

Evaluating Educational Settings through Biometric Data and Virtual Response Testing

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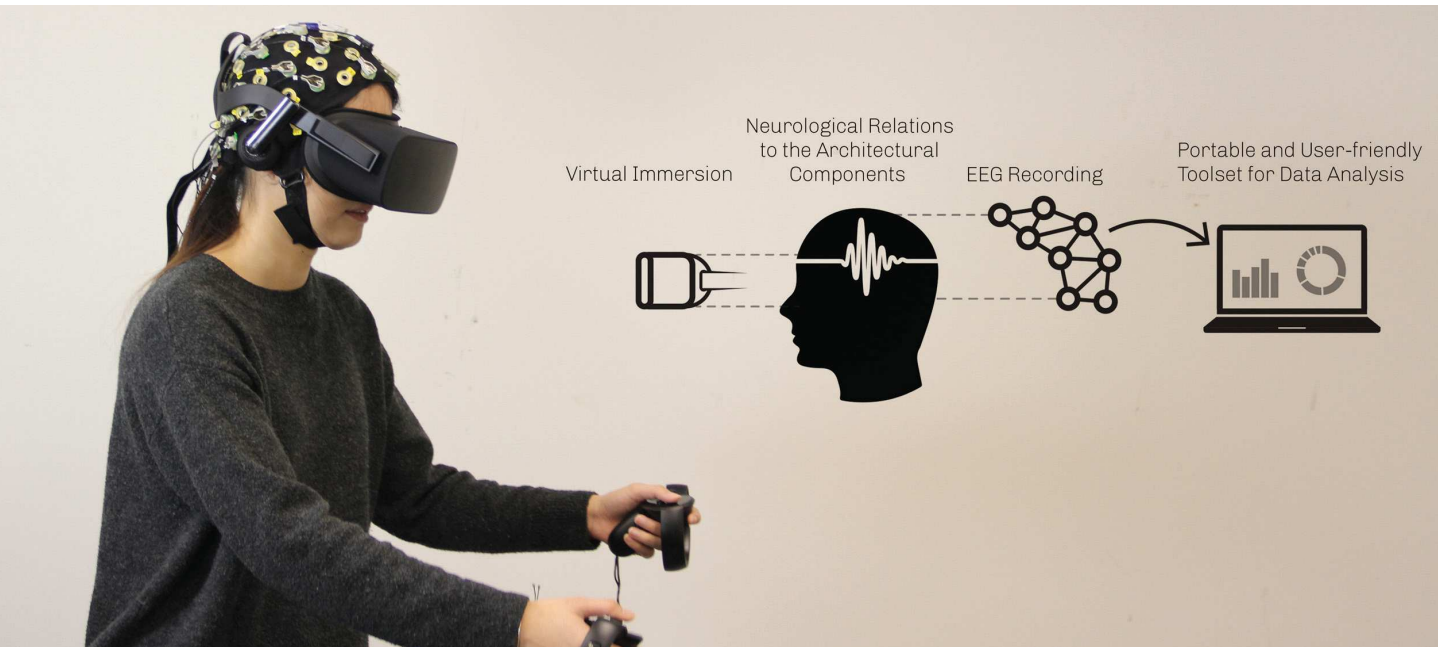
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ABSTRACT

The physical design of the learning environment has been shown to contribute significantly to student performance and educational outcomes. However, the existing literature on this topic relies primarily on generalized observations rather than on rigorous empirical testing. Broad trends in environmental impacts have been noted, but there is a lack of detailed evidence about how specific design variables can affect learning performance. The goal of this study was to apply a new approach in examining classroom design innovations. We developed a protocol to evaluate the effectiveness of classroom designs by measuring the physical responses of study participants as they interacted with different designs using a virtual reality platform. Our hypothesis was that virtual “test runs” can help designers to identify potential problems and successes in their work prior to its being physically constructed. The results of our initial pilot study indicated that this approach could yield important results about human responses to classroom design, and that the virtual environment seemed to be a reliable testing substitute when compared against real classroom environments. In addition to leading toward practical conclusions about specific classroom design variables, this project provides a new kind of research method and toolset to test the potential human impacts of a wide variety of architectural innovations.

- 1 Overview of the research study. Participants' responses were measured while they interacted with architectural designs in a virtual environment.

