1. Research Description: Significance, Innovation, Approach

Overview: The goal of this research project is to develop, test, and validate a data-driven approach using virtual reality (VR) and electroencephalogram (EEG) technology for assessing the effect of architectural building design features on occupants' emotional and cognitive functions - proxies for mental health and wellbeing. The project will provide technology-enabled, repeatable measures for quantifying the "soft" benefits of building design features thus providing an economically viable and repeatable assessment model, pre-build.

Significance: Given that Americans spend about 87% of their time inside buildings, the quality and design of buildings are important contributors to occupant wellbeing. For example, indoor air quality has long been a public health concern, as contaminants in the air we breathe can cause a variety of illnesses including cold symptoms, headaches, allergic reactions, and asthma. In response, the building science community, particularly environmental scientists, have rightfully focused their efforts on reducing or eliminating exposures to indoor air contaminants. However, other more subtle but equally deleterious psychological or mental health effects – characterized by mood changes, increased stress, and decreased productivity - have been more difficult to measure consistently and currently are assessed *post-occupancy* making remediation highly unlikely, as retrofitting buildings is extremely expensive. The trend in "sustainable building" (SB) models catalyzed by the founding of the Green Building Council in 1993, offers a unique opportunity to leverage not just beneficial environmental effects but also occupancy wellbeing effects in the design and construction of new buildings. SB models typically adhere to a rating system that prioritizes energy consumption, water consumption, use of natural resources, indoor environmental air quality and locality. In order to maximize energy efficiency, these buildings prioritize design features to enhance *daylighting levels. This design element also often increases access to outdoor views* and *spatial qualities.* Case studies have consistently demonstrated the potential for sustainable buildings to increase "soft" benefits of improved wellbeing and productivity via self-reported assessments. However, self-assessments are marred by participant biases and the inability to disentangle confounding variables. Current building impact evaluation tools that measure occupants' wellbeing and cognitive functions are user response surveys such as the health and work performance questionnaire (HPQ) and various building wellness surveys. Surveys have two main weaknesses. First, as there are many variables affecting an occupant's response to the built environment, such as familiarity with the space, time of day when the survey is conducted, and the ambient condition of the environment (temperature, smell, noise, etc.), confounding, non-design factors can be hard to disentangle, to control for and difficult to interpret. Second, the survey response is an indirect measure of the environment, reliant on the user's opinions (perceived likes and dislikes) and cannot provide objective data about particular environments and features. What is needed are consistent, reliable, and physiologically based, and separated measures of mental health effects – especially in the pre-build, design phase; **our proposal fills this gap**. Conventional buildings (CB) – those that meet basic building and energy codes but do not prioritize sustainable design elements - provide an excellent control from which to expand research on the co-benefits of SBs to improve occupant mental health and wellbeing beyond the current limited focus on indoor air quality harm reduction. Moreover, buildings are usually one-off projects. Anecdotal evidence and limited case studies are inadequate to leverage changes in mainstream design practices, in which decisions are primarily influenced by building economics and regulations. For systemic change to occur, occupancy wellbeing must be added into the SB base rating system.

Innovation: This proposal combines and leverages the disciplinary strengths of neuroscience with architecture design to create modeling efficiencies that will open new multidisciplinary, neuroscience-driven research avenues in both architecture and psychology. Previous research that investigated the effects of SB's on occupant health and wellbeing have relied on self-reported, qualitative survey assessments. While indicative of the overall positive influence on wellbeing, there has been little understanding of the exact mechanisms by which SB design features influence people's cognitive and affective responses. Missing from this body of work is the systematic collection and interpretation of objective, quantifiable physiological responses to specific design elements. Our experimental design provides a **unique new utility** to three (separately) validated methodologies by combining (1) electroencephalography (EEG) with an emerging design technology – (2) virtual reality (VR) to overcome the dual problems of confounding variables and participant bias during the measurement of elicited user responses to SB features in real time. VR allows three-dimensional, systematic design manipulations that are prohibitively expensive in real environments and EEG neuroimaging offers validated inferences about cognitive and affective processing. Our approach will also combine continuous EEG approaches with (3) event-related potential (ERP) techniques to index relevant brain activity in response to visual stimuli. Neuroscientific research approaches will provide insights to fill this knowledge gap, and test/develop an neuroimaging experimental protocol, combined with VR technology, that could be used as complementary method to the traditional survey methodology, which could be adopted by researchers in other social science and design fields. **This is the first time that the combination of virtual reality technology and EEG/ERP neuroimaging** has been proposed to study the potential healthful outcomes of sustainable building design features.

