Use of augmented-reality in teaching energy efficiency: prototype development and testing

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ABSTRACT: Passive solar and energy efficiency concepts are usually taught through lectures, textbooks, or hands-on experimentation, but the relationship between these concepts is typically not effectively visualized. To address this, this paper reports on the design, development and preliminary testing of a prototype Augmented Reality (AR) application for residential energy use education. This tablet-based AR application simulates the impact of different residential building design characteristics on both indoor temperature (for passive heating/cooling) and annual energy use and cost (for mechanical HVAC). The application was developed by an interdisciplinary team of researchers/educators from three related fields: architecture, interdisciplinary education, and computer science. AR consists of additional information that is visible through a technology interface, shown on top of the images of the real world under study within a digital 3D space. The interdisciplinary model presented in this paper integrates three distinct lenses: 1) passive design and energy efficiency education 2) AR as an interactive modality and 3) a computationally complex building performance simulation model. In particular, the paper reports on the results of an experiment in which junior-level university students in a school of architecture used the prototype. Results from the pre and post knowledge surveys conducted within the experiment show consistent and high improvement in the students' confidence in their knowledge of the topics following the use of the prototype. Student feedback was also generally positive but some issues were identified which may indicate that this prototype would be more effective at the freshmen level. Plans for future development phases for this project include focusing on this new population. The project described in this paper also illustrates the considerable potential that interdisciplinary collaboration offers for architectural research through enabling architectural researchers to tackle more complex issues and developing a better understanding of the research approaches and expectations in other disciplines.

KEYWORDS: Augmented Reality, Energy Efficiency, Passive Design, Education, Performance Simulation

INTRODUCTION

Architecture is a field of knowledge which draws from multiple other disciplines and as such offers strong potential for interdisciplinary work. The case for the important role played by both the human sciences and the physical sciences in architecture has been clearly established in the literature. This paper discusses a project which builds on this interdisciplinary potential and addresses an issue which is gaining considerable importance in architecture and other built environment disciplines: improving the environmental performance of buildings. The growing significance of environmental performance has increased the role of environmental technology, and technology in general, in architecture and architectural education (i.e., Abel, 2000; Kolarevic & Malkawi, 2005; Steele, 2005). While the recognition of the need for better integration of environmental performance criteria in architectural education and the search for means of effectively achieving this is far from being a new concept, recent increases in concern for the environment have given this area of research a renewed sense of urgency. Effectively introducing new generations of architects, in the formative years of their architectural education, to the basic principles and concepts of passive solar design and energy efficiency can have both a direct impact on the students' understanding of the basic principles and relationships involved, as well as an indirect impact on increasing their awareness of the significance of these issues. This can also have a positive impact on their subsequent professional careers. Several approaches for teaching these concepts in architecture curricula can be identified in the literature. Examples of these include introducing them in textbooks, lecture classes, technically-focused design studios, or through hands-on experimentation (e.g. Heliodons). While each of these approaches offers some potential, none of them provide an effective means of visualizing the relationship between the concepts involved.

Augmented reality (AR) consists of additional information that is visible through a technology interface, shown on top of the images of the real world under study within a digital 3D space. To date, few research publications report on the impact of AR-supported collaborative learning spaces. Studies (e.g., Pemberton and Winter, 2009; Van, 2009; and Shelton and Hedley, 2002) show that the use of AR improved students' motivation and engagement, and can significantly improve understanding of scientific principles through providing a unique combination of visual and sensory information that results in a powerful learning experience. Studies also show that AR and game-based learning are likely to gain widespread usage in the near future.

