A NEW METHOD OF HUMAN RESPONSE TESTING TO ENHANCE THE DESIGN PROCESS

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ABSTRACT

This paper presents a new method of human-response testing to enhance the success of designs. Rather than waiting until after a building is constructed to see how the design will affect human users, we developed a high-resolution virtual-reality platform to present design variations to the study participants. This technique allowed us to make very precise adjustments in design variables (e.g., the ceiling height, or the placement of windows) within the same overall structure, thereby obtaining more empirically rigorous comparisons than is possible in traditional post-occupancy studies of completed buildings. In addition, this approach allowed us to collect a variety of biometric data, such as EEG signals, heart rate, head motions, and other indicators of attention and stress, while the study participants interacted with the virtual environments. The overall outcome of this research method will be to improve the human quality of the built environment and to promote data-driven innovation in the design field.

Keywords: Virtual reality, Human-centred Design, Computational design methods, Design process

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1 INTRODUCTION

The current movements toward evidence-based design and human-cantered design encourage researchers to document the effects of the built environment on human outcomes, and to pursue more rigorous post-occupancy studies. This is a valuable direction in the design field, since the characteristics of the built environment can have significant effects on human well-being and productivity. Specific interior design variables, ranging from window placements to wall textures to overall spatial arrangements, have been strongly correlated with health outcomes, emotional mood, stress levels, and productivity, among other human factors (Shin *et al.*, 2014; Choo *et al.*, 2017; Vartanian *et al.*, 2015). However, due to the tremendous investment required by construction, it can be extremely costly to experiment with new architectural designs and to try out innovations that might help to improve the human experience of the environment. This limits our ability to collect reliable data on alternative design possibilities. In addition, the uniqueness of each building and each architectural setting presents significant challenges to rigorously comparing the human effects of a particular design solution against other possible designs.

To address these challenges, our team has developed a toolset to conduct in-depth virtual testing of human responses before the designs are physically constructed. We created a prototype mobile brain-body imaging system (MoBI) that monitors study participants' physical and conscious responses as they interact with a virtual environment. The system collects a variety of biological measurements, including head motions, brain activity, heart rate, and galvanic skin response, and correlates them in real-time with the participants' activities as they explore the environment. These measurements can also be correlated with the participants' subjective, self-reported experiences. This allows us to rigorously examine changes in human responses and capabilities, such as anxiety and concentration, when very specific design variables are digitally altered. Using this approach can allow designers to gain crucial, objective feedback on their work—to help resolve problems or to justify the human benefits of a design—prior to the investment in its physical construction.

2 THE PROBLEM: EVIDENCE-BASED DESIGN NEEDS MORE RIGOROUS AND INEXPENSIVE RESEARCH METHODS

The process of architectural design is becoming more complex in today's world, deviating from traditional paradigms. Advances in virtual design and robotic fabrication are encouraging designers to implement greater innovations in their work. The use of new technology often leads to exciting and effective results, but it also takes us away from tried-and-true solutions, into relatively uncharted territory. This opens up an increased possibility of design mistakes that can reduce, rather than improve, a building's usefulness for its human occupants. For designers and researchers alike, this situation poses a crucial question: how can we move forward to harness the best potential of the innovation allowed by today's technology, while avoiding costly and potentially harmful mistakes?

Despite the demonstrated benefits of evidence-based approaches, there are also challenges and limitations that have led to scepticism and slow adoption in many sectors of the design industry. One of the key challenges is the significant up-front costs of carrying out human-response studies. The long-term benefits of evidence-based design are shared by building owners and the general public. However, there is no general agreement as to what party—design firms, their clients, or academic researchers—should pay for the expenses associated with data-collection. In addition, the generalization of research findings from one design project to another remains tenuous, as the unique nature of each project makes it hard to fully isolate the effects of specific design variables. Finding past human-response studies that provide evidence that is clearly relevant to a new design can be difficult, and the site-specific nature of design studies has led to an accumulation of complex and sometimes contradictory conclusions. There is currently limited consistent research protocol for conducting evidence-based design studies, which further contributes to a lack of commensurability in research results (Hamilton *et al.*, 2010). Furthermore, when new designs are created, it is difficult to make any kind of detailed evaluation of their human effects, positive or negative, until after the buildings are constructed and put into use. The human-cantered and evidence-based design literature relies strongly on post-occupancy studies, which provide valuable data about what worked or did not work in the past, but cannot provide direct feedback about new ideas that have not yet been attempted.

