READ THE ROOM

A pilot design exploration into a neural-adaptive, physically situated virtual environment

A Thesis

Presented to the Faculty of the Graduate School

of Cornell University

In Partial Fulfillment of the Requirements for the Degree of

Master of Science

by

JING WEI QIAN

May 2022

ABSTRACT

This thesis presents an exploration of how human cognition and virtual reality give and guide the many layers of meaning that compose our spatial experience. It will explore how the distinct character of space emerges from the interaction between itself and one or more individuals. It will also address how this interaction can transform multiple surfaces into a narrative that people can engage with.

On a technical level, this thesis explores the design of a physically situated, neural-adaptive embodied XR (extended reality) domestic, public space. It explores how interactive space can enrich our relationship between the built environment and ourselves. Specifically, how one can use their cognitive input and expressive muscle signals to influence the space. In addition, how a sentimentally conscious space can actively engage with the occupants (users) by transforming spatially and triggering sensory responses.

Dedication

Dedicated to my parents and grandparents for supporting me through times of challenge.

Acknowledgements

I would like to thank my mentor, Professor Jenny Sabin, for her endless support over the last two years. She supported my passion and patiently guided me in many moments of doubt and confusion. I also want to thank Professor Harald Haraldsson for his patience and generosity in introducing me to the Cornell XRC community. I believe that my extended exposure to the Cornell Tech community has cemented my desire to point my creative passion toward the intersection of tech and design. I will continue future learning in XR, and I firmly believe it will be a meaningful journey down the line. I want to thank Professor Susan Fussell for giving me the opportunity to join her lab and be exposed to the discipline of HCI. It allowed me to discover the value of creativity and design in the context of user-oriented technology. Finally, I would like to thank my long-term collaborator Heidi He who helped me to resolve countless technical issues and helped this project to move forward.

Table of Contents

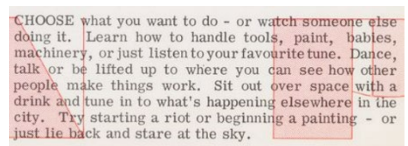
List of Figures

1.INTRODUCTION

1.1 Background

"**CHOOSE** what you want to do – or watch someone else doing it. Learn how to handle tools, paint, babies, machinery, or just listen to your favorite tune. Dance, talk or be listed up to where you can see how other people make things work. Sit out over space with a drink and tune in to what's happening elsewhere in the city. Try starting a riot or beginning a painting-or just lie back and state at the sky."

- *Cedric Price, Fun Palace, 1964*

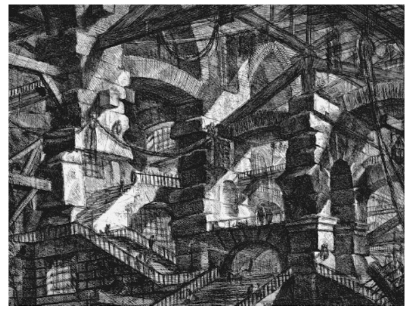

CHOOSE what you want to do - or watch someone else doing it. Learn how to handle tools, paint, babies, machinery, or just listen to your favourite tune. Dance, talk or be lifted up to where you can see how other people make things work. Sit out over space with a drink and tune in to what's happening elsewhere in the city. Try starting a riot or beginning a painting - or just lie back and stare at the sky.

[fig 1] Cedric Price: Fun Palace *Project prompt*

For the past 50 years, technological advancements have equipped architects with new tools and expanded imagination to carry out innovative design process. Speculative architectural visions were also inspired by the contemporary identity of industrial, technological, and cultural achievements. In 1964, British Architecture pioneer Cedric Price proposed Fun Palace, an interactive and transformative complex that can adapt to the occupants' (the users') functional needs. Fundamentally, Price envisioned a mechanically actuated, information driven spatial configuration that can bring a greater degree of freedom to the human users within a limited, physical spatial boundary.

Future visions for interactive architecture can be more than transforming robotic structures. By allowing technology to evolve naturally, it replaces static forms that are set and stable with living, interactive spaces that can be many different things to many different people. Instead of being just the venue for storytelling (whether in libraries, churches, theaters, offices, homes, or sports arenas), this intelligent, space itself becomes the storyteller.

Contemporary cultural trends and technological advancements have always been powerful catalyst for the evolution of architectural design. In addition to aiding the design process, they also serve as powerful drivers that expand people's imaginations of our future relationships with the space and the experience it can afford. Our desire to be present within and manipulate the perceived reality is not inspired by technological advancement, but rather a much more inherent motivation. Before the invention of digital technology, pioneers, artists, writers, and architects have all been inventing the means to "bend reality".



[fig 2]Giovanni Battista Piranesi: The Imaginary Prisons- *The Gothic Arch*

That inherent desire is also why XR (extended reality) technology is an increasingly relevant topic for designers, and it is uniquely compatible with the inquiry of interactive environment. On a higher level neither Virtual nor Augmented reality is a type of "technology", but rather a medium in which one can communicate holistic, immersive spatial experiences. Equipped with relevant skill and knowledge, one can curate experience and facilitate utilities that are limited by our physical realities.

Previous research has found that virtual reality can be an effective research tool for simulating environmental features. This is because it allows researchers to immerse participants in hypothetical contexts and study their responses to controlled environmental manipulations that would be difficult to examine in a real-life environment.

In addition, with the advancement of IoT devices and ubiquitous computing implementations, sensing human data is becoming increasingly accessible and accurate. This advancement will enable other data-driven designers to add a layer of more refined, personal experience on top of the spatially curated environment. Many human-signal (heart rate, gesture, gaze, EEG, EMG etc.) driven interactions are being actively investigated however, there are still many unexplored subjects and concepts to be validate through quantitative/qualitative experimentations.

Nonetheless, I would like to adventurously argue that Virtual Reality can be productively integrated into the quest of interactive space sand address a multitude of questions including but not limited to the followings:

1). Can we deliver quantitative/qualitative information through perceived experience?

2). What can be achieved in virtual and what aspects of our physical reality is necessary to supplement that experience?

3). Can we design an interactive space that re-configures itself based on one's cognitive inputs and present intimate, personal experiences to the users?

1.2 Hypothesis and Questions

This thesis hypothesizes that by building a neural adaptive, interactive VR environment based on existing spaces we can enhance people's understanding of their own cognitive states through understanding of the ambient spaces. Specifically, the project attempts to ask the following questions:

Q1: Can interactive spatial environment be used to enhance self-awareness of one's cognitive state.

Q2: How do visual motion, geometries and pattern influence user sensory responses.

1.4 Methodology

To contextualize the explorations, two case studies were designed to emulate speculative space that reacts to user cognitive states. The case study environments are modeled the same as the physical reference so that the users will not need an arbitrary guardian (protective virtual boundary) that limits their movements and allows the users to move in virtual space with the same amount of freedom as they would in the referenced physical space increase the level of immersion.

Interactive elements were then added to the environments to trigger changes based on the user's passive inputs (relaxation, stress, focus, and engagement level). The hope is that the changing environment will amplify or highlight associated cognitive states and enhance self-awareness and mindfulness. The participants will be debriefed about the triggering factors of the interactive environments, encouraged to engage in conversations while in VR space, and interviewed after the experience.

1.3 Learnings

This thesis explores the design of a physically situated, neural-adaptive embodied XR (extended reality) domestic space. It is a thesis project that has multiple disciplinary intersections. To achieve even the first iteration of the functional prototype a large amount of learning needs to be done. In short summary, this project resulted in productive learnings in the following topics:

1. Signal Processing
2. IoT Service Design, programming
3. Unity (C#)
4. Shader Code (HLSL)
5. Compute Shader
6. Multi-User Interaction Design (Normcore)
7. Interaction Design

2 Context

[fig3] Studio INI's installation Urban Imprint, a canopy opens above the visitors' head as they step under the pavilion

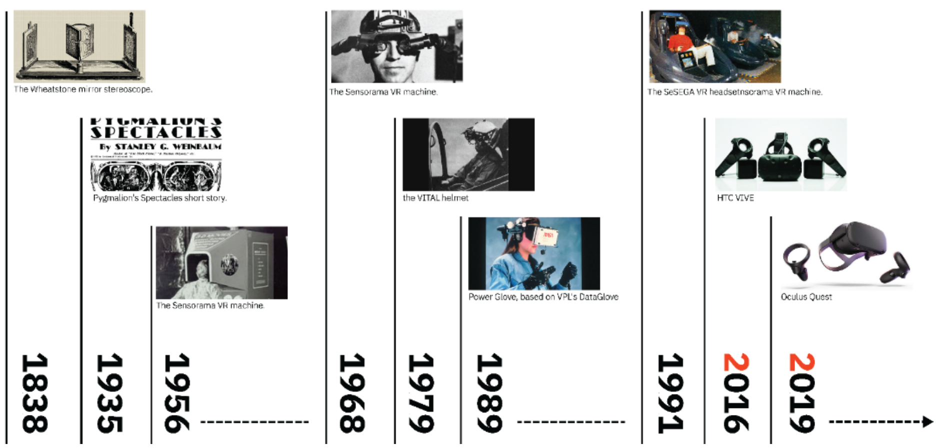
As much as architecture is associated with concrete, monuments, and static establishments, we can no longer dwell in space without interacting with some form of digital systems through dedicated touch points.

However, architecture is more often treated as a physical shell for a network of connected devices. A wall is just a vertical plane for mounting the smart thermal controller, a ceiling is for attaching smoke detectors and lighting systems. It would be hard to argue that architectural design has adopted design process that inherently integrates considerations for technology from the beginning and produces result of an iterative, collaborative synthesis. Of course, this is simply an observation, not in any way a criticism regarding existing design practices. Designers must deal with wicked problems with ambiguous restraints from materiality to client engagements, and paradigm shifts typically trickle in from other disciplines.

It is this project's intention to combine technological tools (commercial EEG/EMG headset, VR headset, open source IOT tool) to explore frameworks that can enable imaginations of future spaces not only in formal spatial languages but also as a dynamic platform that can actively engage with us in our daily lives and help us to form intimate relationships with the space and ourselves.

2.1 Perspectives of inquiry

From an architectural design point of view, this project explores how interactive space can contribute to enrich our relationship with built environment, especially personal space. It attempts to understand how one can extend his/her cognitive input and expressive muscle signals into the space itself. In addition, how a sentimentally conscious space can actively engage with the occupants (users) by transforming spatially and triggering sensory response.



[fig4] Timeline of VR technological development

From a technological-cultural perspective, XR has become increasingly integrated with our daily personal and professional experiences. With Meta (previously Facebook) committing to universalize immersive technology and augmented experiences, virtual reality will continue to be a part of our creative, and professional experiences. It is very likely that with the advancement in both software and hardware will push the prevalence of XR even further

In addition to prototyping novel platform. This project is also supplemented by other inter or cross-disciplinary narratives. The following sub-sections briefly discusses the relevance of cognitive philosophy, conversation theory and cybernetic architecture, and its paradigm evolution.

2.2 Our External Minds

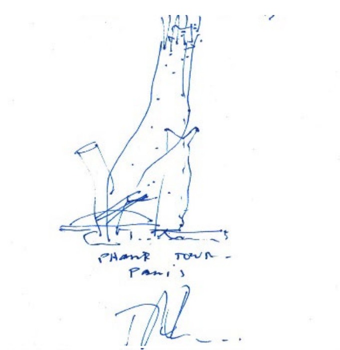
"Where does the mind stop and the rest of the world begin?"