Project Objectives: This proposed project fits two of the central themes of the BBI: mental health (wellbeing) and perception/sensation via an experimental focus on three understudied SB design features: *lighting level/quality*, *accessibility to outdoor views* and *spatial quality* using VR, EEG, and ERP.

The project objectives are to:

1) Develop and validate an experimental EEG/ERP protocol in VR environments that provide objective measures of psychological experiences in both SBs and CBs.
    a. The methodology will disentangle the effect of the experimental setup on sensation and perception by measuring and comparing effects between still images, continuous 2-d videos, and immersive VR environments.
2) Assess the association of SB design features on positive and negative emotional states (proxies for wellbeing) as compared to the absence of these design features in CBs.
3) Examine the effectiveness of stress reduction from SB design elements.

Hypothesis: SBs, relative to CBs, produce positive mental health outcomes as measured by:

a. Increased engagement, involving orienting, attention, and arousal.
b. Increased focus, involving increased executive function.
c. Increases in interest, involving increased positive approach engagement.
d. Reduced stress, involving a decrease in withdrawal action tendencies and arousal. Low to moderate levels of stress can improve productivity, whereas a higher level tends to be destructive and can have long term consequences for health and wellbeing.

Methodology: The goal of this research project is to develop, test, and validate a data-driven approach for understanding the potential physiological influences of sustainable design features (see figure 1). We propose technology-enabled, repeatable measures for quantifying how sustainable design features affect occupancy *emotional states* and *cognitive functions*. In response to these two weakness, this research proposes a novel framework that will test the validity of combining The proposed project will focus on three understudied SB design features: *lighting level/quality*, *accessibility to outdoor views* and *spatial quality* (horizontal vs. vertical, and tree-like forms).

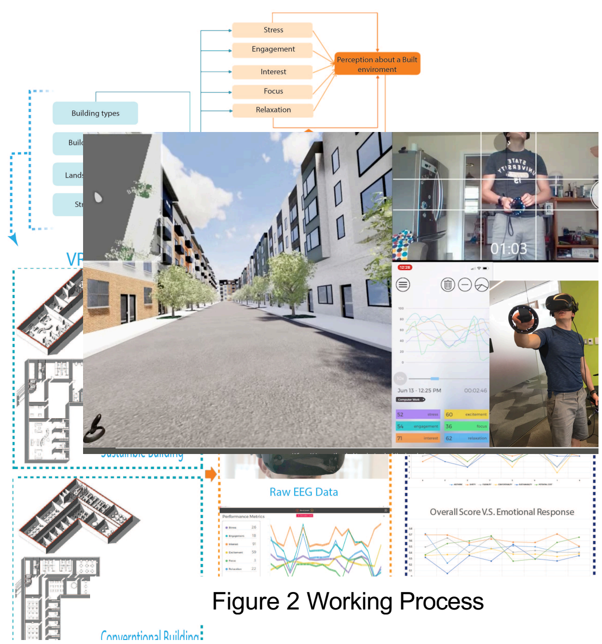

Figure 2 Working Process

Figure 1 Research framework and workflow

Experimental Protocol Development:

Create Virtual Environments*: SB and CB*: We recently were awarded a small seed grant (AIA Upjohn Research Initiative.) to develop the use of VR for this purpose. We completed preliminary work, which validated the compatibility of the technology devices and the methodology (see figure 2). Using this approach, we will create an office floor for the SB and CB control, constructed in VR with the same dimensions, shape, configuration and building materials. The SB experimental design will be augmented with amplified daylight access as well as sufficient overall lighting levels, views to outside from each individual office and a more horizontal spatial quality.