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One final concern about the existing human-response literature is that most studies rely on subjective evaluations such as surveys and interviews, which have limitations when compared to more direct and objective behavioural measurements. Currently, research into human responses to design is beginning to take more of a neurological and hard-science turn, in which researchers not only gather broad behavioural data, but also seek to describe the underlying brain mechanisms that mediate human responses to architectural features (Vartanian *et al*., 2015; Choo *et al*., 2017). The new research method that is described in the current article is a part of this neurological direction in human-response testing. Unfortunately, even in this area, data from neurological assessments often suffers from a lack of consistent research protocols and limited study designs. For example, the majority of existing neurological studies measure the participants' brain responses while they view two-dimensional pictures of architectural designs. These studies may be limited in capturing the relevant brain responses associated with moving fluidly through an immersive, three-dimensional environment. While virtual-reality experiences are also slightly limited in their ability to mimic fully embodied engagements with architecture, they do allow for the possibility of movement and a much richer sense of surroundings, and are thus more likely to capture an accurate reflection of neurological responses.

3 THE SOLUTION: BIOMETRIC DATA AND VIRTUAL RESPONSE TESTING

The new research method that we describe in this paper was developed to address all of the above-mentioned challenges in evidence-based design. Our solution is to immerse volunteer participants in virtual environments, and then comparatively measure their responses to design variables using both biometric data and self-reporting. This approach allows for a precise isolation of the design variables under study, since the virtual environments can be constructed to be identical apart from the specific design alteration that the researcher wants to evaluate. Through the use of biometric data it also provides more objective measurements of human responses than is possible in conventional post-occupancy studies. The research can be carried out at a tiny fraction of the cost that would be associated with constructing new designs and then learning about their successes and flaws retrospectively. While we do not expect this approach to entirely replace traditional post-occupancy studies in actual constructed buildings, we believe that it can greatly enhance the human success of new designs and help to spur responsible and data-driven innovation in the field.

The current project's approach to evidence-based design is commensurate with an incipient neurological direction in the field, in which researchers seek not only to gather broad behavioral data but also to describe the underlying brain mechanisms that mediate human responses to architectural features (Vartanian *et al*., 2013). In recent years several "neuroarchitectural" studies have investigated brain responses to different architectural styles (Choo *et al*., 2017), contours (Vartanian *et al*., 2013), height and enclosure (Vartanian *et al*., 2015), interior space design (Banaei *et al*., 2017), lighting (Shin *et al*., 2014), space with different geometry (Shemesh *et al*., 2017), and color (Küller *et al*., 2009). Other researchers have taken a neurological approach to examining the impact of the built environment on human memory (Sternberg, 2010, p. 147), comparative human responses to built vs. natural environments (Roe *et al*., 2013; Banaei *et al*., 2015), and a systematic approach for gathering requirements through customers' remote access to aircraft and its modules (Gupta *et al*, 2018).

Another vital advantage of this method is that it allows us to develop a consistent research protocol, so that multiple studies can be carried out using the same basic equipment and techniques. This creates a greater possibility of commensurability in evidence-based design studies, so that the results of varied research efforts can be more readily compared. Conventional post-occupancy studies follow a very wide array of different protocols and techniques that make it difficult to compare equivalent results. It is our hope that if researchers and the design industry adopt the use of our virtual testing protocol and the associated mobile brain-body imaging system (MoBI), results from multiple studies can be validated, reproduced, and amalgamated in a cumulative online database of design findings. The use of similar research protocols in these studies will allow for the development of a much more rigorous body of comparative design evidence, and thus help to legitimize this area of study and promote the broader adoption of evidence-based design.