-Andy Clark

Our cognition is not just limited within our skull, skin, or our physiological system. While sentience remains a puzzling topic with no scientific research consensus, we can assume a more abstract but universal perspective of seeing consciousness as an active state of perceiving, processing, and understanding of the mind and its place in nature. However, the process of thinking is not exclusive to our physical constitutions. Cognition and philosophy professor Andy Clark proposed that we as human being can externalize our cognition and incorporate other mediums as a sub-system if our internal thinking. To brutally simplify, just as our body has incorporated alien bacteria DNA into a part of the human cells, our cognitive processes also utilize external objects to carry out parts of our thinking. For example, we rely on physical gestures to amply thinking, architects use paper sketches as a part of the creative loop iterations, and perhaps the most universal example is that almost all our daily activities require connectivity-enabled devices (smartphones, laptop, etc.).

Van Gulick, Robert, "Consciousness", The Stanford Encyclopedia of Philosophy (Winter 2021 Edition), Edward N. Zalta (ed.),.

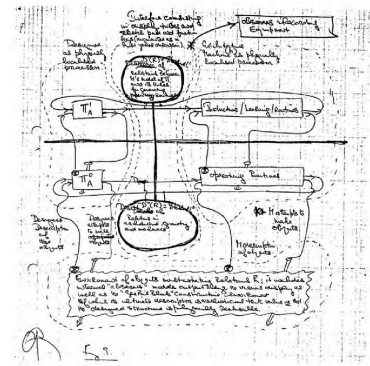
Clark, A., & Chalmers, D. (1998). The Extended Mind. *Analysis, 58*, 7-19.



[fig5] Thom Mayne napkin sketch

2.3 Cybernetic + Architecture

Previous brief discussion of cognitive science intends to show that the development of cybernetic can find similarities with and translated into other disciplines. Cybernetic architecture began partly as Gordan Pask and Cedric Price collaborated on the Fun Palace. Together they formulated a mutually constructive environment in which the human occupants and the device-enabled environment. Being a cybernetic pioneer himself, Pask accumulated significant, rigorous theoretical, speculative, and constructed experiments. In his experimental assembly Colloquy of Mobiles project (1968), Pask demonstrated a self-adjusting system which constants changes its own configuration in order to re-establish default reference when the environment is in flux due to human traffic. It is a system that "rewards" itself and Pask intended to design a system that co-evolve with the human users; however, the reality is that architecture relies on spatial forms to deliver experiences. Our physical gesture is influenced by the perceived physicality of our environment. Consequently, if the environment doesn't physically change, our understanding of the environment will remain the same and so will our behavior. Building megastructures that change its form based on a dynamic information system was a theoretically productive movement but practically impossible objective.



Source: Pask (1976b)

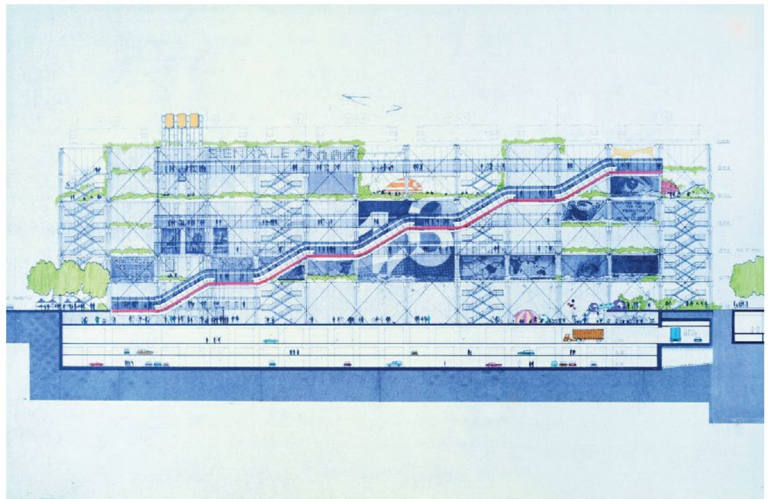
[fig6] Gordon Pask Conversation Model diagram

2.4 Interactive Architecture and Adaptive Strategies

While the cybernetic architecture movement did not come to complete fruition due to practical constraints, built spaces that are integrated with dynamic information system is now universal. In addition to HVAC, lighting systems controlled by back-stage automated controls, several frontier projects bring interactivity to spotlight of visual attentions.

Interactive architecture differs from traditional architecture in that it creates real-time, personalized conversations with its visitors. Interactive architecture uses digital interfaces and smart sensors to create conversations with its visitors. These conversations allow the visitors to input data, which is processed and used to create new information.

Media Facade HongKong and ShangHai Bank by Norman Foster



Renzo Piano and Richard Rogers - Pompidou Centre, 1971 Pencil on paper - as featured in Drawing Architecture

[fig7] Architecture using media façade to mediate information and communicate with visitors

This type of architecture requires intelligence, which is only possible when operate in digital technology. Digital technology requires two elements: data storage and data processing. Storage serves as memory, while processing allows for real-time interactions. This type of architecture is not possible with traditional methods like material and mechanical effects, which lack intelligence and the ability to change in real-time.

The following section will highlight three examples of distinct types of interactive architectural implementations. Of course, as Innovation does not always happen at a linear pace, so the discussion will be categorical rather than chronological.

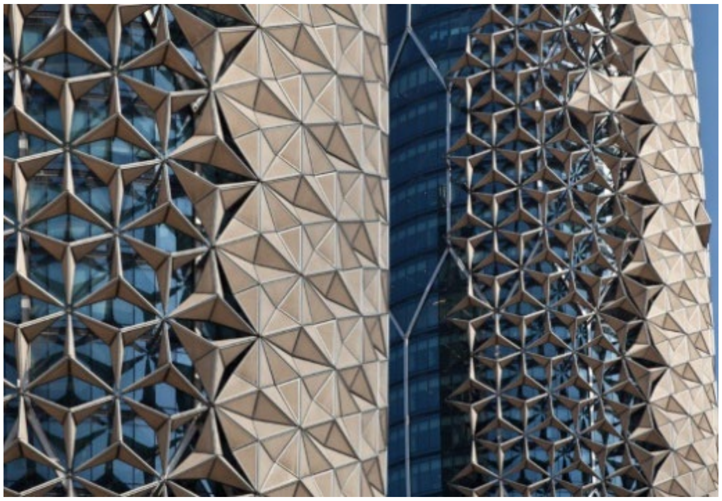
1). Novel Material

[fig8] Façade Image of the La Defense Offices designed by UNStudio

This category is special in a sense that while the transformation of space is not driven by digital processing instruments and mechanical actuations. Innovative, reactive material itself can take environmental input such as light, temperature and humidity as input and the materiality programmed by the architect can react to the environment and can visibly alter the environment. The La Defense project in the Netherlands by UN Studio uses reflective material effects to create a heightened relationship between architecture and its environment. Coated in its entirety with a unique 3M-developed diachronic foil, the façade absorbs its environment and recursively reflects it back through a spectrum of colors. While not intelligent, the structure responds, magnifies, and manipulates its environment within its skin.

2). Mechanical

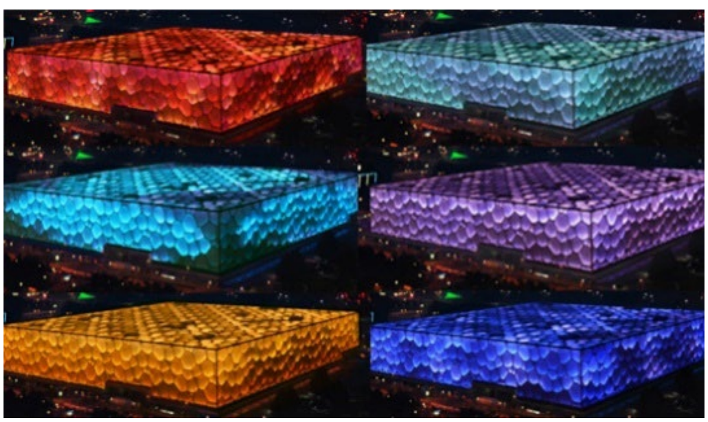
From sliding doors to elevating platforms, mechanically operating part of the architectural building can achieve the most direct impact on environmental alterations. Aedes Architects designed a responsive facade for Abu Dhabi's Al



[fig9] Responsive façade of the Al-Bahar Towers designed by Aedes Architects

Bahar towers, taking cues from the "mashrabiya", a traditional Islamic lattice shading device. The 145-meter towers' Masharabiya shading system was developed by the computational design team at Aedas, using a parametric description for the geometry of the actuated facade panels. This allowed the team to simulate their operation in response to sun exposure and changing incidence angles during different days of the year.

3). Digital

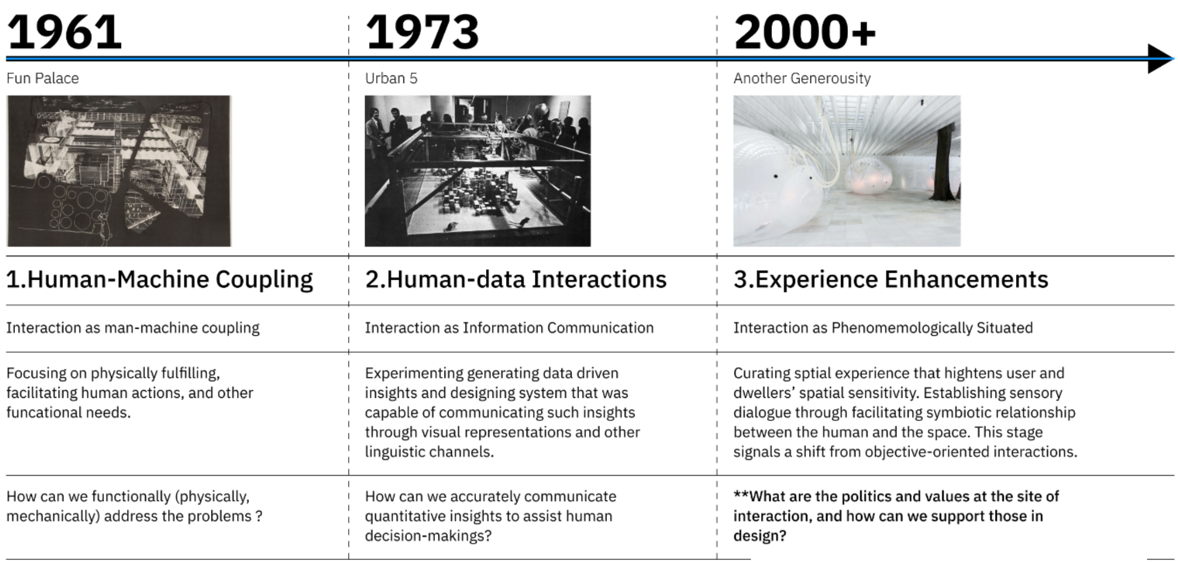


[fig10] Beijing National Aquatic Centers and its ETFE façade combined with interactive lighting system

As much as architecture is historically situated in concreteness and static magnificence. In the information age architectural design has also adopted a certain level of flexibility. As the amount of data available to people continues to grow, the need for customization and personalization also increases. people want their individual experiences to be tailored to their personal preferences, whether that is in the form of their car, their computer, their phone, or their home. Although architectural-scale designs still cannot afford experience delivery on such granularity, interactive elements such as digital lighting system, and LED displays have augmented the enclosure layers of many commercial builds. As the Lighting system changes the buildings face, it also changes the structure's culture identity and sometimes even the implied functions of the interior spaces.