Taking advantage of this innovative technology, this paper reports on the design, development and preliminary testing of a prototype AR application for residential passive design and energy efficiency education. This tablet-based AR application simulates the impact of different residential building design characteristics on both indoor temperature (for passive heating/cooling) and annual energy use and cost (for mechanical HVAC). The application was developed by an interdisciplinary team of researchers/educators from three related fields: architecture, interdisciplinary education, and computer science. The interdisciplinary model presented integrates three distinct lenses: 1) STEM Education 2) AR as an interactive modality and 3) a computationally complex building performance simulation model. The paper will report on the process used to develop the AR application, the components of the developed prototype, and the validation and usability testing conducted for it so far. In particular, the paper will report preliminary results from an experiment in which the prototype was used by undergraduate architecture students from a large public university based the results from pre-post surveys. The paper will also discuss future work planned within this ongoing project and its potential within architectural education programs.

1.0 LITERATURE REVIEW

1.1. Passive design and energy efficiency in architectural education

Discussion of the need to better integrate environmental performance issues, principles, and concepts in architectural education can be traced back to Meunier (1980) who argues for the necessity of introducing performance, measured in non-visual ways, into architectural education through the application of simple scientific principles and the use of multiple testable models, both physical and mathematical. Brown (1980) further argues that "mechanical electrical building design must be integrated with a synthetic building design process so as to combine programmatic elements in a way that is responsive to physical, social and political context." Principles of passive design and energy efficiency are typically introduced into architectural curricula using one or more of the approaches discussed next. The first approach is through the use of *textbooks*. Numerous textbooks have been developed to assist architecture students in understanding the principles of passive design and taking environmental performance criteria into consideration within their design process. Prominent examples include "Inside Out" (Brown and Reynolds 1982), "Sun, Wind, and Light" (Brown and Dekay, 2000), "Mechanical and Electrical Equipment for Buildings" (Grondzik et al. 2010) and "The Green Studio Handbook" (Kwok and Grondzik, 2011). Another approach involves the use of *performance simulation software*, which offer students the potential and ability to experiment with greater complexity in a shorter time frame. The Carbon Neutral Studio Initiative (SBSE 2009) documented several examples of the use of these tools in both lecture classes and studios. While offering considerable potential, many of the available simulation tools require time to acquire the technical skill level needed to take full advantage of their capabilities and potential. A third approach to introducing architectural students to the principles of passive design and energy efficiency involves the use of *hands-on experiments and activities*. The Agents of Change Project (2005) provided training sessions for faculty and teaching assistants in several areas including developing exercises to implement at their home institutions and many of those exercises involved hands-on experiments and activities. A classic example of this approach is the use of Heliodons in introducing students to the principles of solar geometry and passive design. Several versions of the Heliodon can be found ranging from highly sophisticated commercial models to smaller models which can easily be constructed in an architecture school's shop. While being easy to use and very effective in introducing students to the basic principles involved, the time and resource requirements of hands-on experiments make it difficult to use them to understand more complex scenarios. The approach used in developing the prototype discussed in this paper combines the latter two approaches, use of simulation software and hands-on experimentation, and places them in the context of the new and very promising potential offered by AR technology as discussed in the coming sections.

1.2. Use of technology in education

Technology has regularly been used in classrooms and learning environments. Through tools such as the internet, videos, software, games and simulations, our learning experience can be enhanced with real world scenarios (Kirkley & Kirkley, 2005). As real world problems and scenarios grow more complex, newer technology, like simulation and AR, is capable of providing more complex and authentic experiences. Klopfer and Squire (2008) suggest that as AR is established further into handheld devices, there are unique opportunities for uses in education. They point out that handheld devices allow for the collection of real-time data and support collaboration, yet allow for individual exploration. Although there are few studies on learning environment impacts, research by Shelton and Hedley (2002) found AR media was useful in "teaching subject matter students could not possibly experience first-hand in the real world". Regarding simulation, the visual representation of calculated simulation results has the potential to greatly impact the user's ability to understand their implications and identify any relationships and trends they may indicate. McDonald (2010) argues that simulation results must convey meaning and their effects on the performance of the building should be highlighted. Interface design plays a major role in efficient educational technology, unusual computer navigation or unfamiliar actions that obscure the overall experience are common.