The evolution of this new research method was the result of the author's long experience in conducting evidence-based design studies and coming to understand both their advantages and their limitations. For example, in one previous study the author carried out an extensive post-occupancy evaluation of the effectiveness of design innovations in two mental-healthcare facilities (Kalantari &

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Snell, 2017). The researchers collected data on the effects of evidence-based wayfinding strategies, colour schemes, and a new design for nurse's care-stations. Some of these innovations were valued highly by the facilities' staff members, patients, and visitors, but other innovations were not considered to be helpful. Despite the fact that all of the innovations were based on previous research findings, there was a great discrepancy in how the various innovations were received in these particular facilities. This led the author to conclude that there is no firm guarantee that evidence from earlier studies will lead design innovations to work as expected in a new project. Although the lessons learned from previous projects can have an important utility, the site-specific nature of design means that specific implementation of the strategies may have varied results.

This experience prompted the author to begin investigating the possibilities of pre-occupancy virtual testing, so that site- specific design solutions could be rigorously evaluated prior to construction. In a series of studies we used an "augmented-reality" approach to evaluate the effects of different building designs on human stress levels (Kalantari, 2017). This approach involved overlaying digital artifacts onto existing real video images. By making specific adjustments in the designed environment we were able to examine how the participants responded to potential design changes. In addition to conscious responses, we collected a rudimentary set of biometric measurements in these studies, including blood pressure and heart-rate. In conducting this research we began to realize that we had the core of a new evidence-based design method, one that could go beyond existing research studies, producing more rigorous evidence about human reactions to architectural variables than had been possible in the previous literature. Based on the positive results and reception of this approach, we then went on to develop a research protocol for a fully immersive and customizable virtual experience and a more detailed biometric measurement platform.

In developing this new research method, we set down specific goals that we wanted to accomplish. One of the most important factors was to create a virtual research environment that would be easy for designers and study participants to use. Thus a primary goal was (1) developing a virtual architectural platform to enable the intuitive presentation of a wide array of design features to non-specialist participants. The second and equally important task was to allow for reliable data-collection, which involved (2) creating a standardized, mobile, noninvasive, and easy-to-use biophysical measurement system using off-the-shelf components that can be widely distributed to architectural researchers and design firms. Bringing these components together meant (3) developing a standard research protocol to conduct design studies using this equipment and to evaluate patterns within the collected data. Together, these three steps comprised the first phase of our project development. We are currently involved in the second phase of the work, which involves validating the platform and extending its reach within the research community and industry. This second phase involves the tasks of (4) conducting pilot studies to test, calibrate, and validate the system based on real design problems; (5) developing a plug-and-play software tool for use with this equipment, and ensuring that it is readily compatible with common design software such as Rhino and Autodesk Revit; (6) creating a guidebook for designers on how to use the equipment and how to analyse the results; and (7) developing an online platform for collecting results from individual participants, research groups, and design firms.

4 PHASE 1: EQUIPMENT AND RESEARCH PROTOCOL

The MoBI platform uses cutting-edge technologies to overcome the limitations of previous evidence-based design research methods. The first task was to develop a virtual environment that can enable the easy and intuitive presentation of a wide array of architectural design features. For this purpose we used Epic Games' Unreal Engine (www.epicgames.com) as a software platform. The Unreal Engine is one of the most sophisticated virtual-reality simulation programs available today, and it is well-suited for the task of displaying and modifying virtual interior designs. The Unreal Engine uses blueprint scripting, which allows for a quick learning-curve on the part of researchers and designers. All of the front-end interaction and user interactivity in our environment leverages the Blueprint platform, making the construction of new virtual-reality architectural models a relatively easy process. The virtual modelling can be performed using Autodesk Maya, which is a familiar program for most designers, and surface textures can be added either procedurally through Substance Designer or manually through Photoshop.

The virtual experience is presented to research participants using Oculus Rift and HTC Vive head-mounted displays. These headsets are lightweight, comfortable for the user, and have a strong market

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share with ongoing development. To provide for an even greater immersive experience and more physical expression by the participants we also include in our system a treadmill device called the Virtuix Omni. This allows the users to "walk" through the virtual environment using physical leg motions, which can contribute tremendously to the user's sense of immersive experience (Figure 1). For research purposes, the use of the treadmill also allows us to record important data about the participants' responses to the environment, including gait speed and the length of pauses. Accelerometers are included to measure motions of the head and torso.

Figure 1. Off-the-shelf hardware is used in the MoBI research platform, including a VR headset, a treadmill, and an EEG cap.

