four evaluation variables. Detailed information is presented in the following subsections.

Table 3. Statistics for after-scenario survey questions

Evaluation Aspects	Experimental conditions: Virtual reality Mean (SD)	Experimental conditions: 2D Mean (SD)
Usability	4.25 (0.73)	4.27 (0.57)
Utility	4.00 (1.03)	4.14 (0.72)
Visualization characteristics identification	3.71 (0.51)	2.98 (0.54)
Motivation	3.15 (1.17)	3.13 (1.24)

Note: Scores are calculated based on the corresponding values of the Likert scale questions (1 = strongly disagree, 5 = strongly agree); sample size (N) = 40.

Usability

Table 3 reveals that the mean values of usability for both systems are above average (i.e., 3), indicating that both systems are, overall, considered easy to use and acceptable to users. A Wilcoxon Rank Sum Test was carried out to determine whether a significant difference in usability exists between the two systems (Hypothesis 1). The p-value was 0.5816 (Table 4), which is substantially larger than the 0.05 threshold. Hence, the null hypothesis is accepted. Because the t-test result indicates no significant difference between both systems regarding usability, a disaggregated analysis of the underlying constructs is not necessary.

In addition to the survey results, the results of a Wilcoxon Rank Sum Test using the observational data on the accuracy of both systems suggest no significant difference (p-value $= 0.1818$). The time needed to complete each task using either system is indicated in Fig. 5. The average time to complete tasks for the two eco-feedback systems indicated no significant difference (p-value $= 0.2166$).

Utility

To evaluate system utility, participants were asked whether the system could effectively support their needs when accomplishing the given tasks and whether it provided useful information in

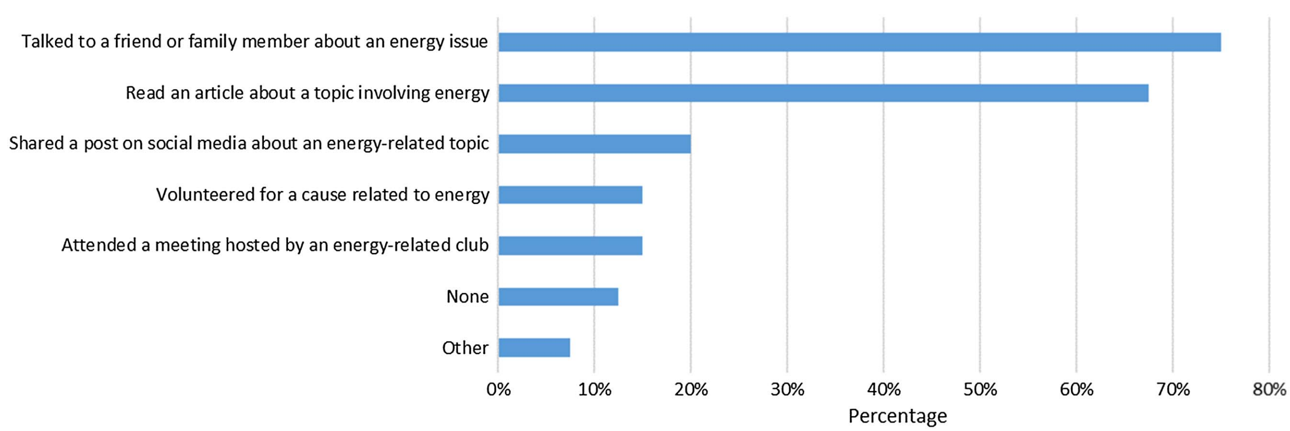


Fig. 4. Participants' reported previous energy-related activities.

Table 4. Hypotheses test results

Hypotheses	p-value	W statistics	Test
H1: Usability	0.5816	742.5	Wilcoxon rank sum test
H2: Utility	0.6161	749.5	
H3: Visualization characteristics identification	<0.0001*	271.5	
H4: Motivation	0.9009	787	

Note: $^{*}p < 0.05$; sample size (N) = 40.

interpreting building energy performance. The results (Table 3) indicate that both systems scored higher than the mean in utility, and no significant difference was identified (p-value = 0.6161) (Table 4).