1.3. Augmented reality (AR)

AR experiences help one understand spatial relationships (Kerawalla, et al., 2006). They provide a physical interaction that brings a new perspective and understanding (Rosenbaum, et al., 2007). Early AR systems have been used in maintenance and repair projects for Boeing, and Columbia University's KARMA (Knowledge AR for Maintenance Assistance) helped explain maintenance and repair tasks. Mobile systems have been tested that could be used for travel, history recreation and touring as well as for U.S. Coast Guard navigation systems. AR has also been used in the medical field guiding doctors performing biopsies (Kirkley & Kirkley, 2005). Publications discussing AR-supported collaborative learning spaces include Pemberton and Winter (2009), who report on a platform that supports remote collaboration. They found that the use of AR improved students' motivation and engagement. Shelton and Hedley (2002) created an AR-based simulation focused conceptually on "rotation/revolution, solstice/equinox, and seasonal variation of light/temperature" (p. 1). They showed that participants significantly improved understanding of the science, and indicated that understanding new concepts had the potential to be fundamentally changed "through a unique combination of visual and sensory information that results in a powerful learning experience" (p. 7).

1.4. AR in education

Billinghurst & Duenser (2012) argue that there are recognized advantages for using AR in education including the increased retention of learned content due to the interactive nature of the technology especially compared to passively learning from textbooks. They further argue that AR can be an effective means of adding meaning to the student's learning experience and can support deep content learning. In general, AR has been shown to have positive educational benefits, but there are usability concerns that potentially threaten motivation and learning benefits. Discussing the use of AR in higher education, Liarokapis and Anderson (2010) presented ways of effectively incorporating AR with existing multimedia materials and identified several usability issues. Moreover, they found that different populations of higher education students may have different preferences for system and interaction design. With regard to architectural education, Webster et al. (1996) developed an early prototype of an AR system for architectural construction, inspection, and renovation which used an optical see-through display to afford users something akin to 'x-ray vision' of the internal structures of buildings. Wang et al. (2008) compiled an extensive review of using mixed reality (i.e. AR) in architectural design and construction, and showed that AR can be used to enable new types of interactions that enhance the design process. Behzadan et al. (2007) also developed a hardware and software framework for visualization of construction processes, thus showing the potential the technology offers for built environment disciplines.

2.0 PROTOTYPE DEVELOPMENT

As discussed previously, this paper reports on the work of an interdisciplinary team of researchers to design, develop, and test a comprehensive project-based and technology-mediated learning environment that combines computationally complex simulations, real time simulations, graphical user interface (GUI), tangible interaction, and visualizations. The vision of the proposed prototype is that effectively combining such new modalities, through supporting deep content learning, transforming inquiry-oriented behaviours into habits-of-mind, and refining appropriate communication skills, will result in an improved learning experience for the students. The proposed prototype aims to teach: 1) the scientific principles behind passive design and energy efficiency, and 2) the practical implication of integrating these principles in the design of single family homes. Through the use of the prototype, students can understand the relationships between architectural design parameters (e.g., building size, form, orientation, material choices, window size and placement, etc.) and the underlying science (e.g., passive solar energy, energy transfer and conversion). Although the prototype discussed here focuses on single-family residential buildings, the concept behind the prototype is applicable to other residential and non-residential building typologies. The following sections describe each of the three major components of the prototype in more detail.

2.1. Real-time simulation and visualization

The first component of the AR prototype combines a visualization of solar simulation and Brownian motion with a combination of 2D GUI and tangible AR interfaces. The tangible AR interface will be discussed more in section 2.3. The GUI works in two modes: 1) the passive mode: which assumes that the house is not air-conditioned and in which users manipulate the design characteristics of the house (e.g., size, form, orientation, material choices, window size and placement, shading size, etc.) in order to achieve internal human thermal comfort conditions, 2) the active mode: which assumes the house is mechanically air-conditioned and in which users can modify the same characteristics and get feedback about the annual energy use and utility costs. Users look through a tablet at markers and see a visualization of the house on the screen. Inside the visualization of the house is another visualization of energy transfer and conversion at the atomic level. Users can change the design characteristics of the house using the tangible interface (see section 3.3) resulting in immediate feedback to the user regarding either internal temperature (the passive mode) or annual energy use and costs (the active mode). Figure 1 shows two screen shots from the AR GUI, one showing the visualization of the sun's position and the other showing the visualization of the Brownian motion.