Another central technology that is used in the platform is electroencephalography (EEG), which has emerged as a powerful tool for quantitatively studying brain responses. By fitting study participants with an EEG cap, researchers can collect a wide range of data about cognition, perception, emotion, and mental activity in complex environments (Gramann *et al*., 2014). These measurements can be synchronized in real-time with other data, including conscious feedback from the participants and recordings of their activities within the virtual space. The EEG device and associated software that is used in the research platform is designed to accommodate a range of head motions, without physically binding the user and while still providing robust data outputs. This capability to allow or free head movements is relatively new in EEG technology, and it provides a much more robust measurement of brain responses during engaged physical activities (Luu *et al*., 2017). The relevant components include a 64-channel Brain Products actiCAP, along with the Brain Amp DC amplifier, the wireless MOVE system, and BrainVision software. The overall data-collection system is further supplemented with electrooculography (EOG) sensors to record eye motions, electrocardiogram sensors (EKG) to record heart rates; and a galvanic sensor response (GSR) unit to record skin conductance (GSR is affected by sweating and has been shown to be a reliable indicator of even minor variations in stress levels) (Sharma & Gedeon, 2012).

After selecting and optimizing the virtual-reality technology and the biological measurement equipment, we developed a general protocol for conducting architectural design studies using our MoBI platform. The purpose of this protocol is so that future researchers can readily replicate findings and conduct additional experiments that will be mutually compatible while minimizing confounding variables. We divided the overall research protocol into four stages: participant preparation, real environment, virtual environment, and exit interview. During the initial preparation stage, the participants are given an introduction to the study and are allowed five minutes to try out and "play with" the equipment. They are informed about the general purpose of the study, but are not made aware of any particular hypotheses or design variables that are being tested. The participants are assured that they can stop the testing at any time and for any reason if they feel uncomfortable. They are then are asked to fill out a brief demographic questionnaire (e.g., age, gender, ethnicity, education, occupation, alcohol/caffeine/substance use, and any known neurological conditions). No personally identifiable information is collected. The reason for asking about drug use and neurological conditions is to help identify any physical factors that may affect the biometric data. The time of day in which the experiment took place should also be recorded on the demographic form, as this may affect some of the biophysical measurements. After this, the research team carefully fits each participant with an EEG cap and other measurement devices as are relevant for the needs of the study.

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During stage two of the experiment, the participants may be asked to perform various tasks and activities in an actual interior environment, without the use of virtual immersion. This research phase is optional. Its purpose is to create a baseline of biometric data and, potentially, to compare the participants' responses in this real environment against their responses in an identical virtual environment. This can help to further validate the toolset and to determine if the experience of virtuality itself has an effect on the biometric data.

In stage three, which is the main body of the experiment, the participants put into place their virtual-reality headsets and are exposed to one or more virtual environments. Again they are reminded that if they need to stop the experiment at any time then they can do so. Some of the virtual environments may be identical to the actual environment that was tested in stage two, or they may be the same environment with specific design changes, or they may be an entirely different world. The specific virtual realities that are tested in each study will depend on the design variables that the researchers want to analyse. The participants will remain in each virtual environment for a set amount of time, usually around ten to fifteen minutes. While in these environments, the participants may be asked to engage in a variety of tasks, ranging from free exploration to specific exercises or games. They may also be asked to report their opinion of the environment or to answer various questions. The types of activities or responses used in a particular study will again depend on the kinds of design variables that are under investigation, as well as the particular human responses that are being evaluated.

To further increase commensurability among various studies, researchers are encouraged to use standard and well-known neuropsychological tests that are backed by extensive empirical research and brain science. For example, to obtain measurements of cognitive functioning and concentration, some of the tasks that may be incorporated within the virtual environments include the Benton Visual Retention Test, the Boston Naming Test, the Figural Fluency Test, and the Hooper Visual Organization Test (Davis, 2010; Lezak *et al.*, 2012). Performance on such measures can be linked in real-time with the biometric data and participant self-reporting to provide triangulated data about mental focus and fatigue. Additional tests may be used to measure factors such as emotional response and mood, for example by using Likert-scale evaluations of perceived pleasure, excitement, and/or stressfulness, which again can be triangulated with the biometric outputs.