INTRODUCTION

The process of designing the built environment is becoming more complex in today's world. Current technology encourages designers to introduce increasing amounts of innovation into their work. While this innovation often leads to exciting and effective results, it also takes us away from tried-and-true solutions into relatively uncharted territory. This opens up the possibility of design mistakes that can reduce, rather than improve, a building's usefulness for its human occupants.

Scholars have demonstrated that the characteristics of the built environment can have significant effects on human well-being. Specific design components have been correlated with health outcomes (Truong and Ma 2006; Wheaton et al. 2015), as well as with human efficiency and productivity (Day 2017). Renewed interest in human-centered design in recent decades has led researchers to document the contributions of architectural design for reducing stress, improving mood, and enhancing visual memory, among other benefits (Ulrich et al. 1991; Sallis et al. 2006). Numerous additional studies have investigated different architectural styles and design choices and how they affect human experiences (Choo et al. 2017; Vecchiato et al. 2015; Vartanian et al. 2013; Roe et al. 2013; Shin et al. 2014; Küller et al. 2009).

When innovative designs are created, it is difficult to accurately evaluate their full human effects, whether positive or negative, until after the buildings are constructed and put into use. This presents contemporary designers with a dilemma. How can we harness the best potential of the innovation allowed by today's technology while avoiding costly and potentially harmful mistakes?

Our research addresses this issue by evaluating the effects of building design on human factors, such as stress, anxiety, and visual memory, prior to the building's construction. We accomplished this by rigorously measuring our participants' physical and conscious reactions as they interacted with various architectural designs using virtual reality technology. The goal in this experiment was to show that virtual "test runs" can help designers to identify potential problems as well as successful innovations in their work prior to any extensive investment in physically constructing the designs.

LEARNING ENVIRONMENTS

The specific architectural context that we chose for this experiment is the classroom environment. Previous research has shown that student performance can be significantly affected by physical design factors, and that

poor-quality learning environments can create barriers to education such as impaired concentration, boredom, and claustrophobia (Chan and Richardson 2005). A high-quality learning environment, in contrast, has been shown to support student engagement and inquiry (Martín 2010).

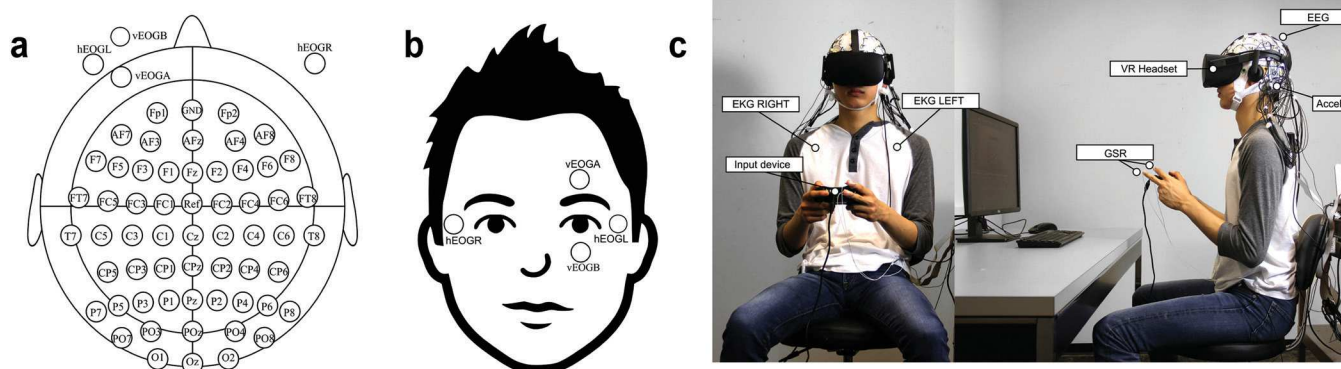
Despite the well-established link between learning environments and student outcomes, the specific physical elements within these environments that affect students the most have not been rigorously broken down and empirically investigated. Paul Temple observed that, "Where connections between the built environment and educational activities are made, the basis for doing so tends to be casual observation and anecdotes rather than firm evidence" (Temple 2007). Many other researchers have indicated a need for more rigorous studies to investigate the specific elements of the physical environment that might be important from a design perspective to help support student achievement (Woolner et al. 2007; Kaup et al. 2013).