2.5 The Paradigm Shifts in Cybernetic Design Narratives

The synthesis between information processing and interactive



[fig11] Phases of interactive architecture discourse

spatial transformation started as early as 1960s. Nicolas Negroponte once envisioned in his "architecture machines" that the advancement of intelligent system combined with the increasingly miniaturized kinetic components can enable a new kind of responsive/interactive environment in which human occupants' needs can be actively detected/predicted and met by the shifting spatial programming

Over the course of cybernetic architecture history one can observe that as technology and culture further evolve, so are the epistemological and research objective of responsive/cybernetic architecture. To overview, there are three distinct stages of cybernetic architectural paradigm:

1. Human-Machine Interactions (1961)

Since the post Second World War people were still imagining the power of industrial machinery with utopian visions. In this era the cybernetic architecture was concerned with solving human problems with architecture as activated machines. Interactions were designed as human-machine symbiosis and the purpose of the speculative structure was to physically fulfill the demand of the occupants' functional need.

2. Human-data Interactions (1973)

As computation technology becomes increasingly prevalent, some educational institutions have also started to experiment with the potential of computers and speculate about collaboration between humans and computers. Nicolas Negroponte's group experimented with a reactive, non-AI-driven agent that can respond to basic word input and visualize changes based on daily English inputs.

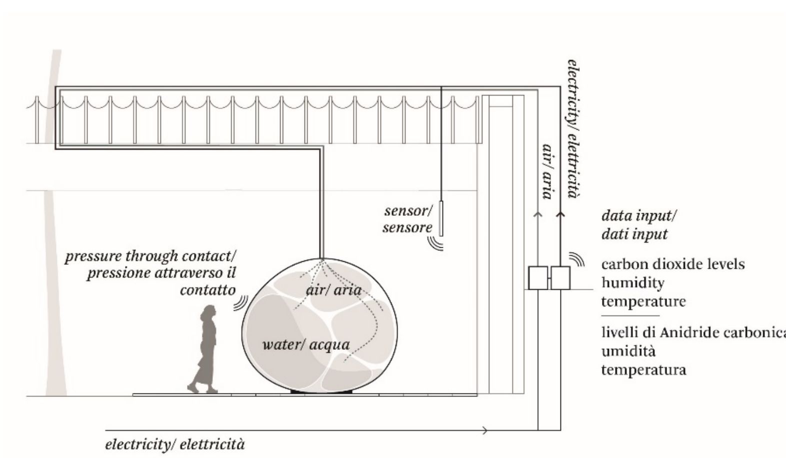
[fig12] Nicolas Negroponte

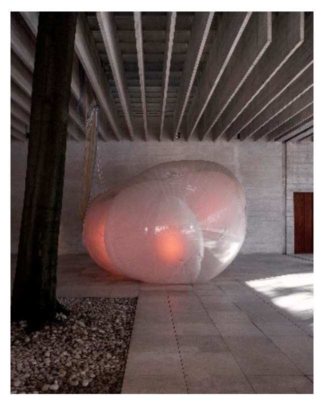
Urban 5

This example emphasizes the process of information as the interactions between human and automated agents. Interactions were designed as a process of information exchange between human users and digital processors. The goal of successful interactions would be that a human's input is accurately interpreted, and the machine's (digital agent) output would be visualized in a format that the human users can accurately internalize. Just as Gordon Pask suggested in his conversation theory that a successful learning process is a recursive communication process involving bi-directional interpretation, representation, and confirmation. This era of interactive architectural inquiry focuses on developing a computational model that can enable productive communication and collaborations between humans and computers. focuses on developing a computational model that can enable productive communication and collaborations between human and computers.

3. Expanded Experience (2000)

Fast forward in the 2000s, as personal computing and connectivity becomes increasing accessible through smart-devices, systematic computational design seems to fade into the background. What emerged as a new design metaphor that positions interactions as phenomenologically situated actions? Previous paradigm focuses on how productive information can be effectively exchanged during a conversation between human partners (man-machine or man to man). However, the new interactive architecture paradigm shifts away from objective-oriented interactions and prioritizes curating inclusive spatial experience that can heighten user's awareness. Example work such as Another Generosity (2018)





[fig13] Lunden Architecture, *Another Generosity*, 2018

by Lunden Architecture explores alternative objectives such as using interactive, spatial altering installation to enhance the users' understanding of their relationship with the surrounding environment. In this current era, the design inquiry of an interactive space becomes that "What are the dynamics and values at the site of interaction, and how can we actively support them by design?"

2.6 Commercial BCI, VR, and Interactive Environment

Brain-computer interfaces (BCIs) are devices that monitor and decode brain activity and create control signals to communicate or control external devices. While research grade equipment such as Biosemi EEG cap produces more accurate results, commercial equipment with open-source connectivity such as neuralSku, OpenBCI, and Emotiv have been improving and gaining more usage in various contexts. Currently, not only the do the commercial-grade BCI equipment can produce accurate results, but headsets also such as BCI EPOC offers non-obstructive ergonomics and wireless connectivity, making it a highly desirable device to be deployed under various contexts. Recent review study indicates that as one of the available EEG devices available to consumers, EPOC demonstrated feasibility for both user-oriented prototyping and scientific-focused research. Since 2010 EPOC has been used in hundreds of scientific applications as its low-cost entry requirements, user-friendly design, and wireless capabilities are practically expedient for researchers and engineers alike.

[fig14] Biosemi EEG cap

[fig15] Emotiv Epoc headset

Similar to commercial BCI technologies, AR/VR technology has rapidly matured in recent years, delivering a more immersive and realistic experience to users. It has also become more widely available, with a range of applications and experiences that are more stimulating and expressive than traditional desktop applications. AR/VR technology can be used in a variety of areas, including entertainment, education, art, and health.

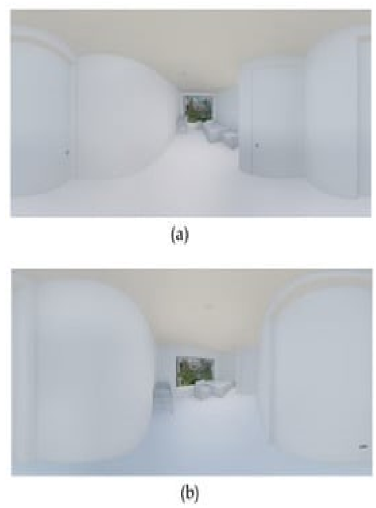
The combination of Brain-Computer Interfaces (BCI) with AR/VR can create more communication pathways by increasing the communication bandwidth between humans and AR/VR. This can be done explicitly with active BCIs, which allow users to issue commands to devices or enter text without any physical involvement, or implicitly with passive BCIs, which monitor a user's state and can adjust the VR/AR interface accordingly.

BCIs and AR/VR technologies offer the potential for immersive scenarios that create artificially perceived realities. These scenarios can be used in basic BCI research, as well as in a variety of other fields such as therapeutic applications, Human-Computer Interaction, and more. To take full advantage of these technologies, however, methodological advances are required in areas such as BCI interaction and stimulus design, synchronization, and VR/AR specific artifacts.

While there are limited numbers of pre-existing studies that intersects such technologies. During the earlier stages of literature review, we came to understand that there are two major categories of studies which involve both VR, and architectural design:

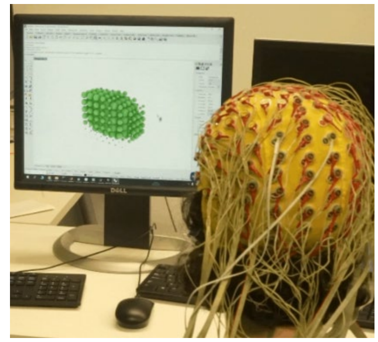
1). Using simulated environments to stimulated sensory responses and evaluate user's emotional association and preferences regarding specific settings of the virtual environments. For example, Kim et al. (2021) explored architectural design elements that can evoke the feeling of spaciousness in a relatively small living environment. In the study, EEG signals were used as evaluation benchmarks to determine relaxation-arousal levels and to measure the neural-physiological responses from participants who experience different spatial configurations.

2). Using EEG signals to enable designer-tool interactions. Under this category, the BCI interface allows the user to



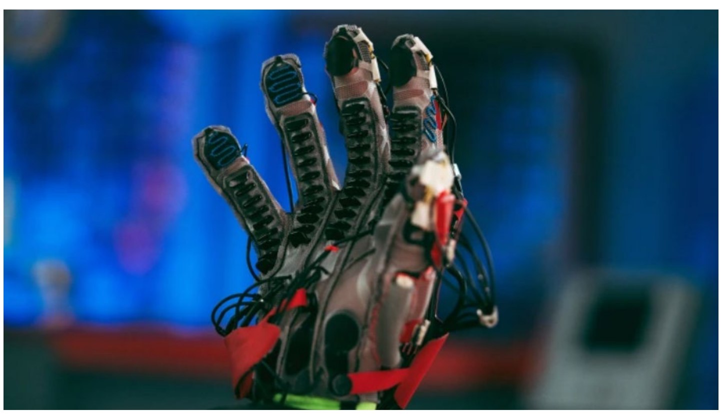
[fig16] Environment from Kim et al (2021) *Effects of Changes to Architectural Elements on Human Relaxation-Arousal Responses: Based on VR and EEG* showing 2 different VR configurations with different visual attributes.

actively engage and manipulate geometries and object orientations. Qi et al in demonstrated a prototype that uses kinetic impulses identified by trained EEG data as design inputs and change geometry in real time. In another instance of the project, Qi's team enabled the users to move window placements based on pre-trained kinetic imagery (Imagining physically moving forward, left, right and back). This method of interactions can potentially be utilized to develop assistive features that can provide alternative interactive affordance for individuals who are unable to physically interact with digital devices.



[fig17] Illustration from Qi et al (2021) *MindSculpt* Showing interactive interface in which the trained designers uses trained behavior to trigger geometrical changes

Overall the development and continue hybridization of both VR and BCI technologies present provide unique opportunities for explorations. In addition, as more resources are invested into the advancement of immersive environments, technologies that will enable a higher level of immersion is also being actively developed.



[fig18] Haptic glove prototype from reality labs research.

Such technologies can potentially enable much more immersive and physiologically holistic experience in virtual environment. While the topics of haptic is not within the scope of this project, it is important to highlight such development and be positively optimistic that in the future, virtual experience can be just as immersive as our physical reality.

3 Technical Prototyping

3.1 EEG and EMG detection/visualization

The premise of this experiment is that subjects can passively manipulate/influence perceived spatial qualities such as openness, brightness, curvature, and organization.

Many existing XR-mediated enabled interactive BCI studies utilize 2D controls [Putze et al. 2019; Vourvopoulos et al. 2016] or object-oriented interactions [Škola et al. 2018]. 2D controls (touchpoints) in immersive environment are intuitive and simple because such UI design implemented in the existing studies are informed by conventional web, mobile oriented design. Any users who are familiar with smartphones should not struggle to learning perform tasks in such immersive environments. However, there has been yet an example in which the user's passive cognitive input directly influences architectural-scale elements and changes the perceived spatial environments.