Experimental Protocol Development: Four experimental tasks will be derived from the VR environment. Stimuli for tasks 1-3 would be taken from these VR environments, and task 4 would use the full VR experience of those environments. 1, Still image blocks from SBs and CBs representing key differences, 2, sequenced still images, in which still images from SBs and CBs will taken sequentially (e.g. every 15 meters), simulating movement through the buildings, 3, a continuous video following the same path through the building as the sequenced still imaged (task 2), and 4, virtual reality, in which participants move through the same path, but in in a VR environment at their own pace.

EEG/ERP Measurement: The core measurement approach will incorporate widely validated ERP techniques, applied with still images, and then both ERP and continuous EEG measures with the continuous video and VR tasks, depicting movement through the buildings. Continuous EEG recordings would be taken throughout all tasks (with triggers inserted for relevant events to assess ERPs). The advantage of this approach is to leverage the large body of work detailing cognitive and affective responding based on event-related activity from the still image blocks to define key differences in response patters between the SBs and CBs. Findings at this level will be interesting on their own, and will additionally serve to guide analysis of the subsequent tasks 2-4 (i.e. Sequenced Still Images, Continuous Video, Virtual Reality). Tasks 2-4 will then add increasing amount of motion, up to the full VR experience, providing a bridge between the constrained still image presentation and relatively less constrained VR experience.

EEG Assessment: Cognitive and Affective Constructs Indexed. EEG/ERP measures will index cognitive and affective constructs relevant to assessing differences between SBs and CBs.

Measure	Construct and Description
Peripheral Physiological	
Skin Conductance (SC)	Arousal (level; SCL) and Orienting (event-related responses; SCR)[1, 2]
Electrocardiogram (ECG)	Regulatory Effort/Fatigue (heart rate variability)[3]
EEG/ERP Neuroimaging (96-channel)	
ERP: Late Positive Potential (LPP)	Cue-reactivity – salience and arousal, sustained attention[2]
EEG/ERP: Interchannel phase-synchrony ICPS	Engagement of motor and visual areas (theta-band)[4], Executive function (e.g. theta-band medial to lateral PFC connectivity)[4-6]
EEG/ERP: Medial-frontal theta amplitude	Orienting, Salience, and attention[7-14]
EEG: Alpha power	Inhibitory control and arousal[15]
EEG: Alpha asymmetry	Approach/withdraw action tendencies[16, 17]

Expected Outcomes: Upon conclusion of the proposed research, we will have demonstrated proof of concept for a data driven approach to measuring the impact of SB design elements on human emotional and well-being states. This model has great potential to open new avenues for inquiry on how technology-based tools can be leveraged to influence mainstream design choices that incorporate the promotion of health benefits alongside calculations of cost, efficiency, and environmental impact. Public health considerations in sustainable building design choices may in the future, become the smart, cost-effective way to design, build and live.

Summary. Thus, the proposed study will combine use of VR (Prof. Hu's Lab) and electrophysiological equipment (Dr. Bernat's lab), to collect EEG/ERP measures (as well as heart (ECG) and skin conductance (SC)) from 50 adults (college aged, half women). $50 incentives will be provided for each participant. Analyses will determine the cognitive and affective impacts of the three specific visual SB design elements, in the experimental environment. These measurements serve as a proxy for assessing the health promoting benefits of the introduced sustainable design elements. Subsequent grant applications would be based on the developed tasks and measurement framework, and would focus on testing additional building features and populations.