The previous work that has been done in this area suggests, at best, some general themes in the optimal design of learning spaces. Perhaps the most dominant theme in the recent research literature is that educational spaces need to be flexible, both pedagogically and physically, so that they can be adjusted to reflect the nuances of different knowledge areas and learning styles (Butin 2000). This theme reflects the growing understanding among teachers that there is great educational value in active and collaborative learning, detailed student-faculty interactions, and opportunities for intellectual creativity. Along with this emerging new pedagogy comes an increased interest in transforming the physical environment of traditional classrooms so that it can more easily accommodate collaborative and active learning in a technology-rich setting (Brooks et al. 2012).

Other general factors that have been associated with better student performance include educational environments that incorporate more "naturalness" (in light, sound, temperature, air quality, and links to nature) (Daisey et al. 2003; Wangocki and Wyon 2007); learning environments that create a greater sense of individuality, ownership, and flexibility (Zeisel et al. 2003; Ulrich 2004); and environments that provide greater stimulation and sensory impact (Küller et al. 2009; Fisher et al. 2014). The detailed investigation of these factors remains a relatively new and undeveloped area in the design literature, and nearly all of the existing work describes a hope that future investigations can adopt more rigorous empirical methods to further isolate the relevant factors and their impact on student experiences.



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2 Overview of the study design.

3 The experimental setup for data recording: (a) EEG electrode locations, (b) EOG electrode locations, and (c) all sensor equipment as worn by a study participant.

RESEARCH METHODS AND EQUIPMENT

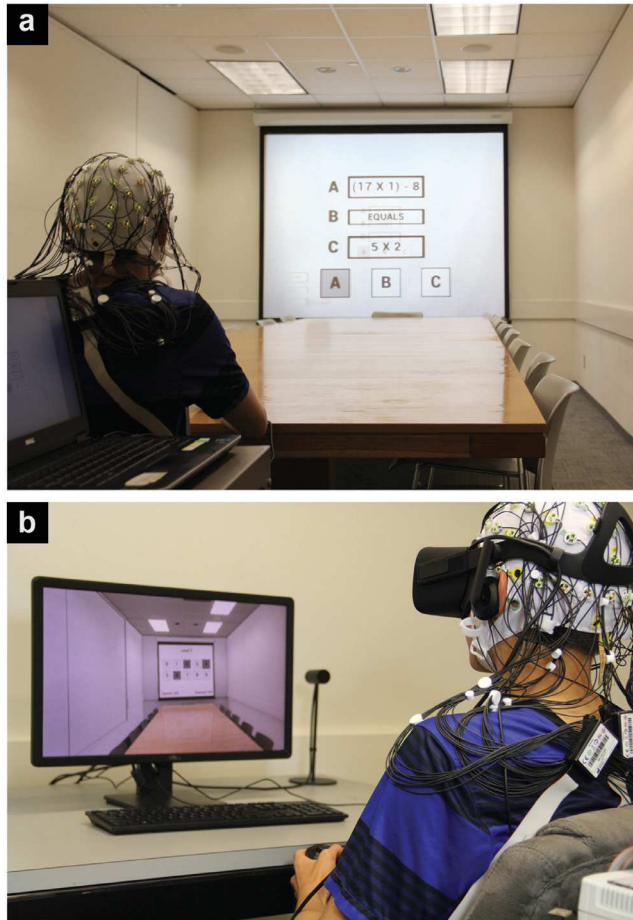
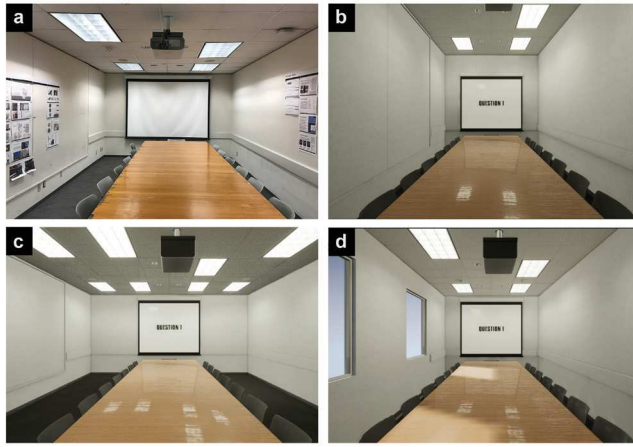
In creating the current study, we wanted to develop a standardized and intuitive toolset with the potential to be used in many other architectural research projects. The goal was to allow designers to test new ideas and evaluate the effects of different designs on human experiences and responses. For this purpose, we developed a protocol to use virtual reality experiences in conjunction with noninvasive biophysical measurements and self-reporting. This allowed us to objectively analyze the participants' responses to changes in specific design variables.