Visualization Characteristics Identification

Questions on visualization characteristics were adopted to examine whether participants could effectively distinguish the visualization characteristics between 2D and VR. The results (Table 3) indicate that the VR system scored higher than the 2D system, and a significant difference (p-value < 0.0001) was identified in the visualization characteristics, indicating that the participants can differentiate between the visualization characteristics of the two systems (Table 4). Next, the Wilcoxon Rank Sum Test was applied for each underlying construct of the visualization characteristics. The results of the Wilcoxon Rank Sum Test for the disaggregated visualization characteristics are listed in Table 5.

The disaggregated results suggest that the p-values for immersion, distraction, presence, involvement, intuitiveness, and simulator sickness are less than the threshold, indicating statistically significant differences between the two versions of the eco-feedback systems regarding these six underlying constructs. Notably, the p-values for the distraction and one of the intuitiveness characteristics are slightly less than the 0.05 threshold, indicating that the users found the VR system to be more distracting when the functionalities within were considered less intuitive.

Motivation

As an eco-feedback tool, knowing whether the proposed system could effectively encourage sustainable behaviors is critical. According to the Wilcoxon Rank Sum Test, no significant difference (p-value = 0.9009) was found for motivation (Table 4), suggesting a rejection of the fourth hypothesis. Both systems scored slightly higher than the average value for motivation (Table 3).

Notably, the standard deviation values of motivation fluctuate significantly, meaning that perceptions of energy-conservation motivation toward the two systems vary substantially among the participants. In the next subsection, the driving factors affecting user selections toward the preferred and more motivating system are further investigated using both quantitative and qualitative data.

Driving Factors for System Preference and Perceived Motivation

At the end of the survey, participants were asked about their preferences and perceived energy-saving motivations toward the two systems. Participants indicated polarized attitudes toward the two systems (Table 6). The results revealed that 23 (57.5%) participants identified the VR system as more motivating compared with

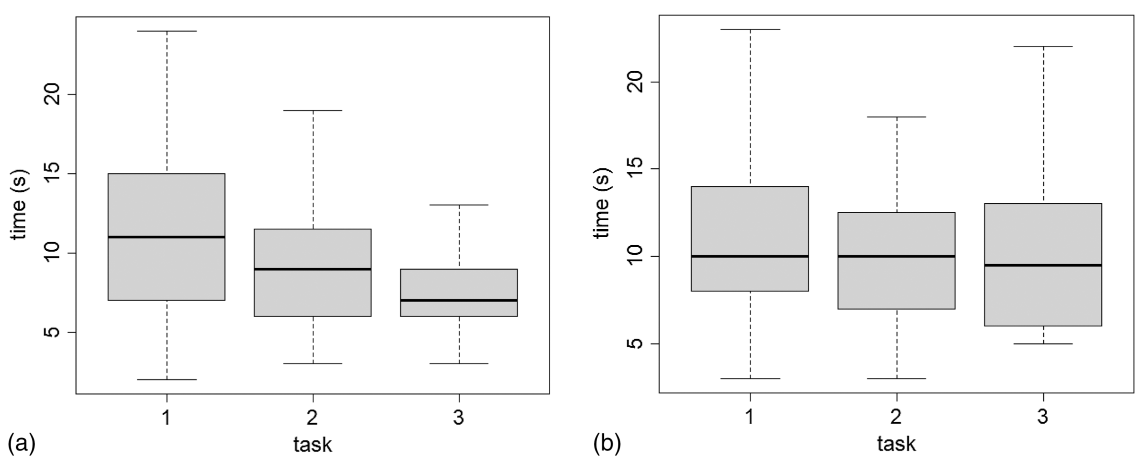


Fig. 5. Task completion time of (a) 2D; and (b) VR eco-feedback system.

Table 5. Comparison results of t-test that underlie constructing visualization characteristics between two eco-feedback systems

Category	Questions	p-value
Immersion	I felt a sense of being immersed in the virtual environment	<0.001*
Intuitiveness	I felt control over the system	0.2569
	I DID NOT have a clear idea of how to perform a particular function	0.0496*
Control factor/natural	My interactions with the environment DID NOT seem natural	0.4901
Realism/natural	Scenes in the virtual environment seemed consistent with my real-world experiences	0.2193
Distraction/interface quality	I concentrated on the assigned tasks rather than on the mechanisms used to perform those tasks	0.0372*
Presence	I felt a sense of presence (i.e., being there)	<0.001*
Involvement	I was involved in the virtual environment	<0.001*
Simulator sickness	I felt sick/nauseous when using the system	<0.001*

Note: $^{*}p < 0.05$.