In most research studies, it will be desirable to expose each participant to several different virtual environments. The protocol is that once testing in a particular environment is completed, the participant should remove the virtual-reality headset and take a two-minute break, before returning to explore and complete tests in a different virtual environment. The order in which the environments (i.e., the different designs) are presented should vary randomly for each participant, to help eliminate any fatigue or familiarization effects. The presentation order may also be recorded as a potential experimental variable. Finally, during stage 4 of the experiment, each participant will be debriefed and/or complete a short exit survey. This will give the participants an opportunity to comment on the overall experience, to compare the different designs that they have encountered, and to provide any general opinions and feedback on the study as a whole.

5 PHASE 2: PILOT STUDIES AND DISSEMINATION

With the research equipment and general protocol in place, there are a massive number of potential design variables and human responses that can be tested using our MoBI platform. Responses to healthcare designs, educational designs, residential environments, retail stores, public spaces such as parks and museums, overall urban environments, and landscape designs, just to name a few, are all amiable to rigorous investigation using this approach. Researchers may choose to study environmental effects on anxiety, wayfinding, learning performance, productivity, or a host of other human factors (Figure 7). To test and calibrate our method we have conducted two small pilot studies so far, one focused on an interior design (a classroom environment) and another focused on external architecture (a building façade). We investigated the effects of design changes in these environments for the human factors of attention, stress, and wayfinding. Our goal in choosing these research topics was to conduct investigations that demonstrate the potential of the testing equipment and have a wide significance in the design literature. While the data from the pilot studies has not yet been fully analysed, a brief presentation of these studies can demonstrate the implementation of our method and the transformative potential of virtual response-testing for the design field.

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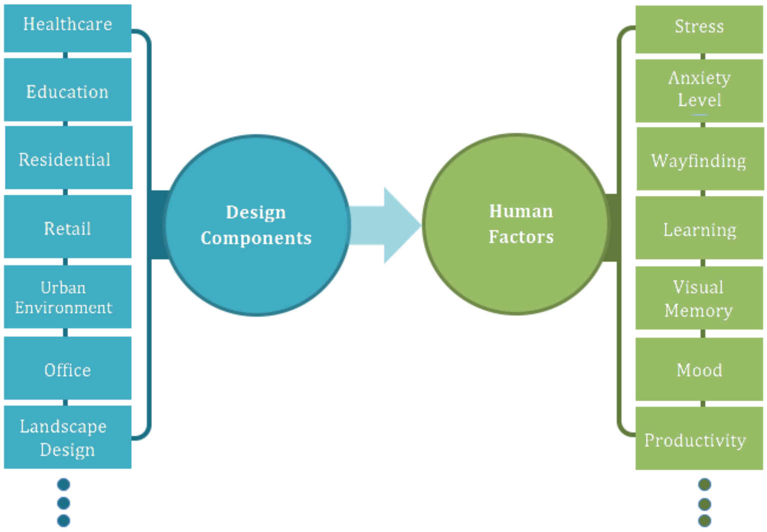

Figure 2. Overview of various design components and human factors that can potentially be studied using our virtual-reality testing approach.

In Pilot Study A, the participants were presented with an interior classroom view, with various modifications to the room's height, width, window locations, furniture design, spatial texture, lighting, and color. The choice of design variables to modify in this study was based on a literature review of previous educational design research (Li & Sullivan, 2016). While the virtual immersion time-period is too brief to measure substantial learning outcomes, we can use the testing protocol to evaluate the possible effects of classroom design on students' concentration and stress levels. To do this, we asked the research participants to complete various neuropsychological tests and games while they were in an actual classroom, and then again while they were in a virtual classroom. Some of the participants experienced a virtual classroom that was nearly identical to the actual one, whereas other participants (randomly selected) experienced a virtual classroom that had been digitally re-designed (Figure 3). This allowed us to compare results between actuality and virtuality, with no design changes; as well as the effects of modifying specific design variables. The biometric data that we recorded can be triangulated with the results of the attention and stress tasks that the participants completed.