While it is easy to say, "a virtual environment that changes with your cognitive states," prototyping a functional environment requires technical breakthroughs in multiple aspects of the project.

The first step is to create a robust data-stream management system that works with the BCI headset. For this project, the Emotiv Epoc was chosen as the EEG headset because it is wireless, lightweight, and its electrode positions are compatible with the Quest 2 headset without causing user discomfort.

The Epoc's native API features a pre-trained feature detection model that allows the users to understand the following cognitive performance matrix: Relaxation, Excitement, Stress, Focus, Engagement, and Interest). In addition, EMG

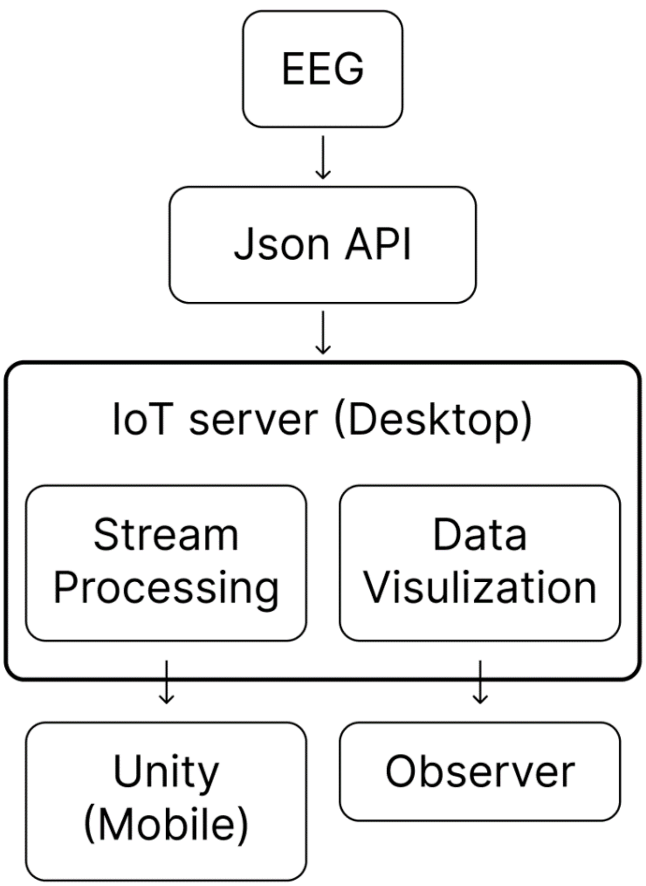
[fig18] blinds control via AR using the SSVEP-BCI, Putze et al. (2019) Window

[fig18] User setup with a HMD and an EEG cap with the electrodes over the motor and sensorimotor cortices, Vourvopoulos et al. (2016)

[fig18] VR training environment. Participants try to move the virtual hands by using MI of left and right hand, Škola et al. (2018)

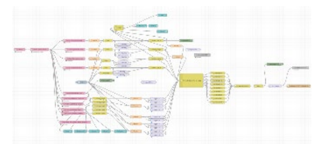
(Electromyography) derived facial detection data was also available via Epoc's native API.

The first challenge was to prototype a system that could reliably extract and trasmit analytical insights from the headset to external systems. One of the advantages of utilizing a commercial-grade EEG system is that expensive, traditional signal amplifiers are not required to denoise and extract the signals; however, most such headsets are under proprietary digital protections. Luckily, data were successfully extracted through a deprecated API which was used to connect previous generations of the headset with an open-source, JSON based IoT platform Node-Red. This development led to further development of the BCI to Server system.



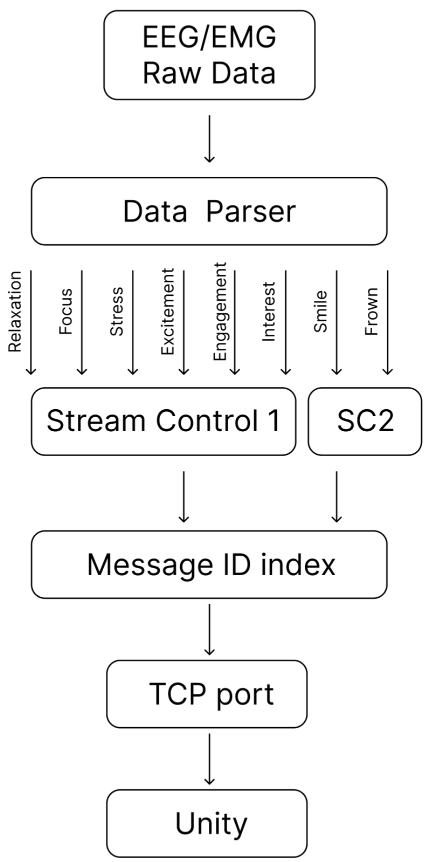
[fig19] Higher level architectural diagram of EEG to Unity system

A second problem after obtaining access to analytical data was that not all data streams were transmitted in a standardized frequency. For example, EEG signals were typically sampled at 128Hz, but the EMG signals were sampled at a much faster rate. Consequently, Cognitive insights were not communicated at the same pace, which can cause synchronization problems for the interactive system.



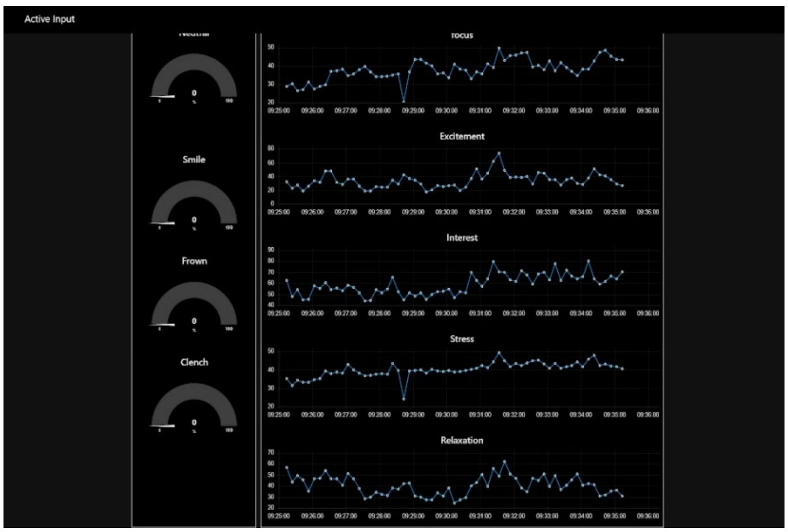
[fig20] Implemented Node-Red system that extracts, sort and synchronizes EEG data

To address the data rate synchronization challenge, a message control system was created to ensure that the rate of incoming data stream remains constant and can be sent to the subscribing clients without causing buffer overflow.



[fig21] Higher level architecture diagram of Node-Red System platform. Showing the modular design which can be deployed not only for Epoc headset but other similar commercial-grade EEG headsets.

In addition to its technical functions, the prototyped platform is based on an open-source modular platform which means that it is also compatible with other available EEG/BCI systems (ex. NeuroSky, OpenBCI, Biosemi, etc). This platform will allow any future researcher and engineers to work with their future projects intersecting VR, IoT, and BCI with ease. The wireless communication protocol can also minimize set up time and improve user comfort as conventional EEG headcaps are very restraining.



[fig22] Dashboard UI interface showing

Another functional feature that was prototyped was the visualization interface. This is a locally hosted interface built upon the *Node-Red-Dashboard-UI* library. The interface is relatively lightweight and runs in parallel as the main Node-Red flow is deployed. The visual platform allows both the users and the observers to track cognitive value output. While the cognitive state data is generated by long-term, passive EEG data analysis and is visualized in a chart format, the EMG-derived facial expression data is almost instantaneous and should be visualized by an interactive pie chart.

In order to avoid reinventing existing product or similar prototypes, we also searched for potential conceptually similar projects both within and outside of the context of VR, BCI, or Architecture. We can confirm that at the time of the thesis writing there were no similar projects that utilizes BCI driven, multi-user enabled VR environments to drive spatial changes.

3. 2 Quest2, Unity, and URP Pipeline

Virtual reality headsets are no longer a fringe technology that is only impressive in theory. They have matured over multiple iterations and are now approaching broad mainstream appeal. Most games or simulations will not need to be custom-made for their specific hardware since current-generation headsets are approaching a platform-independent standard.

At the time of the thesis early phase (2021 Spring), Oculus Quest 2 was chosen as the platform upon which the prototype will be developed. Compared to its available competitors, the Quest 2 headset is the most high-powered standalone VR HMD. While there were other models, such as the HTC Vive and Vive Pro offer high resolutions, they were not considered because the tether-based connectivity and station-based tracking can undermine the intuitiveness of future implementations. One advantage of the Vive headsets was considered, which was that higher fidelity environments could potentially lead to a higher level of immersion. Upon further consideration, the team realized that high-fidelity environments are hard to implement with interactive features. Because ease of use is highly prioritized in this project, Quest 2 is eventually chosen as the foundational hardware.

While Quest 2 was the most practical choice for HMD hardware, it also has unique challenges that we need to overcome by implementing unique methods that sustain performance. Maintaining a minimum framerate is a critical element for supporting user comfort. Around 57.7% of people experience VR sickness, which shares symptoms such as nausea, eye fatigue, and disorientation with motion sickness. Additionally, during the first tests with the Oculus Quest 2, the author found that it could also lead to a short and mild headache.

Motion sickness can be defined as discomfort that is caused when the body's senses do not match up with the environment. For example, experiencing motion sickness on a flight is common when there is turbulence because the body's senses tell it that it is still when in fact, it is moving. The cause of motion sickness is not yet fully understood, but one theory is that it is the result of a sensory conflict. This theory suggests that the more the body predicts the sensory input it will receive, the less likely it is to experience motion sickness. This theory can be applied to VR sickness, which is caused when the body's senses do not match what it is seeing in the virtual environment. People who wear headsets often have different distances between their eyes, also known as the IPD (interpupillary distance). Some headsets, like the first Oculus Quest, provide a sliding mechanism that allows the user to accommodate their IPD very precisely, eliminating or at least minimizing IPD-related issues.

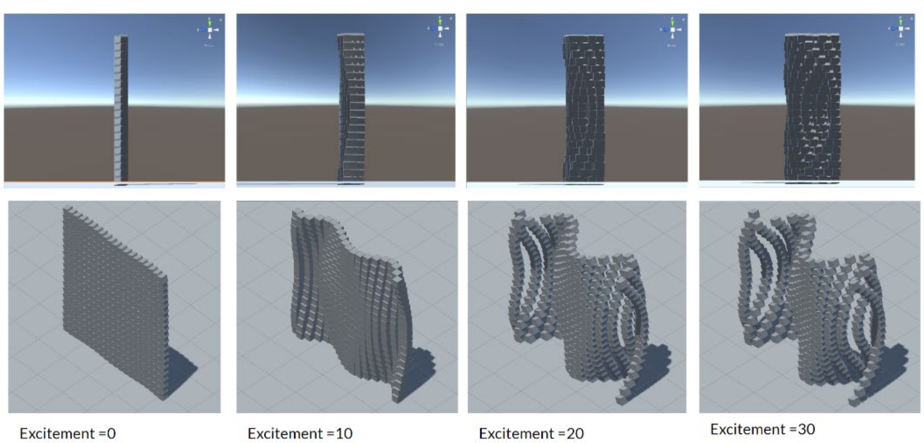
The team needs to keep the framerate as high as possible in order to reduce the likelihood and severity of sensory irritation. This will come at the cost of lower grade graphics, the quality of which directly correlates with the framerate. Environment uploaded to the headset by the user will need to be processed in such a way that enables the VR application to visualize them without a high-performance impact. Texture and 3D assets need to be downscaled (i.e., their resolution needs to be lowered), and thumbnails (low-resolution versions of images) need to be employed wherever possible. To avoid subjects withdrawing from the experience and being hindered in their interactions with the space, measures will need to be employed to lessen this effect. Throughout the project, the author and his teammate learned additional graphics pipeline techniques that helped generate the desired effect without undermining the fluidity of the experience.