An overview of the experimental process is shown in Figure 1 and 2. The participants were first informed about the purpose of the study and allowed a few minutes to try out the virtual reality equipment and its controls. They then filled out a basic demographic questionnaire, which asked for non-personally-identifiable information such as age, gender, occupation, race, ethnicity, drug use, and neurological conditions. The purpose of collecting drug and neurological data was to screen for factors that might affect the biophysical measurements. After completing the initial questionnaire, the participants donned the measurement equipment, and their baseline data was recorded in a standard (real) classroom. They then used

the virtual-reality platform to explore a variety of different design modifications. They performed a variety of learning tasks in these environments, while changes in their biometric readings were recorded. Finally, after the physical measurements were completed, the participants filled out an exit survey to collect their subjective evaluations of the virtual reality experience and the classroom designs.

To obtain measurements of their physical responses, the participants were instrumented with a non-invasive electroencephalography (EEG) cap to record electrical activity in their brains; electro-oculography sensors (EOG) to record eye motions; electrocardiogram sensors (EKG) to record their heartbeat; a galvanic sensor response (GSR) unit to record skin conductance; and a tri-axial head accelerometer to record their head motions. All of this biological data was recorded at 500 Hz and synchronized using the 64-channel ActiCHamp module (Brain Products GmbH, Germany) with Ag/AgCl active electrodes. A total of 63 electrodes were used (57 for EEG, 4 for EOG, and 2 for EKG). Figure 3 shows the electrode placement on a study participant.

In preparation for the study, the participants were asked to refrain from using any hair products that might increase the impedance at the scalp/electrode interface (conditioner, hair gel, etc.). Each subject's head circumference was measured to allow for the selection of an appropriately sized EEG cap. Prior to donning the cap, the skin on the face around the eyes, the temples, and the earlobes were gently cleaned with alcohol wipes to remove any dirt and



4 The design features of (a) the real classroom that were modified in the virtual environments included (b) ceiling height, (c) room width, and (d) window placements.

5 The research participants completed learning tasks in (a) the real classroom and (b) a virtual rendering of the classroom.

skin oils. The cap was carefully aligned on the participants' heads according to standard protocol (with the FP1 and FP2 electrodes at 10% of the distance from the nasion to the inion along the midsagittal plane, and the Cz electrode at the vertex of the head). After donning the cap, a conductive electrolyte gel was applied between the electrode tips and the scalp to reduce the interface impedance. The impedance was maintained below 50 k Ω for all participants, and in most cases it was reduced to below 20 k Ω .

The biometric data were recorded using the BrainVision Recorder software (Brain Products GmbH, Germany). The 57 EEG channels were arranged according to the international 10–20 system. The Lab Streaming Layer program (developed by C. Kothe at the Swartz Center for Computational Neuroscience, U.C. San Diego) was used to synchronize this biometric data with the participants' activities and responses within the virtual environment.