The initial analysis of results from Pilot Study A has revealed one significant conclusion so far—the results of the attention and stress tasks and biometric data did not differ significantly between the actual classroom and the identical virtual classroom. This is a very promising result, as it lends credence to the hypothesis that virtual response testing can be a reliable substitute for evaluating human responses in actual constructed buildings. While we do not expect that our method will ever completely eliminate the need for post-occupancy evaluations in the real world, the evidence that we have collected so far indicates that the results of virtual testing are likely to be transferrable to real contexts. In future publications, we will continue to analyse the results of our tests for specific classroom design changes, and determine how these results align with previous real-world studies.

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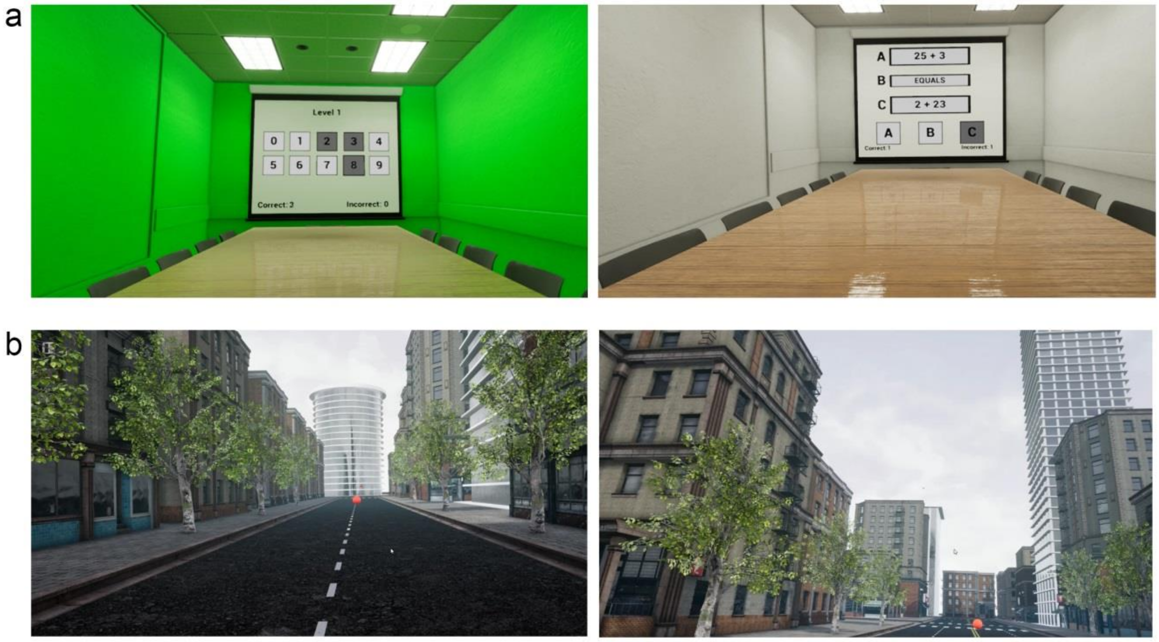

Figure 3. Study participants engaged in memory and attention tasks in an actual classroom and a virtual rendering of the classroom as well as changes to the room's width and height, colour, the addition of windows, and various furniture designs (a); in the experiment B, participants engaged in walking toward buildings with various modifications in an urban context.

In Pilot Study B, participants were presented with an external building view, with various modifications to the building's overall shape (circle, square, triangle, and polygon), height (tall, medium, and low), visual surface pattern (vertical, horizontal, grid, diagonal, circular, and organic), and material (concrete or glass). We again used neuropsychological tests, triangulated with biometric data, to help measure the participants' stress levels. In this study, however, we added an additional component to take full advantage of the mobility and immersion effects of our testing equipment. After recording their responses for a brief period of stationary observation, we asked the participants to "walk" through the virtual environment and to examine the buildings from different angles, while we recorded their head and eye movements, gaits, and pauses, along with other biometric data. This provides us with a rich data-set that can be used to examine which aspects of the environment prompted specific behaviours and/or stress responses. For example, did a participant feel stress (increased heart rate, sweating, specific patterns of brain activity) when they looked up toward the top of a tall building exterior? Or did they lower their head as they moved closer to the building and avoid looking upward at all? These questions can all be answered using our testing platform. We also asked the participants in this study to complete a wayfinding task within the virtual space, so that we could evaluate any possible effects that the exterior building designs might have on their capability to select efficient walking paths, and to see if there were related stress responses during this wayfinding.