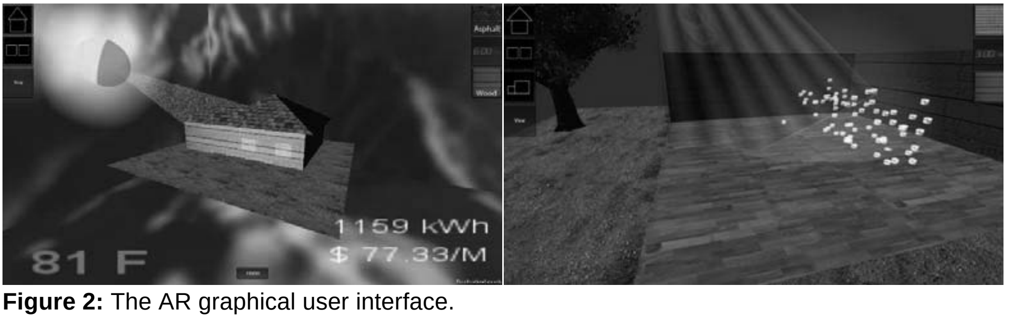

Figure 2: The AR graphical user interface.

2.2. Computationally-complex performance simulation

Internal temperature, annual energy use, and annual utilities cots data used in the prototype were pre-calculated using the performance simulation package IES-VE Pro. This process included developing a baseline model for a typical residential building in a major US city and simulating its performance in both passive and active modes. Nine baseline models were developed and simulated representing three different single-family house (SFH) sizes and form proportions. These included a small SFH (1,800 ft^2), an average SFH (2,160 ft^2), and a large SFH (2,450 ft^2). Each of these three sizes was simulated in three different proportions: 1:1, 1:2, and 1:3, maintaining the floor area and volume of the house in each case. This aimed to capture the considerable impact that building form and proportion have on both passive performance and cooling/heating energy use. The characteristics of the base models were developed based on census data and data from the Residential Energy Consumption Survey (RECS), and aimed to represent as much as possible the typical characteristics of single family homes in the project location. Characteristics not available in census data and RECS were based on NREL's Building America House Simulation Protocol (Hendron & Engebrecht, 2010).

All nine base-models were calibrated using the Building America House Simulation Protocol. This process aimed to insure that the results of the simulation closely matched actual conditions and that results of future parametric simulations reflects as much as possible the actual impact of each of the variables tested on the house performance (both in the passive and air-conditioned modes). A parametric analysis was then conducted, which included changing the values of selected building characteristics and repeating the simulation in both the active and passive modes to evaluate the impact of those changes on the performance metrics mentioned above. Building characteristics modified included: glazing size and orientation, existence and size of shading devices, glazing type, wall/room thermal resistance (R-values), and wall roof exterior finish materials. In all, 45 scenarios were simulated. Figure 2 shows screen shorts of one of the simulated scenarios including both a wireframe and rendered view.

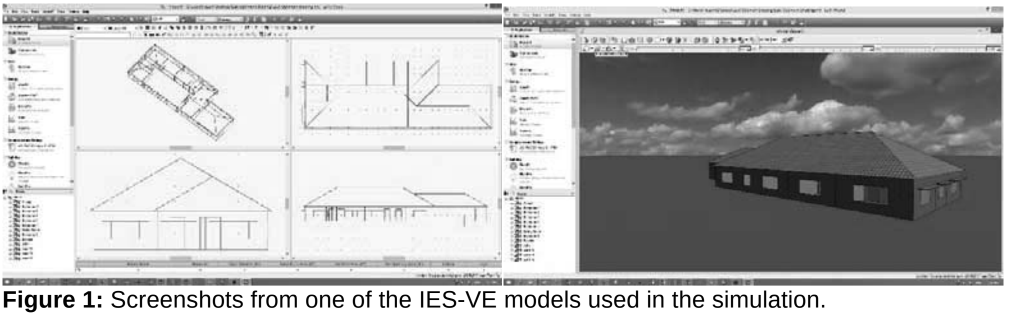

Figure 1: Screenshots from one of the IES-VE models used in the simulation.