Table 6. Preference and perceived motivation toward two systems

Evaluation aspects	Frequency (Percentage) VR	2D
Motivation: which system is more likely to motivate you to reduce energy	23 (57.5%)	17 (42.5%)
Preference: which system do you prefer	19 (47.5%)	21 (52.5%)

17 (42.5%) participants who chose the 2D system (with one participant indicating that neither system motivated them to save energy). Regarding system preference, 19 (47.5%) respondents chose the VR system, and the rest (52.5%) chose the 2D system, which corresponds with users' responses under the satisfaction category of usability for which the significance value (i.e., $p = 0.8415$) was much higher than 0.05, indicating no significant difference between the two systems for overall user satisfaction.

The reasons people chose either system were collected qualitatively through open-ended questions (Figs. 6 and 7). The results indicate that ease of use and the overview picture (i.e., the bird's-eye view of building energy performance across campus) rank top among the reasons for respondents' preferences for the 2D system. Characteristics such as entertaining, immersive, realistic, and engaging, along with ease of use, were mostly identified by participants as reasons for their preferences for the VR system.

Regarding perceived energy-saving motivation, respondents who selected the 2D system mostly referred to the fact that this system could provide an overall picture of building energy performance across the campus (e.g., "... easier to see the widespread energy usage in the map," "... better overall idea about energy consumption around campus") and enabled them to immediately identify inefficient ones (e.g., "red buildings pop out immediately," "... make a quick analysis some buildings are more inefficient than others"). The reasons that the VR system was more motivating, as reported by participants, fall heavily on system features, such as engaging, entertaining, realistic, and immersive. The VR-integrated system was reported to enhance their awareness and understanding of energy usage (e.g., "... stand next to the buildings I spend a lot of time in and see how the consumption changes ...," "... in a real world to recognize how energy cost in your building," "... making me feel the energy use," "... understand and see the energy use on campus").

In an open-ended question, participants were asked to provide comments on the system that they had just experienced. For the 2D system, eight comments suggested that the system was easy to use,

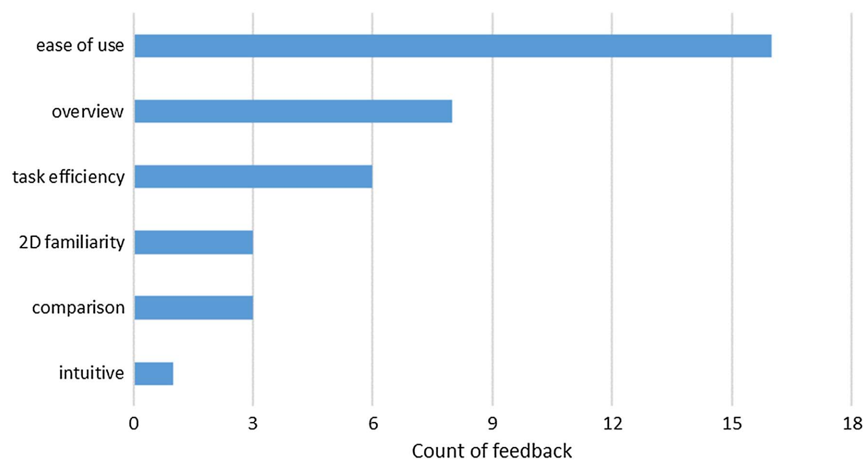


Fig. 6. Reasons for preference toward 2D system.