When initiating a new unity project, a render pipeline needs to be selected. For the moment, Unity has three graphics templates: Default (Legacy), URP (Universal Rendering Pipeline), and HDRP (High-Definition Rendering Pipeline). URP was selected as the project's underlying graphics pipeline because URP has been proven to have higher performance compared to the Legacy default pipeline while affording materials with higher resolution with minimally sacrificing framerate.

3. 3 Technical Solutions

One straightforward way of achieving the effect of spatial transformation is to implement a game object control system, just like how most interactive environments are created with Unity Editor, but as previous section has discussed, as impressive as the hardware appears to be, Quest2's standalone, mobile-based processing units, and android API do create its own unique limitations.

What seemed smooth on the desktop editor might not be rendered at the same framerate when built onto the VR headset. In addition, because this thesis attempts to designing interactive spatial experience, which heavily relied on



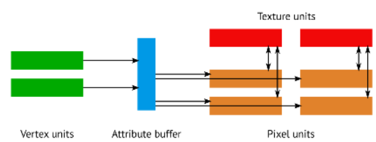
[fig23] Earlier prototype showing procedurally generated virtual elements connected with the excitement out put from the user wearing an EEG headset

procedural mesh manipulations and object generations. Such techniques are considerably more computationally costly compare to simple game object transformations based on x, y, z scale. In fact, one of the earlier iterations discovered that the mobile processor of Quest 2 can only manage to render approximately 800 game objects with a comfortable framerate (60.7). These apparent limitations motivated future learnings and explorations into the following rendering techniques.

1). Compute Shader

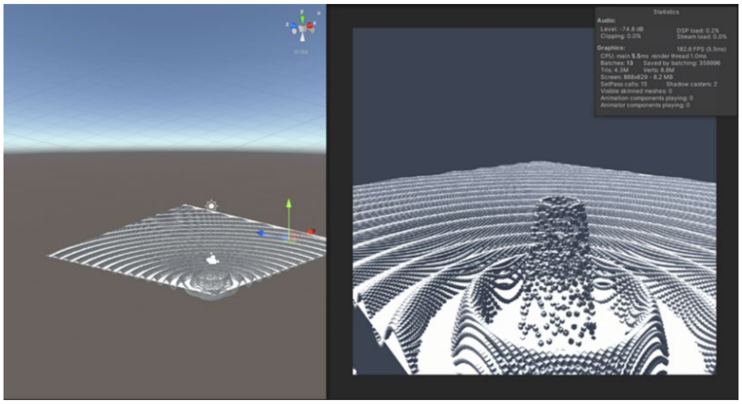
GPUs are designed primarily for parallel processing, with a few cores that specialize in graphics-related tasks such as accessing textures and rendering triangles. A GPU consists of a number of "compute units", which are roughly equivalent to a CPU core. However, because GPUs are focused on parallelism, their cores are designed differently in some major ways.

Compute Shader is a visual programming language that directly interacts with Graphics Processing Unit (GPU). GPUs are machines that can execute code, much like CPUs. They are used to run shaders and render triangles. While GPUs used to only be able to render triangles, they have gradually become more like CPUs due to the need to execute pixel and vertex shaders. Eventually, graphic APIs added compute shaders, which are special shaders that don't use the fixed graphics pipeline and allow for arbitrary computations to be run on the GPU.



[fig24] General GPU pipeline and parallel processing

Our earlier iterations built with compute shader yielded significant performance improvement. By scripting every instance of the object generations this iteration achieved smoothly rendering 90,000 particles at 182.6 frames per second.

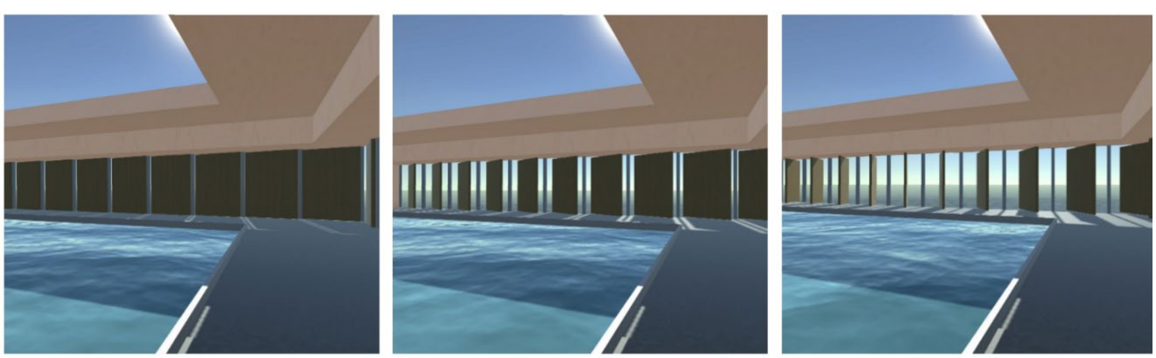


[fig25] Early prototype showing procedurally generated array using

2). VFX (Visual Effects Graph

Although compute shader can help to drastically improve the environment performance, it is very difficult to code low-level language such as GLSL (compute shader code) that directly interacts with the GPU. More challengingly, due to the lack of documentations and foreign language syntax. It was difficult for the team to progress beyond the earlier, primitive iterations. The team then discovered Unity's relatively new VFX system.

The Visual Effect Graph lets the designers create visual effects using node-based visual logic. The designer can use it for functions ranging from simple effects or very complex simulations. Unity stores Visual Effect Graphs in Visual Effect Assets that one can use on the referenced Visual Effect Component. On a lower level, the VFX system is built upon the compute shader architecture which would still allow similar performance.



Low Relaxation | Medium Relaxation | High Relaxation

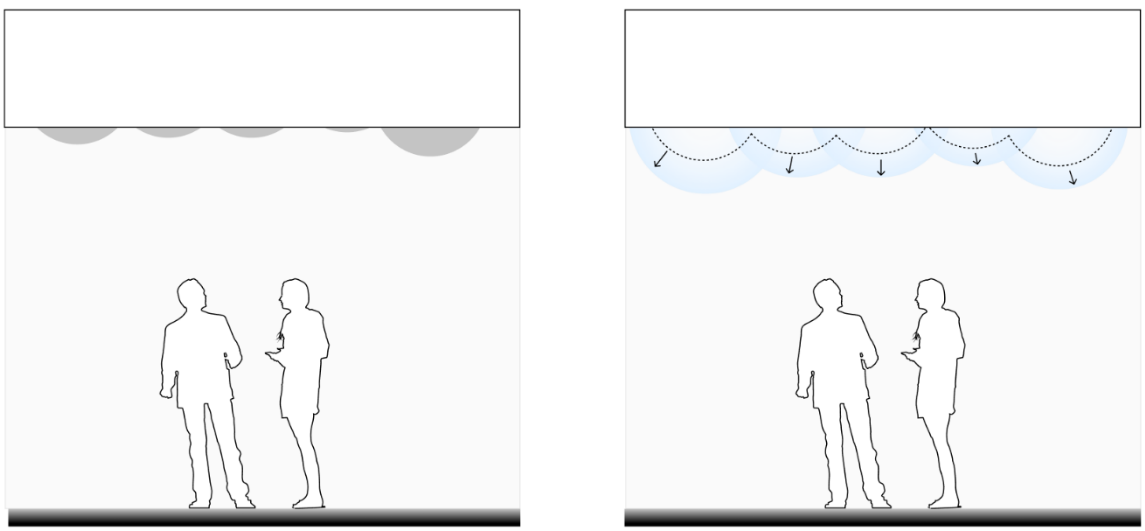
As one can see in the above figure, the environment prototyped with node based VFX graph can afford much more visually elaborate environment with procedurally generated interactive elements.

[fig26] Environment prototype made with Node-based interface VFX design

3. 4 Design patterns through VFX

After gaining proficiency in VFX graph and integrating the assets into ongoing prototype and multi-user real time views, Virtual spatial transformations that were achievable by VFX graph were prototyped to stimulate sensory responses. The following effects were created:

Bubbling Surface

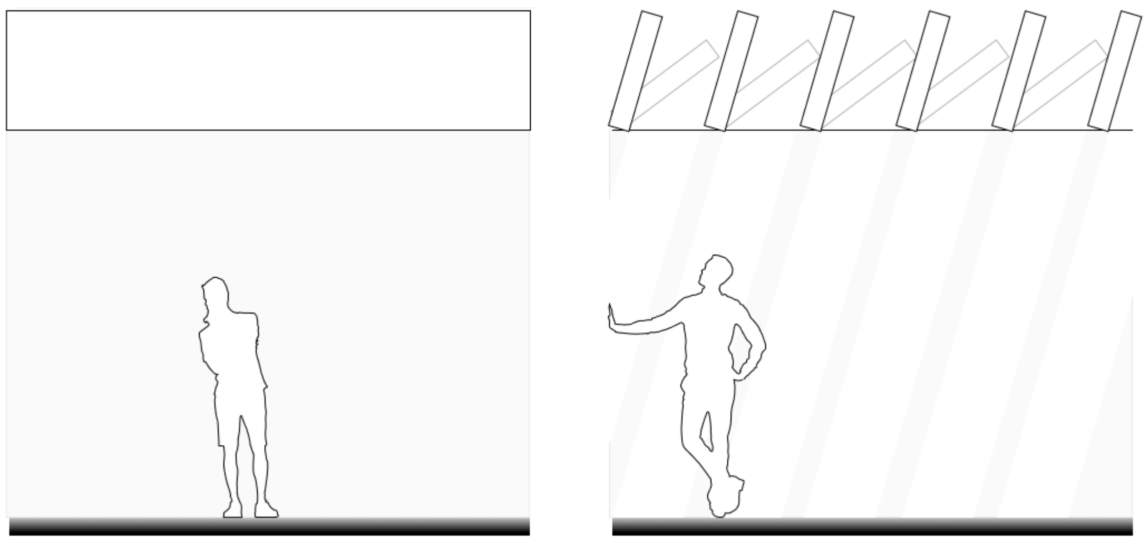


Previous studies [5,6] have shown that people prefer objects with curved contours over objects with sharp contours. In addition, Leder et al. Investigated the interplay between visual features and general valence as positive or negative. After replicating curvature preferences for neutral objects, Leder et. examined if emotional valence-through response

[fig27] Virtual environment that becomes visually curved when smile is detected

prioritization-modulates the preference for curved objects. Leder found that people indeed preferred the curved versions of objects to the sharp versions of the same objects, but only if the objects were neutral or positive in emotional valence. These research findings motivated this interactive design in the hope that by introducing objects with smoother surface curvature, positive sensory responses can be stimulated.