2.3. Tangible AR interface: use of the Heliodon

The final component of the prototype included a physical model of the SFH mounted on a simplified Heliodon that allowed the user to change the orientation, time of day and year, and latitude of the house. The model and Heliodon were instrumented with a series of sensors, which are tracked by the AR interface. Users are able to physically change house characteristics (e.g. house size, proportions, glazing types, shading, surface properties) and based on their selections, the AR interface would show a visualization of the selected set of characteristics as well as the resulting performance of the house (either energy use and utility cost for the active mode, or internal temperature for the passive mode). Performance data were pulled by the AR interface from the previously simulated scenarios. Users can also change the time of day and year using the Heliodon although this would only impact the passive mode (i.e. internal temperature). Figure 3 shows one of the two usability pilot studies conducted for the prototype.

Figure 3: The full prototype in one of the cycles of usability testing.

3.0 MODEL TESTING AND VALIDATION

3.1. Preliminary usability testing

Two pilot studies with nine teachers and thirteen high school students were conducted to evaluate the usability and acceptability of the prototype. In particular, user feedback was collected through surveys and interviews and that data, as well as the observations made by the research team, were used to further develop the prototype and address issues identified through the testing (Ferrer et al., 2013).

3.2. Prototype testing in architectural curricula

While the initial development and testing of the prototype was primarily aimed at the high school context, the research team recognized that a potential exists for using the prototype in undergraduate education and in particular in architectural education. To investigate this potential, an experiment was conducted in which junior-level architecture students in a large public university directly interacted with the prototype. The experiment was conducted as part of the lab component of an environmental control systems course. While the experiment was conducted as part of the class activity, several measures were put in place to eliminate the potential of bias in the results. First, participation in the experiment was made optional and an equivalent activity was made available for students unwilling to participate. Second, the faculty member, who is also a member of the research team, was not involved in conducting the experiment and was not informed of the names of participating students. Finally, collection of information from the students regarding the experiment was done completely anonymously and no records linking responses to student names were maintained. In total, 118 students participated in the experiment. The design of the experiment consisted of three major activities described as follows:

1) Two weeks prior to being exposed to the prototype, all students were asked to answer an anonymous knowledge survey (Nuhfer, 2003) consisting of nine questions about passive solar design and energy efficiency principles. Students were asked to indicate their level of confidence in knowing the answer to these questions on a scale of one to five, with one meaning the student had no confidence in being able to answer the question and five meaning the student was very confident of the answer. In total, 118 students responded to the pre survey.
2) Students were divided into teams and each team was exposed to the prototype in two consecutive rounds of lab sessions. In the first round of lab sessions, students were introduced to the prototype and its functionality and then they were invited to independently explore its use in both the passive and active modes. Students were also asked to investigate the impact of each of a number of building design characteristics on the model performance.
3) Prior to the second round of lab sessions, the prototypes were set to the characteristics resulting in the worst possible performance. In the sessions, students were asked to use the prototype to identify a set of characteristics that will result in achieving specific levels of performance improvements (a reduction in energy use of 10%, 20%, and 30% for the active mode; and a comparable reduction in internal temperature for the passive mode).
4) Following the second lab sessions, all students were asked to answer the same knowledge survey, also anonymously. Students were also asked to provide comments on

their experiences using the prototype. In total, 100 students responded to the post surveys and provided written comments. Both lab sessions were also video recorded.