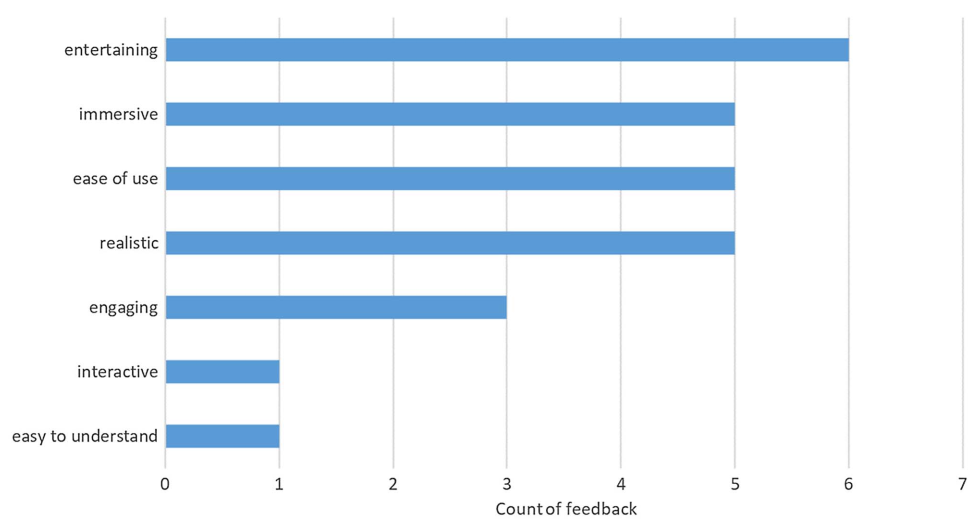


Fig. 7. Reasons for preference toward VR system.

Table 7. Statistics of those who chose the VR eco-feedback system as preferred and more motivating system

Subgroups (number of participants)	Evaluation aspects	Mean Scores		W statistic	p-value
		VR system	2D system		
Users who preferred VR system ($N = 19$)	Visualization characteristic identification	4.26	3.33	334	<0.001*
	Usability	4.69	4.28	277.5	0.0044*
Users who were more motivated by VR system ($N = 23$)	Visualization characteristic identification	4.11	3.33	467.5	<0.001*
	Usability	4.48	4.22	343	0.0885
Users who preferred 2D system ($N = 21$)	Visualization characteristic identification	3.69	3.48	267	0.2462
	Usability	3.85	4.26	146.5	0.0633
Users who were more motivated by 2D system (N = 17)	Visualization characteristic identification	3.77	3.52	183	0.1899
	Usability	3.93	4.33	112	0.2684

Note: $^*p < 0.05$.

although the VR system was more interesting in visualization ($N = 3$). Complaints ($N = 8$) mostly focused on the difficulty in reading the energy usage values that hovered above building models. Participants were attracted by the immersive and realistic experience using the VR system; however, some of the comments ($N = 7$) criticized that the system was not very easy to use or that users experienced discomfort when using the system. Suggestions to add more information about energy usage within each building appeared in comments for both systems ($N = 7$).

To further verify the findings of the qualitative analysis, quantitative analysis based on the survey data was conducted using a t-test to assess the existence of a significant difference. Participants were divided into subgroups based on their selections. Table 7 indicates the survey results of those who preferred or felt more motivated using the VR eco-feedback system. As the table indicates, those who preferred the VR eco-feedback system scored significantly higher on visualization characteristics identification and usability in the VR eco-feedback system than in the 2D eco-feedback system, meaning they tended to identify the unique characteristics of a VR system and thought that the VR system was easier to use. Those who felt that the VR system was more motivating could also identify the characteristics of the system but thought that both systems were of similar usability.

Table 7 also lists the results of the participants who thought that the 2D system was preferable or motivating. Those participants thought that both systems were of similar usability (i.e., no significant difference identified between the usability scores), whereas the 2D system scored higher in usability. Notably, participants who preferred or felt more motivated toward the 2D system could not effectively identify the unique characteristics offered by the VR system.

Discussion

Information representation plays a critical role in determining the effectiveness of eco-feedback systems (Francisco et al. 2018), which becomes increasingly important as the eco-feedback systems scale up to the community level and involve more temporal and spatial information complexities. The present study explored the potential offered by advanced visualization technology (i.e., virtual reality) in information representation as an eco-feedback system. The effectiveness of the proposed prototype system was explored through a within-subject experimental design by comparing the system's performance with a control group (i.e., 2D eco-feedback system) involving four different system design aspects. A series of hypothesis tests were carried out to quantitatively evaluate the usefulness of the proposed system. In addition, relative to the traditional 2D representation, we investigated the system that users found to be preferable or motivating toward sustainable behaviors and explored the possible decisive factors in their selection. The results of this study help deepen our understanding of the potential and limitations of introducing innovative information representation techniques into eco-feedback systems and provide valuable input for future directions of eco-feedback system developments to promote community/urban sustainability management.