Finally, near the end of Pilot Study B, we used the virtual-reality capabilities of our platform to allow the research participants to create their own preferred building design by adjusting digital sliders to change the relevant variables (footprint shape, building height, visual surface pattern, and material). In this way, we were able to obtain very specific data about the study participants' conscious preferences, which can then be correlated with their measured physiological reactions to the same variables. Eventually such an approach could also be correlated to demographic variables, making it possible to analyse preferences and responses according to gender, rural vs. urban background, disability status, and many other socioeconomic variables. This has the advantage of potentially prompting designers to think more broadly about the assumptions that they make in their work, and to cultivate a greater awareness of the needs of under-served groups.

In the future we will continue to finalize the data analysis and expand both of these pilot studies. In addition, we will proceed with the remaining steps of our development plan, which involve creating a plug-and-play software tool for use with the equipment, an instructional guidebook for designers and researchers, and eventually, an online platform for collecting and disseminating results. The goal of

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the software plug-in is to allow designers to submit their standard 3D models directly from the Dynamo or Grasshopper architectural design systems (currently the two most-used software programs in the design industry) for virtual-reality testing in the MoBI platform. The software tool will also be able to handle some of the basic data-recording and analysis procedures during the testing process. Once an extensive dataset has been developed through the use of our virtual testing equipment, this same plug-in will even be able to provide broader design feedback based on previous user responses to similar designs.

We are working to create a detailed and accessible guidebook for both the software and hardware components of the platform. This will improve the ability of other researchers to produce reliable results using the same testing protocol. We want the equipment set-up and data-gathering process to be as simple and streamlined as possible, so that even designers and researchers without a great deal of experience in this area can readily learn how to conduct virtual response-testing for their design ideas. This will help to encourage interest in and broader adoption of the method. Eventually, our aim is to establish standardized virtual-reality testing as a source of "big data" for the design industry. We will incorporate into our software plug-in tool an option for design firms and research labs to validate their results, and then upload the validated results to an open-access online database. This database will aggregate rigorous evidence from across the globe, and systematically tag, categorize, and compare the findings based on the type of project (e.g., "healthcare"), the design detail (e.g., "nurse station"), and the human factor being investigated (e.g. "stress"). Our hope is that the existence of such a database will help to promote the greater adoption of evidence-based design standards throughout the industry.

6 CONCLUSION

The new method of virtual response-testing with biometric data that is described in this paper has a great potential to help designers to create higher-quality human environments. It can allow for more innovation and experimentation in the industry, because designers will be able to gain robust feedback on their ideas prior to physical construction. This means that designers can take more risks, catch potential problems sooner, and inexpensively develop a body of evidence to justify the value of a new concept. In the academic realm, this method responds to a growing call for improved techniques in evidence-based design, and it helps to build stronger bridges between design research, neuroscience, and information technology. Many fields of endeavour have benefited from the recent explosion of "big data" from large-scale public testing, but design fields have remained somewhat lacking in this area, due to the difficulty of obtaining quantitative data about human responses to design. The virtual response-testing method has the potential to change that situation, providing designers, educators, and psychologists with an important toolset for evaluating the relationship between architectural form and human experience.

The suggested method does not lead to a one-size-fits-all design approach. By including demographic variables in the analysis designers can become more aware of human variability in responses to design, and in particular, more aware of the responses of specific populations, including disabled individuals, women, and other minority groups, whose needs and perspectives have been historically overlooked in the field. In addition, our approach will make it more feasible for researchers to carry out human response testing on an international scale. This is significant because most existing post-occupancy studies have been conducted in a small number of developed countries, with results that may not be fully generalizable to the global population (Kalantari *et al.*, 2017). By greatly reducing the cost and the implementation time of human-response testing, our method will promote the widespread and nuanced adoption of evidence-based design approaches in the international context. Perhaps most importantly, the virtual response-testing method can encourage more active participation of the greater public in shaping design outcomes. By looking to the public to provide feedback and participate in design evaluations, our method helps designers to ensure that they are truly serving the needs of the community.

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