Opening Ceiling

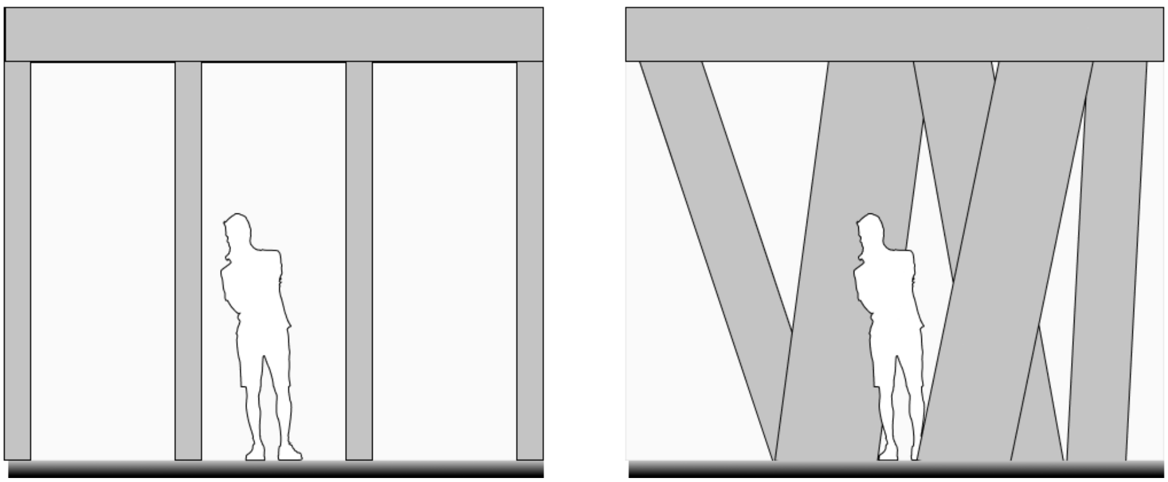


Visibility and lighting intensity has been associated with an interior space's perceived spaciousness. Ozdemir [7], in her 2010 study, has examined window views' effect on the perception of spaciousness, brightness, and, ultimately, room satisfaction in a campus building. Eighteen identically sized offices in the three-story Department of Landscape Architecture at Ankara University were chosen for this case study. Within a case study research design, the openness and naturalness characteristics of the window views were assessed by expert reviewers as well as room occupants. Eighteen single-room occupants were interviewed to assess their perceptions of spaciousness, room brightness, and satisfaction with rooms and window views. As predicted, the rooms on the upper floor were perceived larger due to

[fig28] Virtual environment that becomes visually transparent and bright if user relaxation level is increased

expanded open window views, and lower floor rooms were perceived as darker. This interaction was designed to mimic the effect of opening the window (or ceiling) and induce the feeling of relaxation and calmness.

Shifting Columns

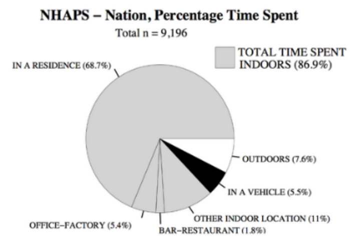


In addition to functioning as a load-bearing structural element, columns are also a spatial organization tool that regulates human movement and influences human visual perceptions.[9]. In an environment that is supported by columns situated in regular patterns, the dwellers can easily navigate the space. In contrast, the same space with irregularly oriented columns with enlarged dimensions can appear confusing and spatially tightening. Under such environments, the space can be hard to navigate due to the lack of distinguishable landmarks and narrow spaces, and at the same time can potentially amplify a sense of urgency, loss, and anxiety.

[fig29] Virtual environment that becomes spatially disorganized and tight if the user stress is elevated

4.Pilot Case-Studies

The physical environment can greatly impact people's behavior, as it can provide opportunities for certain activities or allow access to the broader social, political, and cultural worlds. Modern North American, on average, spends 91% of their waking hours indoors. Our daily interactions are "afforded" [Gibson, 1979] by the spaces we dwell, and our feelings are influenced by various aspects of the room as well. By understanding how different environments affect people's behavior, researchers can develop more effective interventions to improve desirable behavior. These interventions can include things like providing more sidewalks to encourage physical activity or informing people about how their environment affects their behavior.



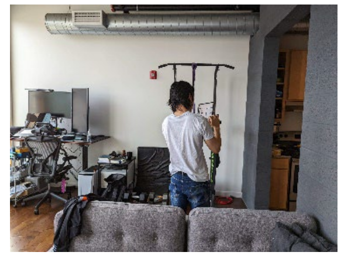
[fig] Pie chart from the NHAPS study showing that Americans spend 86.9% of time indoors, plus another 5.5% inside a vehicle.

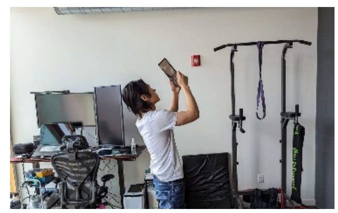
Two design probes were prototyped to inspire participants to respond to interactive elements and hopefully elicit insights. While a design probe has been deployed to prototype smaller-scale objects to relate to specific themes pertaining to certain themes [7,8], the author believes that a design probe can also be deployed to study simulated spaces that are augmented with interactive elements. The spaces will be designed referencing physical environments that are familiar to both author and anticipated participants. For this project, two virtual spaces were created to use as design probes: a studio apartment in Ithaca and the dome space located within the Milstein Hall at Cornell University. By implementing interactive features onto existing spaces, the author hopes to better understand the spatial and sensory effects of the interactive elements.

4. 1 Building a digital-twin virtual space

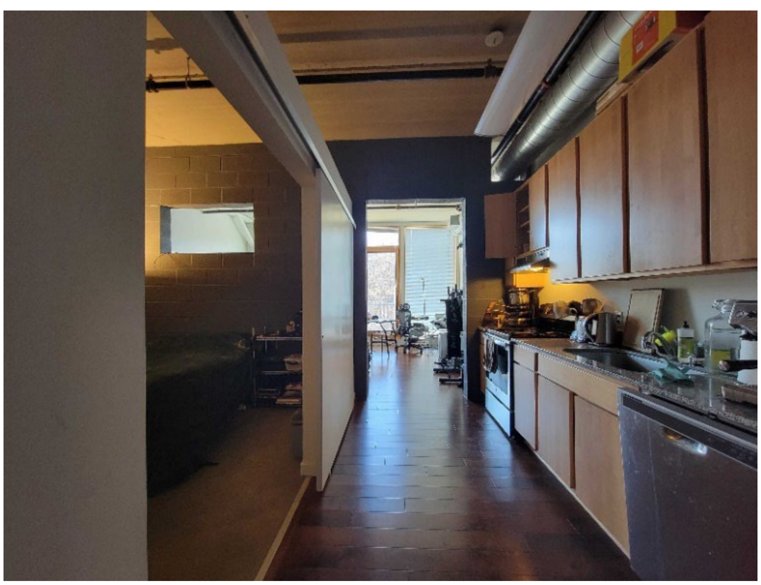
The first goal of creating a digital-twin virtual space is that the local users can navigate the environment without accidentally colliding with the physical boundary. This requires the virtual space and furniture to be modeled precisely as their physical dimension and location in real life.

In order to achieve this, both AR measuring apps and laser measuring tools were used to model the physical apartment space. AR tools were used to identify surfaces and general configurations of the floor plan, ceiling, window boundaries, and the laser tool was used to provide precision measurements for mode refinement. While this process is highly time-consuming, the result was that after calibration, the user could navigate the virtual space just as if they were in the physical reality without the risk of physical collisions. The ability to navigate freely in a virtual space is highly important as it lowers the chance for immersion disruptions.

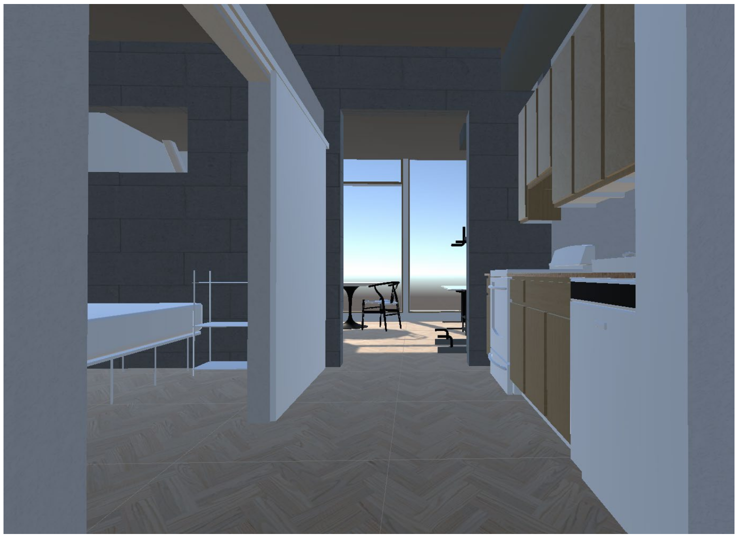




[fig30] Creating digital twin space using IOS AR scanning tool

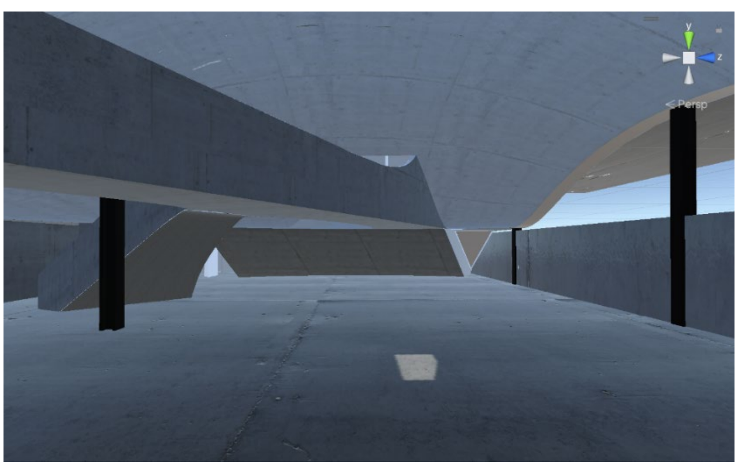


[fig31] Apartment Interior photograph



[fig32] Interior View of the Virtual apartment

[fig33] Interior View of the physical Milstein Hall dome space



[fig34] Interior View of the Virtual Milstein Hall dome space

4. 2 Within-subjects case studies: Domestic and Public Space

This project aims to understand whether interactive architectural environments [Appendix F] can afford expressions of human cognitive states such as stress, relaxation, focus, and engagement through modulating spatial defining characteristics. The author wishes to speculatively explore the future in which people can use BCI and VR to enable new types of human-to-human and human-to-space immersive applications.