4.0 EXPERIMENT RESULTS

The results of the experiment reported in this paper include both quantitative results (based on a comparison between the pre and post survey responses) as well as qualitative results (based on student comments, video recordings, and research team observations). With regard to the survey responses, comparing the pre and post surveys showed a notable increase in the students' confidence in their ability to answer all the survey questions following the two lab sessions. In the pre survey, student confidence levels ranged between 2.74 and 3.52 (on a 1-5 scale) indicating an average confidence level in all questions. The average response was 3.19 and the standard deviation was 0.29. Students showed the lowest level of confidence (2.74) in the question addressing their ability to optimize design characteristics in order to improve performance. In comparison, responses to the post survey ranged between 4.27 and 4.44 with an average of 4.41 and a standard deviation of 0.09. The percentage of increase in students' confidence for individual questions ranged from 25% to 57% with an average increase of 39% and a standard deviation of 11%. The highest percentage of improvement, 57%, was found in the optimization question, which showed the least level of confidence in the pre-survey, while the lowest percentages of improvement were found in the questions relating to the impact of window size and shading on performance. Students answering "very confident" for the optimization question increased from 7 to 39 (6% to 39%). Figure 4 shows the average response for each of the survey questions in both the pre and post surveys.

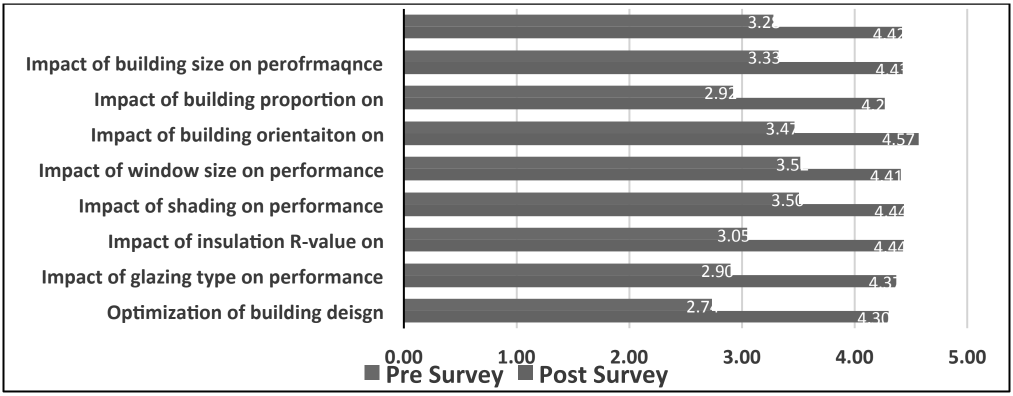

Figure 4: Comparison between student responses to pre and post survey questions.

The student comments and feedback collected after the two lab sessions were categorized into four major sections: *potential, content, function and usability, and passive design*. With regard to *potential*, the comments were overwhelmingly positive although in some cases the comments were qualified by references to some usability issues discussed later. Representative examples include: "*offers potential and a great idea*", and "*great potential and visual representation*". With regard to *conten*t, the comments were generally positive and indicated that the students managed to clearly understand the content through the use of the prototype. On the other hand, some students commented that the variables they could manipulate were limited and/or simplified and recommended increasing the complexity of the prototype as well as the scope of buildings it can deal with. Example comments include: "*Clear representation of passive and active functions within the building*", and "*Would like to see more building material options*". With regard to *function and usability* most comments stated that the GUI was intuitive, user friendly, and easy to understand and navigate. On the other hand, several minor technical usability issues were identified in the comments relating to some of the tablets not functioning occasionally, not recognizing some of the sensors, or freezing and needing to be restarted. Examples of comments include: "*dummy proof*", "*fairly user friendly*", "*fun and entertaining*", "*good and cool way to learn but bugs were a hassle*", "*worked at the beginning but then stopped*". Finally, with regard to *passive design* the comments were again overwhelmingly positive and indicated an appreciation of the potential the prototype offered in this area. Example comments include: "*If it were developed further it would be a great tool for designers*", "*Great way to explore the basic principles of passive design and solar efficiency*". Observation of the video recordings generally showed that students were engaged with the prototype and that it was successful in provoking discussions and collaborative activities. The usability issues stated in the comments were also visible and frequent and in some cases led to the students appearing frustrated. Those usability issues make the positive outcome of the knowledge survey even more significant as it indicates that the results could have potentially been even better if those technical issues were resolved.