Usability and Utility

As a result of insufficient statistical evidence, suggesting a failure to reject both null hypotheses of H1 and H2, it is suggested that no significant differences between the two eco-feedback systems exist in system usability and utility. Because both systems scored higher than 4 on usability and utility based on the survey data, it can be inferred that, overall, users found both systems to be useful.

Accuracy results on questions concerning color coding also support the nonsignificant difference. The outcomes of the color coding agree with previous studies (Bonino et al. 2012; Francisco et al. 2018), whereas in our study, the accuracy of the user understanding of color coding is better than that in Bonino et al. (2012) and Francisco et al. (2018), which might result from our surveyed population being smaller, predominantly young college students, and relatively knowledgeable about campus energy. Nevertheless, the observational data collected during users using both systems suggest that a smaller proportion of participants related the color coding with building energy performance when completing given tasks, whereas an increasing number of users began to comprehend the color coding during repetitive tasks. The gap between observation and survey suggests a possible learning process, as was suggested from one participant's comment: "didn't realize there was a relationship between color and energy use until the exercise was over." This difference also confirms previous findings (Adams et al. 1999; Campbell and Fiske 1959) on the bias introduced by relying too much on self-reported data. This study integrates both self-reported survey data and observational data to ensure higher validity. More participants related the color coding with energy performance during the description tasks using the 2D eco-feedback system. The VR eco-feedback system likely burdened users' cognitive load (Makransky et al. 2019), slowing them down when associating the color with energy performance while the growing awareness of color coding during repetitive tasks still supports that users can effectively correlate the color with energy performance, given enough time.

The time and accuracy related to completing tasks using both systems do not vary significantly once they have learned how to use each system, whereas the VR system requires a longer initial time to grasp the basic operations. Thus, usability and utility in our proposed system were confirmed by users as critical evaluation elements in system design and development (Bastien 2010), despite possible burdens on cognitive load.

Visualization Characteristics Identification

By supplementing the usability testing in the virtual environment, the null hypothesis of Hypothesis 3 was rejected, supporting the concept that users can effectively identify several VR characteristics offered by the proposed system involving immersion, sense of presence, involvement, and simulator sickness. Those perspectives were proposed by previous studies (Kalawsky 1999; Schuemie et al. 2001; Witmer and Singer 1998) as critical characteristics generated by VR that work together to create a realistic experience. Visualizing data, especially those involving complex information, such as scientific data, multidimensional data, or spatial data, in an immersive environment is suggested to be more understandable for both professionals and the general public (Johnston et al. 2018; Park et al. 2000). The strong sense of presence provided in a highly immersive environment is suggested to help with spatial navigation tasks compared with a 2D system (Slobounov et al. 2015), which is preferable for eco-feedback systems at the community scale. Therefore, these critical factors that can possibly facilitate information communication of community-scale eco-feedback systems were efficiently identified by general users, confirming the promising potential offered by VR technology. The results also suggest some significant differences between the two systems in terms of distraction and functional intuitiveness. As previously mentioned, the VR system might have, to some degree, increased users' cognitive load, and they received much more information than in a 2D system (Ware and Franck 1994). How the users evaluate the overall workload in both systems needs to be further examined because users did not perceive a larger workload compared with a 2D environment, although loaded with more information in the VR environment (Millais et al. 2018). Users may feel distracted completing tasks when they used the VR eco-feedback system for the first time; one participant commented that the animation in VR is "really distracting the first few times," which echoes the findings from Millais et al. (2018) due to more physical movement involved in VR. Regarding the intuitiveness of performing a particular function, the 2D system scored higher than the VR system, indicating that users found the functionalities in the 2D system to be more intuitive. This difference can be explained by the qualitative data for which users expressed that they were more familiar with 2D desktop applications; therefore, the interaction in the 2D system seemed more straightforward to them. Moreover, the observational data suggest that interactions with the time slider in the VR eco-feedback system is somewhat counterintuitive, and most users intuitively attempted to change the time using the joystick when they were supposed to drag the button on the slider with the help of the hand. In their comments, users also put forward this limitation.

Thus, it can be inferred that users could effectively identify several important characteristics generated by the virtual environment, whereas some aspects of VR are not adequately explored and realized in the present prototype system. Future design iterations can help address these issues to fully realize the potential of VR in eco-feedback information communication.