4.2.1 Participants

For this study, I sought to recruit participants who had experience with VR technology and were comfortable when situated in an immersive environment. Due to time limitations, I was unable to recruit participants through IRB approved SONA (Communication/Information Science Research Participation System), but I did formulate a list of criteria for qualifying participants who potentially represent future user groups:

1). 18+ of age with normal visions
2). Able to converse in English as the participants will be required to provide qualitative feedbacks
3). Experience with VR devices, familiarity with navigating in virtual environments
4). Not prone to motion sickness
5). Not actively taking mood-altering or anti-depressant dugs

One consideration that was not listed as a part of the participant requirements was a background in architectural, interior, or graphics backgrounds. While participants of design backgrounds can identify sensory responses and provide detailed descriptions of wen hat spatial aspects triggered such responses, I believe that participants from the non-design background can provide equally insightful feedback.

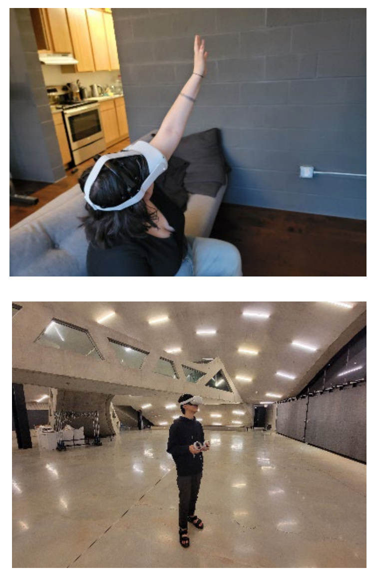
I recruited student participants through snowball sampling, and while the time for the pilot study was limited, 4 in total signed up for the experiment, and 1 participant was not able to attend the session. In total, 3 participants successfully completed 60-90 minutes long study each. 2 of the participants are from the B. Arch program, and one is from M.S Biology with no design background.

4.2.2 Method

1). Before the experiment, the participant was asked to familiarize themselves with the physical space since the virtual environment was built to replicate the physical dimension of the real-world space. Then the participants answered pre-experiment survey questions [Appendix A] to indicate their state of cognitive performance at the moment of the experiment.

2). The participant was instructed that they were about to enter a virtual "augmented space" in which the architectural characteristics are influenced by one of their passive mental state (Interest, Engagement, Focus, Relaxation, Stress, and Excitement), the data association would be kept secret at first and will be revealed approximately 5 minutes into the experiment.

3). As the participant entered the space, they were given 2 minutes to familiarize with the virtual environment and reorient themselves. After confirming that the space is functional, the interviewer and the participant will be engaged in a natural conversation. The first part of the chat session was strictly 5 minutes, and the interviewer asked questions regarding the participants' first impression of the space and monitored the EEG data. After revealing the specific cognitive state data associated with spatial transformations (relaxation for the apartment scene and stress for the dome



[fig34]Experiment Documentation

Upper: participant 1 interacting with apartment virtual scene

Lower: participant 2 observing virtual changes in scene) [], the interviewer will continue the conversation while exploring topics that might induce various responses (stress, relaxation, etc.)

4). After the virtual interactions, the participant was asked to reflect on their perceptions of the spatial changes, the sensory responses induced by the perceived transformation, and their thoughts on adapting behavior to the application of BCI-enabled technologies. The interview is semi-structured with a list of questions prepared [Appendix A] to elicit the most important aspects of the inquiry, while the rest of the conversations happened organically by voluntary elaborations or follow-up questions eliciting further insights.

5). Audio conversations from the experiment were recorded by OBS Studio and partially transcribed. I employed thematic analysis methods [Braun, 2006] to analyze the interview audio recordings and the resulting major themes will be described below.

4.3 Thematic Findings

4.3.1 Spatial feedback increased the users' self-awareness and self-interventions

All three participants indicated that the environment increased their level of self-awareness to various degree. P1 suggested that *"even when she did not know which cognitive state was associated with the perceived transformation in the apartment scene, she actively tried to monitor her internal state of being by introspection."* After revealing the cognitive data and spatial association, P1 actively engaged in a short improvised deep-breath exercise in an attempt to change the spatial quality of the environment with effective performance.

Similarly, P2 and P3 became more actively introspecting and intervened by engaging in similar mindfulness practices such as deep-breath exercises while remaining silent. I want to note that terms such as “meditation,” “mindfulness,” and “mental health” were not mentioned throughout the entire process by the interviewer. Without elicitation, all participants proposed potential applications related to mental wellbeing.

When asked whether if the perceived spatial changes induce any associated sensory stimulations, P2 suggested that *“while the implemented changes are rudimentary in geometric design, the pulsing animation and other aspects such as orientation complexity, visibility strongly amplified the perceived cognitive state.”*

Interestingly, during the Dome scene, P2 was asked to gauge his stress level on a scale from 0-100, to which he answered “*70 ish*”, and at the time, the data visualizer displayed 75 as his stress level at the moment. This question was also repeated for P3 for confirmation however P3 was not able to provide a valid evaluation and rejected to answer the question. *(“I just don’t know how to compare that I just know that I am kind of stressed.” P3)*

After the interview, P3 made a very insightful observation that *“she noticed that apartment bubbling ceiling is more effective because the change is situated on the ceiling and will always have enough distance between herself. In contrast, the columns in the dome scene can come too close and be stress-inducing.”* Similar comments were also made by P2, who tried to dodge and *“squeeze through”* the gap space between the columns.

4.3.2 Preference for transparency is different between apartment and dome scene

On the topic of acceptance of this application of BCI technology, participants expressed mixed emotions. One participant said that they would *“very much prefer this kind of environment in a single-user setting for meditation and* *casual mental breaks."* However at the same time they appear to be very reluctant when asked whether if they like to use this kind of environment in a semi-public, multi-user context. P1 suggested that "she would be ok if the multi-user application is implemented in the apartment scene." P3 suggested similar sentiment that *"if she is in her own virtural-twin apartment modeled after her actual home she would actually enable this kind of interaction most of the time."* When followed upon this particular comment P3 said *"first of all it is very cool and she really likes the bubbly ceiling. Second of all she is very aware of the importance of mental health but her work, lifestyle does not actively encourage introspective, alone-time."*

P2, on the other hand, suggested having a *"slider to modulate a percentage-based multiplier of the effect so that he can actively change the intensity of his input."* He commented that maybe at home with his virtually present friend he can dial up the gauge to allow higher level of expressions.

4.3.3 Interactive affordance of the neural-reactive spaces

Very surprisingly, P1 used the interactive environment to probe and compare her personal stress point among a selection of conversation topics. P1 reported that "she actively took the lead of the conversation with the interviewer at one point and started to talk about topics such as post-graduation plans, final deadlines, personal health issues, and job hunting."

By comparing the spatial reactions, she arrived at the belief that the post-graduation plan drastically increased her level of perceived stress even though she "does not feel any physiological sensations when thinking about any of those particular subjects." While there is no conclusive evidence that her stress level spike can be directly attributed to her concern for post-graduation plans, this is genuinely an interesting human-space interaction behavior that may inform future design considerations.

P2, on the other hand, did not take comparative actions like P1 but instead suggested practical application scenarios such as "*remote mental health therapy as the therapist can more easily gain insights regarding the patients' internal states."* P2 commented that "*while he does not know how to implement this feature in a multi-user, virtual public space but certainly can add one channel of communication for users who are challenged to express to the fullest ability.*"

P3 maintains that she would use this at home as an augmented, virtual version of her home space.

4.3.4 User preference for positive over negative expressions

All 3 participants indicated that while in a single-user context, they are relatively comfortable with the expression of "negative data such as stress," They all believe that in a public, multi-user context, they would either "disable the negative data link or look for an alternative design language that communicates such data." P3 says she believes "normally people would find it rude or confrontational that one clearly expresses their negative sentiment even if the frustration is wholly justified by context. There are always alternative strategies when one is in an unsatisfactory social situation" P2 also expressed a similar belief that "because of his Asian culture, it is almost a social taboo to be angry or negative in public. Being negative in front of others can be contagious and can be perceived as selfish. Usually, he just withdraws and disengages from the interaction and does not respond until circumstances have improved."

P1 has a mixed perspective regarding this particular theme and said that "while she believes that if the interaction is with people who she is close with, she would like to be honest and express sentiments such as stress, anger, and frustration to address an issue; However, she does not think that the interactive spatial environment with its current design is the best way just at the moment."

P1 further elaborates her perspective by narrating a fictional situation in which if “she is mad about something during a conversation with her friend but fails to address the underlying issue clearly/timely, the environment will express negative sentiment; however, without confirmation from P1, such expression can be misinterpreted as passive-aggression towards her friend.”

5 Conclusion

This thesis was initially inspired by a speculative imagination that intelligent, interactive living environments in the future can fulfill our essential daily functions and our desire for meaningful, immersive interactions with our space, our friends, and ourselves. As the push for remote communication and immersive collaboration further deepens, we can easily imagine a future in which we live in our physical realities and simultaneously have access to novel interactions only afforded by a virtual world.

This project presents an early prototype with novel inputs and an alternative relationship between the user and the immersive environment. Although there are no conclusive findings due to limitations such as time restraints, technical challenges, and unfamiliar design/collaboration frameworks, challenges encountered during this thesis project are constructive, meaningful long-term learning objectives for future iterations.

Within a limited time frame under very volatile circumstances (COVID, etc.), this project managed to bring introductory insights regarding the deployment of BCI technology in an immersive, interactive environment. I have also prototyped a lightweight, robust communication server capable of adapting to future iterations of BCI-VR prototypes.

Overall, this project resulted in meaningful personal learning and produced subjects worthy of future inquiries. Future work should develop more robust user experience experiments and develop potential guidelines for BCI-VR environmental design. Further learning about HCI principles and developing quantitative and qualitative research skills will help me investigate this topic further, and I look forward to the next chapter of my journey.