Approach to collaboration: This research proposes a novel framework that will test the validity of combining EEG with an emerging design technology - VR to overcome the dual problems of confounding variables and participant self-reporting biases during the measurement of elicited user responses to SB features in real time. VR allows three-dimensional, systematic design manipulations that are prohibitively expensive in real environments and EEG/ERP approaches offer validated measures of cognitive and affective processing. Our proposed approach is based on EEG/ERP measured during engagement with still image blocks, sequenced still images, prerecorded video sequences, and VR. In this project, the visual stimuli are: *lighting level/quality*, *accessibility to outdoor views* and *spatial quality.*

Professor Ming Hu who has been an extensive practice experience with VR. Her research focus in at the intersection of green technology, building systems and environmental health, she specializing in the energy and environmental performance of buildings. Her research approach includes simulation, building information modelling and virtual reality.

Dr. Edward Bernat has demonstrated expertise characterizing brain mechanisms that underlie individual differences in cognitive and affective processing. This involves basic science work developing measures for critical mechanisms, and clinical-translational work assessing how these mechanisms relate to psychopathology and individual differences.

4. Project Timeline

The proposed project period is from June 1st 2019 to May 30th 2020. The following table highlights the project action items along the timeline. Deliverables. We plan to have the protocol developed, with IRB approval, during Q1. During Q2 we plan to have an initial set of participants, and begin data analysis. By Q3, we will have most of the data collected, a good part of the analytic approach developed, and core ideas for an initial manuscript. For Q4, we will complete the data analysis, prepare to submit the manuscript, and develop the grant proposal.

Project Action Items	BBI Funding Period June 1, 2019 – April 30, 2020											
	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Research team organization	X											
Obtain IRB approval	X											
Protocol Development	X	X	X									
Data collection				X	X	X	X	X	X	X		
Data analysis						X	X	X	X	X	X	X
Manuscript preparation								X	X	X	X	X
Grant proposal preparation										X	X	X
Deliverables:			Q1			Q2			Q3			Q4

5. Funding Target:

The proposed work will result in pilot data to secure external funding from the following mechanisms/agencies: National Science Foundation (NSF) Integrative Strategies for Understanding Neural and Cognitive Systems (NCS); U.S. Department of Housing and Urban Development; American Institute of Architects (AIA). NCS is part of NSF's participation in the Brian Research Through Advancing Innovative Neurotechnologies (BRAIN) initiative (up to $ 600K /3 years). BBI funding is critical to our future grant application, especially for NSF funding across three levels. First, the verified research framework/method and collected pilot data from this proposed study will enable us to apply for *Integrative Strategies for Understanding Neural and Cognitive Systems* (due February 26, 2020) that fund that funds innovative boundary-crossing proposal that could map out new research frontiers. Second, the proposed team consist of specialists in urban/architecture design and psychology/neuroscience, and the proposed project will allow the team fine tuning and research workflow revision if necessary, in order to prepared for other built environment related program. Third, the results of this proof of concept will allow this team to invite a public health specialist to integrate EEG/fMRI tools with conventional public health survey method to further validate and expand the data-driven predictive model needed for future large scale research programs for NIH funding.

ESTIMATED BUDGET

Cost Categories	Description	Costs
Post-doc (Dr. Bernat's Lab)*	33% time commitment to develop tasks, conduct EEG experiments and perform data analysis	**$25,000**
Post-bacc (Dr. Bernat's Lab)*	50% time to develop tasks and manage participants	**$20,000**
GRA (Dr. Hu's Lab)*	100% time to construct VR environments	**$15,000**
Participant Incentive	$50 compensation for participation (max 50 participants)	**$2,500**
Equipment	2 Sets of VR-ready Computer (Dell XPS Tower Special Edition (8930) + Head mount viewer (Oculus Rift)	**$10,500**
Supplies	EEG and lab supplies ($25/participant)	**$1,250**
Publication	Open access publication fee	**$750**
*Technician and student salaries include fringe benefits.		
Total		**$75,000**

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