Motivation

The null hypothesis of Hypothesis 4 was not rejected, indicating that participants in general considered both systems to be similarly motivating in possibly adopting energy-saving behavior. Notably, the standard deviation for motivation is relatively large, suggesting that perceived motivation using both systems varies sharply across users. This finding is confirmed by data from user selections of their preferred and more motivating system. The data represent quite polarized results: the preference results indicate a near dichotomy between the two systems, whereas slightly more users found the VR eco-feedback system more motivating.

In all, based on both self-report and observation data, the proposed community-scale VR eco-feedback system was deemed a useful eco-feedback tool, although some VR potentials are not fully capitalized. Notably, a significant difference exists in simulation sickness, which is likely to impair the acceptance of the VR system and be subject to personal characteristics that are not controllable. Thus, future design should also consider the differences among users to improve the system's versatility.

Driving Factors in Preference and Perceived Motivation

Participants had quite different preferences and perceived motivations toward the two systems when their contributing factors varied sharply. As the qualitative analysis results imply, participants' preferences and perceived energy-conservation motivation in the 2D system mostly stem from usability concerns, such as ease of use and the overall picture of energy usage information across the campus. For the VR system, VR characteristics such as being immersive and realistic are more likely to promote energy-saving motivations and preferences for the system. Other characteristics such as engaging and entertaining also enhance motivation and preference and are recognized by other eco-feedback studies as critical elements in determining the potential of eco-feedback systems (Buchanan et al. 2015; Jain et al. 2012; Quintal et al. 2013; Strengers 2011). Entertaining also plays a nonnegligible part in promoting changes in sustainable behavior because it arouses intrinsic satisfaction, such as interest, curiosity, and enjoyment, which is decisive to the durability of user adherence to behavioral changes (He et al. 2010; Lewis et al. 2016).

The total population was further divided into subgroups according to their selections, and their evaluation of the two systems was analyzed to quantitatively investigate the possible driving factors affecting their decision. Users who preferred the VR eco-feedback system could discriminate the visualization characteristics between the two systems. Interestingly, they also thought that the VR system was more usable than the 2D system, although the overall population found that both systems had equivalent usability. Those who felt that the VR system was more motivating could also identify the VR characteristics. Although there was no significant difference, the VR system scored higher than the 2D system in usability, which is opposite from the overall comparison in Table 3. Thus, the unique characteristics of VR, along with system usability, are inferred as the likely decisive factors in promoting user preference and perceived motivation toward the VR system.

Regarding those who selected the 2D system as their preferred and more motivating system, they could not identify the characteristics offered by the VR system. Although respondents reported usability as the main driving factor for their choice, the quantitative results suggest that they did not perceive significant differences in usability between the two systems. Other underlying elements (e.g., easy access to an overview of the campus's energy performance) might work together to contribute to their preferences and perceived motivations. Notably, users can access the overview of building energy performance across the campus in the VR system by zooming all the way out, but few users attempted to do so. This finding suggests that further design developments can address this issue, such as making the view switch easier and be more obvious.

The findings suggest that VR characteristics are important in encouraging participants' choices toward the VR system. Usability is also a nonnegligible element in users' decision making. Differences between the two groups in terms of the identification of visualization characteristics might be associated with their personal characteristics, such as the immersive tendency, which is a measure of individual capability or the tendency to be involved or immersed (Witmer and Singer 1998). Researchers attempted to explore diverse techniques in eco-feedback systems to encourage sustainable behaviors. Targeted or tailored design and information have been suggested as key to effectively achieving sustainability goals (Khosrowpour et al. 2016; Khosrowpour and Taylor 2015). A single representation that meets all users' needs in eco-feedback techniques appears not to exist. By introducing a new information representation technique in eco-feedback systems, the characteristics and variabilities among the communities receiving the information should also be carefully considered.

Tackling the increasing urban energy consumption has become a global challenge facing city managers who are responsible for promoting sustainable city development through optimal resource management and offering a high-quality life for citizens (Yamamura et al. 2017). Public participation is an essential element in achieving sustainability goals set by the government. The worldwide open data initiatives enabled by advanced metering infrastructures have opened the door to engage the public in facilitating city management and sustainability (Attard et al. 2015). Communicating city data in a more understandable, accessible, and engaging way is decisive to the performance of such information policies. This study leveraged VR technology into a community-scale eco-feedback system to encourage local participation in energy sustainability and examined the information visualization and communication potential offered by VR to help with future urban energy management strategies.