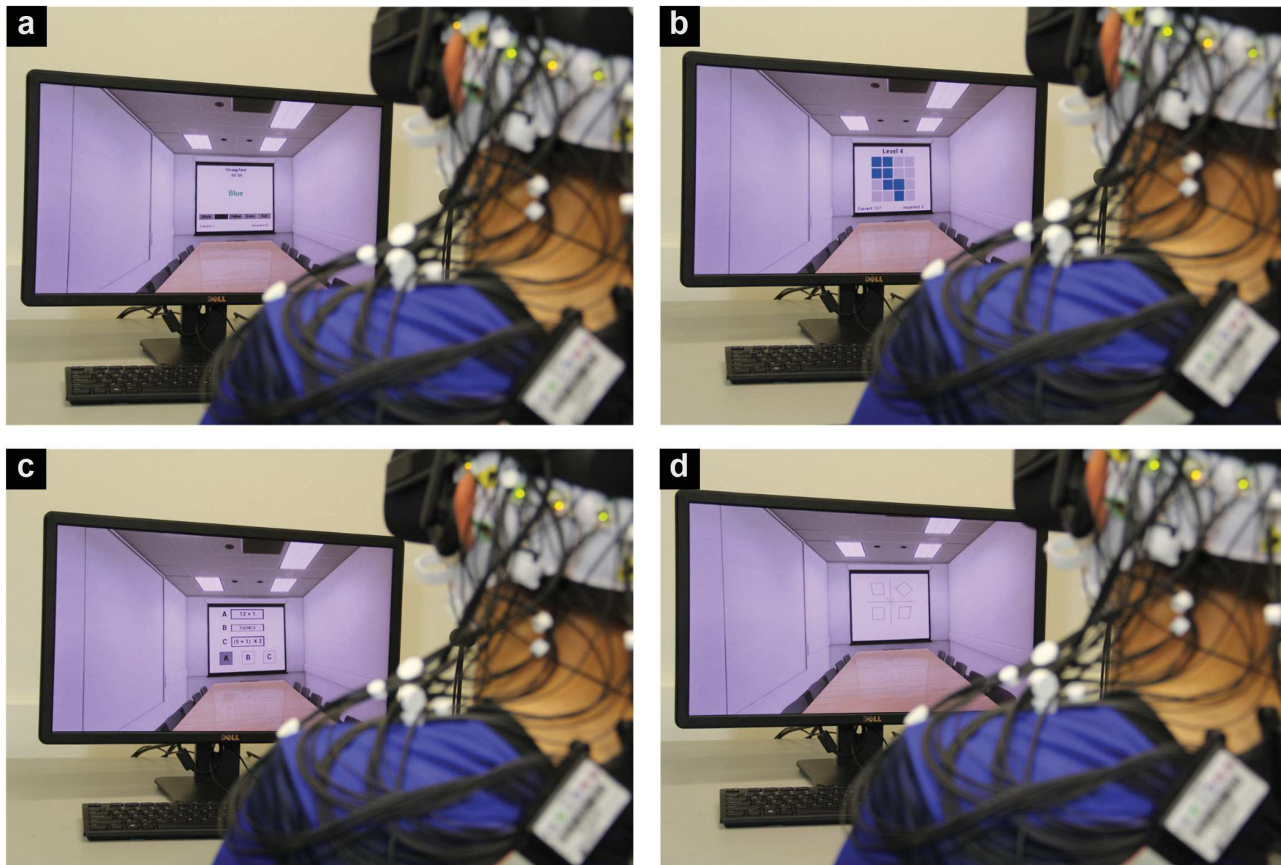
EXPERIMENTAL PROTOCOL

The experiments were conducted in a real classroom, combined with a virtual rendering of the classroom that allowed the researchers to make targeted design changes (Figure 4 and 5). The initial stages of the experiment took place without the use of a VR headset. To establish baseline data, the participants were first asked to sit quietly facing a blank computer monitor for one minute. They were then asked to sit quietly with their eyes closed for one minute. Finally, the participants were asked to complete several memory-oriented tasks using the standard equipment in the real classroom. These tasks included the Stroop attention test, a spatial-memory test, an arithmetic test, and a Benton visual-retention test.

After completing these tasks in the real classroom and then taking a short break, the participants donned virtual-reality headsets (these were placed over their EEG caps). The virtual environments that they encountered were similar to the real classroom but incorporated targeted changes to specific design variables. The type of design changes that the participants encountered in the virtual classrooms included different ceiling heights, different window placements, and different wall textures. The participants were asked to complete the same memory-oriented tasks while immersed in these virtual spaces (Figure 6).

RESULTS OF THE PILOT STUDY

Our initial pilot test was carried out with only one study participant, and with one design alteration (the addition of windows to the classroom). Despite the limited nature of this data, the pilot test yielded promising results and demonstrated that the collected biometric data has



6 The memory-oriented tasks completed by the participants included (a) the Stroop attention test, (b) a spatial memory test, (c) an arithmetic test, and (d) the Benton visual retention test.

the potential to provide valuable insights about human responses to design variables. The pilot study data is summarized in Figure 7, showing a comparison between baseline states, activities carried out in the real classroom, activities in an identical virtual classroom, and activities in a virtual classroom with added windows. The data indicate a sharp increase in stress responses during the memory-oriented activities, as compared to the passive baseline. However, the magnitude of these stress responses was smaller in the virtual classroom with windows as compared to the virtual classroom without windows.