CONCLUSIONS

This paper reported on the process of designing, developing and conducting preliminary usability and effectiveness testing for an innovative prototype AR application for residential passive design and energy efficiency education. The prototype was developed by an interdisciplinary team of researchers from computer science, education, and architecture. The prototype combines computationally complex simulations, real time simulations, graphical user interface (GUI), tangible interaction, and visualizations. Through taking advantage of the considerable potential offered by AR and combining these modalities, the prototype aims to create a learning environment that supports deep content learning, transforms inquiry-oriented behaviors into habits-of-mind, and refines appropriate communication skills. While the prototype offers potential for several educational levels, this paper focused on the potential it offers for architectural education specifically in relation to the teaching of passive design and energy efficiency principles. Through the use of this prototype, students can develop a better understanding of the scientific principles involved as well as of the impact of a variety of building design characteristics on the performance of the building in both active and passive modes.

The results of the experiment described in this paper indicate a strong potential for the use of the proposed prototype in architectural programs. Comparison between students' confidence in their knowledge of the topics addressed before and after using the prototype shows consistent and high levels of improvement in all aspects measured by the survey, with the highest improvement being in their confidence in their ability to address complex tasks such as the optimization of multiple design characteristics, which are typically the most difficult issues to tackle at this level. Student feedback also indicated a generally positive response to the prototype and an appreciation of the potential it offers. This positive response is particularly interesting as it came in spite of the experiment being affected by several minor usability and functionality issues which would typically have a negative impact on the results. We believe this to indicate that the prototype can have an even more positive impact once fully developed and tested. On the other hand, student feedback from the experiment showed that the current prototype may be too limited in offering the variety of variables and level of complexity expected by, and perhaps needed for, students at the junior level (the population of the study). While the current plans for developing the prototype do include increasing its level of complexity by adding additional variables and scenarios as well as including other residential and potentially non-residential building typologies, the results indicate that the prototype may be more effective at the freshmen level where it could be used to introduce students, potentially for the first time, to the principles and concepts of solar geometry, passive design, and energy efficiency. Plans for future development phases for this project include focusing on this new population as well as expanding the experiments to undergraduate freshmen students in other disciplines such as science, engineering, education, etc. Planned expansions also involve the use of control groups and more detailed statistical analysis to increase the reliability of the results. Other potential future directions for the project include focusing on user behavior issues, expanding the prototype to the urban scale, and expanding the performance metrics covered beyond temperature, energy and cost. Even though the preliminary results of this experiment were positive, more testing is needed to determine the effectiveness of the proposed prototype as well the best approaches of integrating its use in architectural curricula.

The project described in this paper also illustrates the considerable potential that interdisciplinary collaboration offers for architectural research. While certainly not unique, the composition of the interdisciplinary team working in this study is not typical in architectural research. Working in such a diverse interdisciplinary team, while presenting its own set of challenges, enabled the research team to develop a project that offers considerable long term potential in each of the three disciplines involved, and through the collaboration enhanced their own personal knowledge of the other two disciplines. The project also provided a unique opportunity for several architectural graduate research assistants to be exposed to more structured forms of research, which they were not accustomed to. Working in such a diverse interdisciplinary team also presented some challenges. These included the need for the researchers to develop a common language and an appreciation of the differences in approaches and expectations of research in each of the three disciplines involved. Having an effective means of communication played a major role in developing this common ground. Over the course of the project, there were also some minor logistical and administrative challenges that the team dealt with. These issues were, in general, relatively easy to resolve especially given the diverse nature of the academic and administrative units that the researchers belong to.

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