This study implemented a robust experiment by integrating data from both survey and observation and involved collecting and analyzing both quantitative and qualitative data, ensuring this study's validity. Several biases that might be introduced by within-subject experiments were carefully considered and examined. To our knowledge, this study offers the first investigation of the applicability and effectiveness of VR as a promising information representation in eco-feedback systems. For the evaluation, a 2D eco-feedback system served as a control group. The results suggest that participants demonstrated polarized attitudes toward the two eco-feedback systems with respect to preference and motivation. VR characteristics, including immersion, presence, involvement, and simulator sickness, along with system usefulness, are critical to participants' decisions. One size does not fit all. Urban management is evolving from unanimous treatment to emphasizing the importance of tailored interventions (Guzmán et al. 2017). Therefore, to better promote public engagement in community/urban energy management and ultimately encourage sustainable behavioral changes, considering users' diverse preferences can possibly improve the effectiveness of an eco-feedback system in information communication.

Limitations and Future Work

This study faces several limitations that can be addressed in future research. Given the accessibility requirement of VR, community members or building occupants might find accessing a VR system difficult or unaffordable. As one of the participants advised, the VR system was not as readily available as the 2D system for mobilization. Moreover, the existence of missing data and the limited number of buildings of certain building types are likely to challenge the reliability of the normative comparison results. Both systems are currently in a prototype development phase, and improvements are needed to develop a more useful application, including changing the color-coding scheme to one that is more friendly to color blind people. The potential of VR in the information representation of eco-feedback systems has yet to be fully explored. Interactions in the immersive environment can be changed to more intuitive ones based on observations during user testing. VR is suggested as being advantageous in communicating dimension data, whereas only electricity data are currently visualized. Multidimensional and more disaggregated data generated during the building operation process, including grid data, renewable energy data, EV charging, and others, will be added to help occupants better understand the sustainability performance of the community. Any experimental design should be aware of possible biases introduced. Self-selection bias is inevitable because it is impossible to always obtain data from a broad base of the total population. All of the participants of this study were from Georgia Tech, which makes them nonrepresentative of the overall population. The results of this study can only apply to communities of similar characteristics. The applicability to other contexts needs to be further studied.

Conclusions

Advanced metering sensors are becoming ubiquitous in our cities, generating large quantities of data in real time. The success of urban management in the present information era heavily relies on how to effectively harness and communicate useful information from the data. Eco-feedback systems leverage the data richness in the urban infrastructure to encourage more sustainable behaviors. This study proposed a novel approach to communicate community-scale energy consumption information with users and aimed to enhance the effectiveness of eco-feedback systems. Both self-reported and observational data helped us gain insights into user perceptions and attitudes toward the proposed VR eco-feedback system, with a 2D system as the control group. Participants demonstrated polarized attitudes toward the two systems with respect to preference and perceived energy-saving motivation. The analysis results suggest that the VR characteristics, namely, immersion, presence, involvement and simulator sickness, and system usefulness, are critical to explaining users' dichotomous choices.

Overall, a one-size eco-feedback system does not fit all. Because eco-feedback systems are expanded beyond a single building, aided by the increasing availability of energy data produced by citywide smart meter networks, the effectiveness of urban eco-feedback systems heavily depends on how the information is visualized and communicated to community users. Thus, the findings of this study indicate that eco-feedback developers should design such systems to be versatile enough to incorporate different preferences of community users who are receiving the information or be able to deliver energy feedback that meets various user preferences. Such eco-feedback systems may more effectively encourage sustainable behaviors and meet municipal sustainability goals by involving public participation in urban energy management.

Data Availability Statement

Some or all of the data, models, or code that support the findings of this study are available from the corresponding author on reasonable request. A screen recording of the user testing for this study is available in the Supplemental Materials. Additional data that support the findings of this study, including the survey template and deidentified raw survey results, are available from the corresponding author on reasonable request.

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Supplemental Materials

Video S1 is available online in the ASCE Library (www.ascelibrary.org).

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