Another notable finding in our pilot test was that the participant's responses were very similar in the real classroom and in the identical virtual classroom (without any design changes). This suggests that the virtual replication can likely be viewed as a suitable substitute for testing the real design.

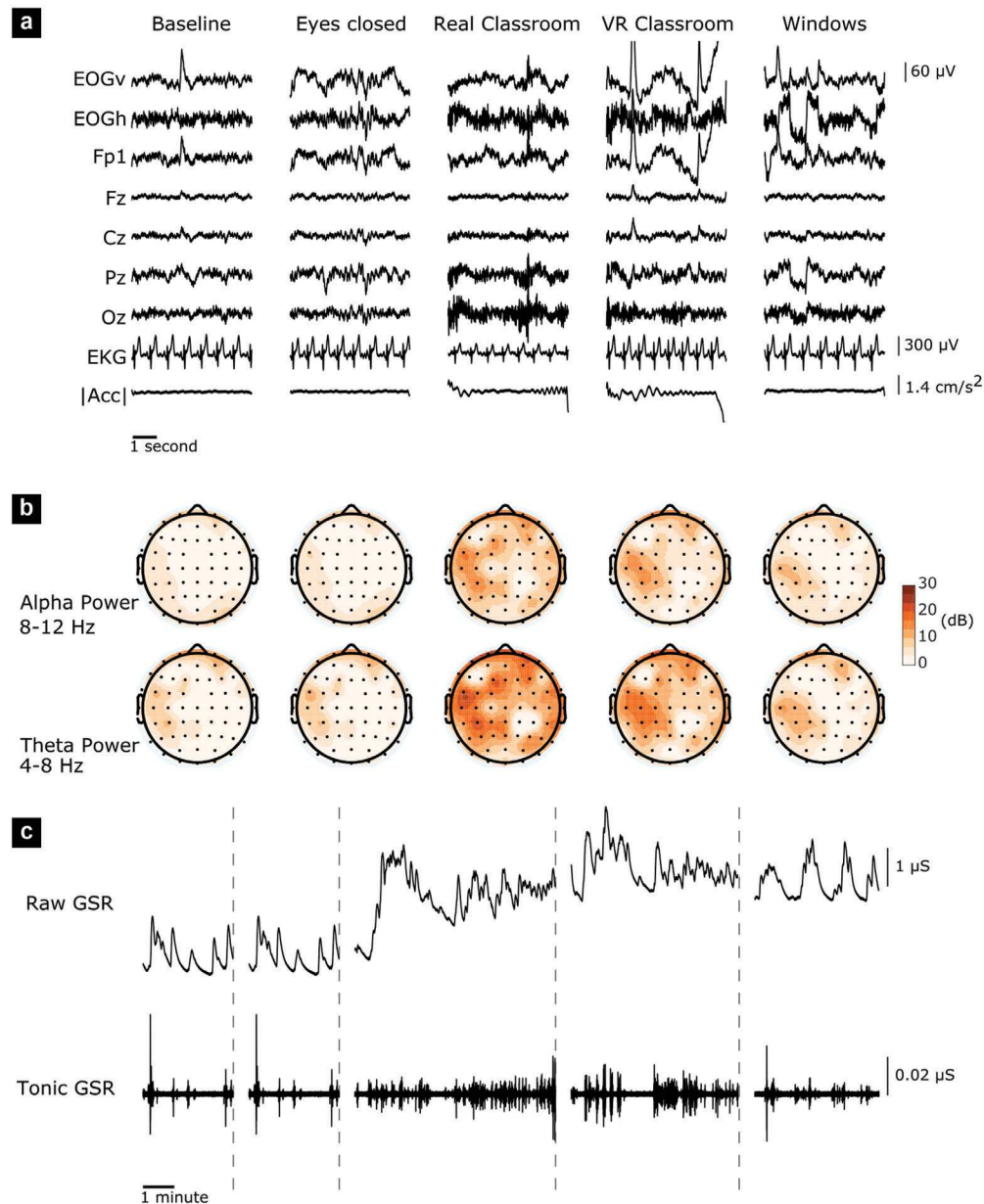
The full results of this study have not yet been rigorously analyzed. In future work, we will continue to collect and analyze data from larger numbers of research participants to obtain rigorous results and finalize conclusions about the effect of each design variable. This will allow us to put

forth strong and empirically grounded findings about the specific classroom variables that we are studying, and also to fully validate the equipment and research protocol for use in additional design studies.

CONCLUSION

This project demonstrated a new and practical toolset to evaluate the human impacts of architectural design innovations. The research responds to a growing call in the field for evidence-based design and for an inexpensive means of evaluating the potential human effects of new designs. Our research addressed this challenge by developing a prototype brain-body imaging interface that can be used in conjunction with virtual immersion. This allows participants' conscious and unconscious reactions to new architectural designs to be evaluated prior to the building's physical construction.

To test the idea, we developed a generalizable research protocol and conducted an initial study. Although the full study and data analysis has not yet been completed, the results of our pilot tests demonstrated the value of this approach. We found that the biometric equipment could yield important results about human responses to



7 Data obtained from the pilot study participant for five conditions (indicated in columns): baseline eyes open, baseline eyes closed, real classroom, virtual classroom, and virtual classroom with added windows. The figure rows show (a) the initial 5 s of data from selected EEG, EOG, EKG and head-acceleration channels; (b) total alpha (8–12 Hz) and theta (4–8 Hz) power in all EEG channels, and (c) raw and tonic GSR (skin conductivity) signals.

architecture, and that the virtually replicated environment seemed to be a reliable testing substitute for the final constructed design.

Current information technology has allowed many fields to benefit from “big data” analysis in their optimization of resources. However, design fields are somewhat lacking in this area, due to the difficulty of obtaining quantitative data about human responses to design and the tremendous investment required to construct and test new

architectural ideas. Our research method has the potential to provide designers, educators, and psychologists with an important new toolset for developing data resources to evaluate the relationship between architectural form and human experience. The construction of a broad, amalgamated data-set based on these evaluations, following a shared research protocol, could contribute significantly to the optimization of design and the quality of our built environment.

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IMAGE CREDITS

All drawings and images by the authors.

Saleh Kalantari is the director of the Design and Augmented Intelligence Lab (DAIL) and an assistant professor at Cornell University. He is the founding principal of Kalantari Studios, a design and research lab producing buildings, installations, and speculative projects of various scales. He previously worked as a research director and designer at Parkin Architects Ltd., where his team won multiple recognitions. His work brings together the expansive possibilities of cutting-edge computational design with a concern for environmental psychology and the human qualities of built environments. Dr. Kalantari has previously taught at multiple architecture schools including the University of Houston, Washington State University and Texas A&M University.

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Joshua Stanton Smith is a designer, technologist, educator and video game enthusiast. He is currently the Director of Virtual Reality and Augmented Reality at Luxigon. He is also the founding partner of Terraloom, a multidisciplinary office that aims to create interactive digital space existing at the intersection of architecture, immersive realities and video game creation. His work in animation, virtual reality and architectural visualization have been exhibited around the world and have helped his clients win countless competitions. Joshua is currently Adjunct Faculty at the University of Houston and a Teaching Associate at Harvard Graduate School of Design.

Jesus Cruz-Garza develops strategies for the decoding of brain activity signals through mobile brain-body imaging in real-world settings. His contributions to the field include the use of electroencephalography (EEG) to characterize the neural code of expressive movement, exploring the emergence and development of learning in human infants and the development of tools to understand the neural basis of the human creative process in unconstrained reflection and production. Jesus graduated from BS Engineering Physics at Tecnologico de Monterrey, Mexico. He is currently a Ph.D. candidate in Electrical Engineering at the University of Houston.

Pamela Banner is an undergraduate research assistant at the Non Invasive Brain Machine Interface Systems (BMIST) Lab at the University of Houston. She is currently pursuing her Bachelor of Science in Mechanical Engineering at Yale University. Her interest in the intersection between engineering, neuroscience and architecture brought her to participate in the NSF Research Experience for Undergraduates (REU) program for Neurotechnologies. She hopes to continue to investigate how architecture and engineering can best be combined to design spaces conducive to cognitive performance and reductive of stress factors in the future.