Appendix A – Pre-Experiment Survey

Pre-experiment survey

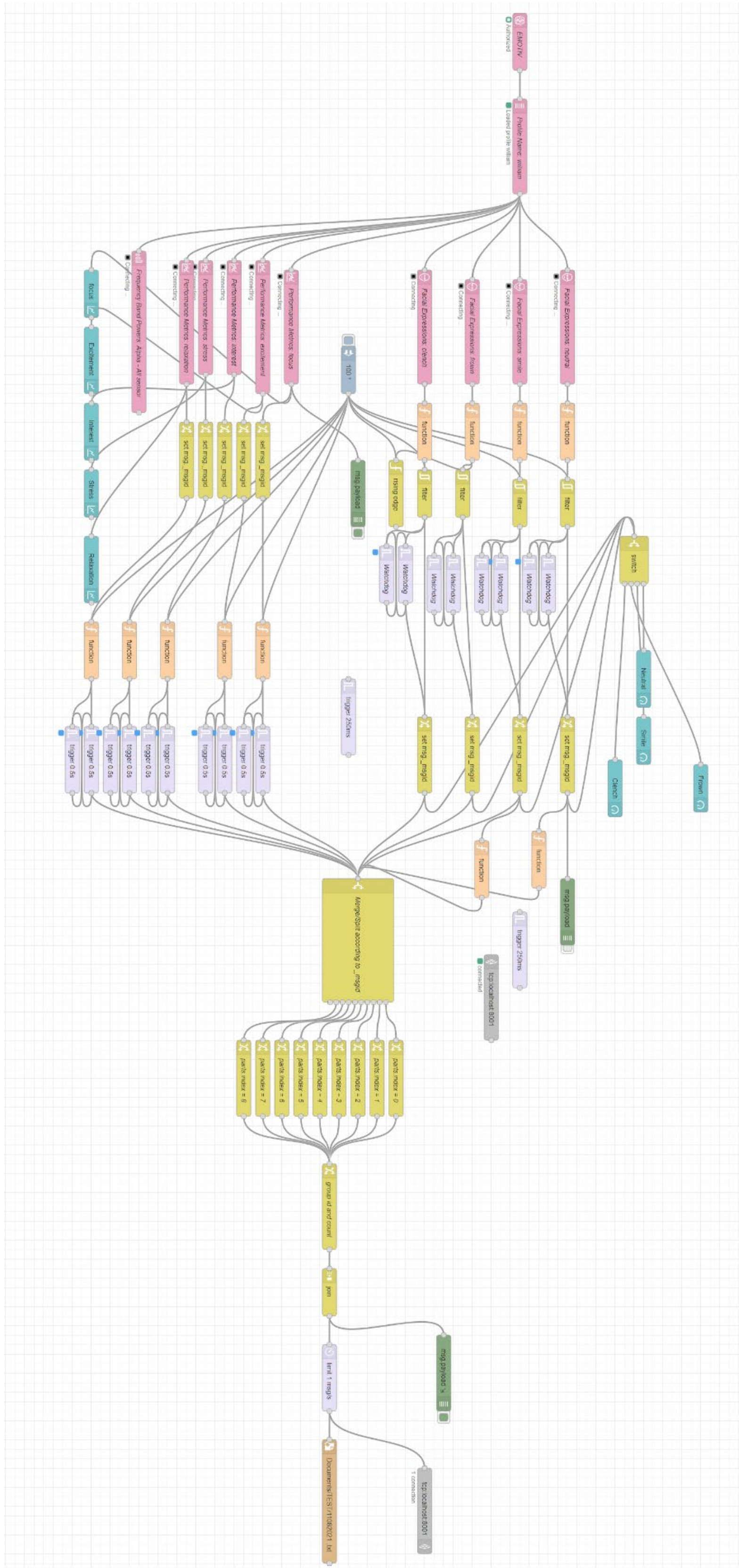
1. What is your gender?
2. What is your age?
3. What is the major you study?
4. How are you feeling today on a scale from 0 to 10 please rate your tiredness?
5. How many hours you slept last night?
6. Do you actively engage in mindfulness practices?
7. This is an optional question, are you taking any mood-altering medications?
8. Are you familiar with the space that we are in right now?
9. Have you interacted with VR before?
10. Do you own any personal VR devices?
11. Have you ever experienced VR-related motion sickness?
12. Have you interacted with BCI technology before?
13. Do you grant me permission to take photographs and record audio for documentations?

Appendix B – Post-Experiment Interview

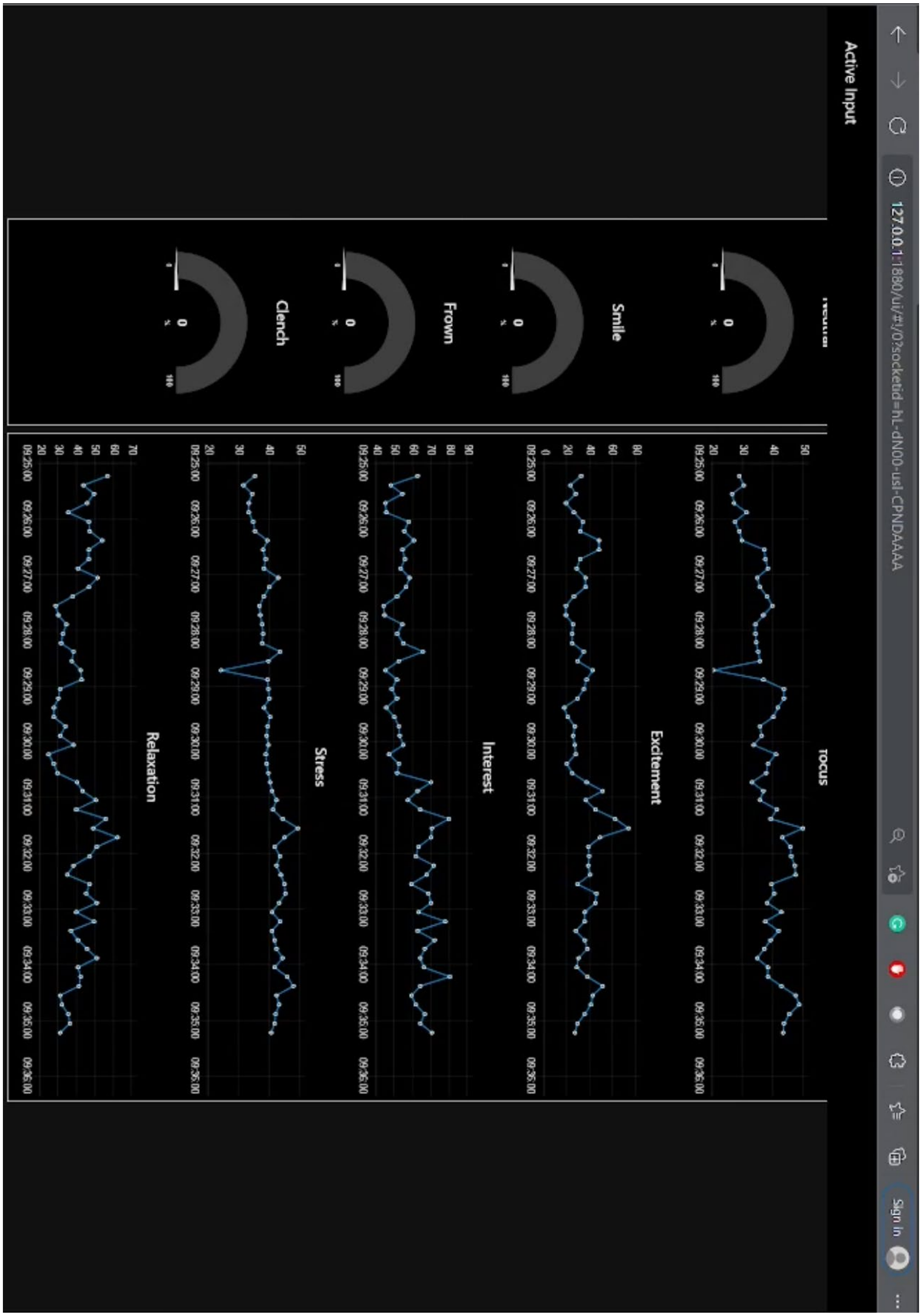
Interview Questions:

1. What do you feel about the virtual environment?
2. Did the virtual environment accurately represent the referenced physical space?
3. Did you feel physically restricted while situated in the VR environment?
4. Were you mostly relaxed throughout our conversations?
5. During our interactions can you recall if there was an instance that you felt stress? Could you recall the specifics?
6. Could you identify specific instances when you think I am stressed (or less relaxed)?
7. Were your interpretations driven by our conversations or did you understood the mood by observing the environment?
8. How did seeing the environment transformation trigger by my cognitive state influence your responses?
9. If so, please highlight specific instances during the interactions.
10. Do you think these instances benefitted/hindered the overall interactions?
11. Your ease of understanding the cognitive level?
12. Were the spatial interactions intuitive to understand?
13. How do you think of the designed interactions and did the changes have other unexpected effects?
14. Did the spatial interactions caused you any discomfort throughout the interactions.

Appendix C – Node-red Setup



Appendix D – Visualization System



Appendix E – Survey Summaries

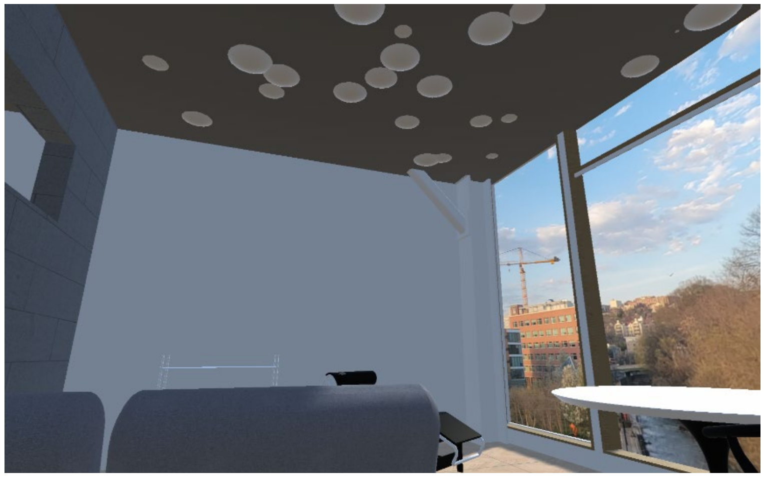
Participant 1 [F]		
1	Female	Notes: The interview was conducted on 04/16/2022 Saturday during 6:00 pm-7:15pm. Participant is familiar with both scenes in VR.
2	22	
3	Architecture senior	
4	3, feeling rested and does not feel tired	
5	7 hours with good sleep quality	
6	No	
7	No	
8	Yes	
9	Yes, it was for another student's VR project	
10	No	
11	No	
12	No	
13	Yes	

Participant 2 [M]		
1	Male	Notes: The interview was conducted on 04/17/2022 Saturday during 5:00 pm-6:30 pm. Participant is familiar with both scenes in VR. Participant noted that
2	21	
3	Architecture 4th year	
4	2, feeling rested "ready to work through the night"	
5	8 hours with good sleep quality	
6	No	

7	No	even though he has had experience with BCI device in the past he has not had the experience with commercial-grade EEG headset.
8	Yes	
9	Yes	
10	No	
11	Yes, but that was a very long time ago	
12	Yes, as a BCI experiment participant	
13	Yes	

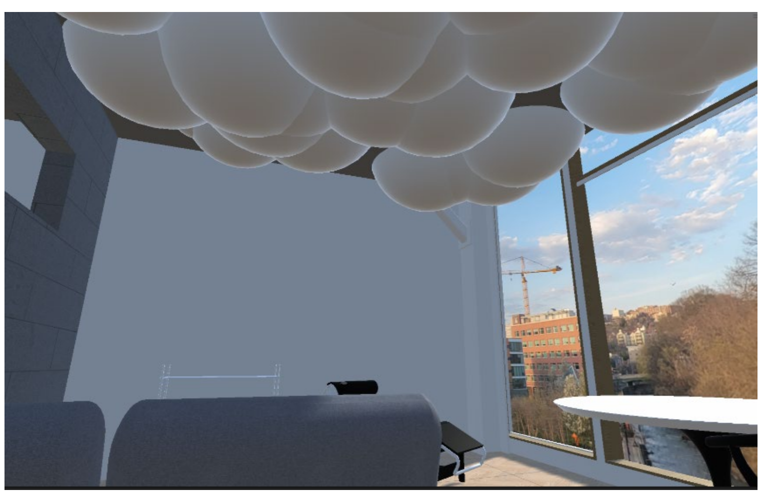
Participant 3 [F]		
1	Female	Notes: The interview was conducted on 04/25/2022 Saturday during 7:30 pm-8:40 pm. Participant is familiar with the second VR scene (Milstein Dome).
2	23	
3	Biology Graduate Student	
4	3, rested and refreshes	
5	10 hours	
6	No	
7	No	
8	Yes (Milstein Dome)	
9	Yes	
10	Yes, Quest 2 and game weekly	
11	Yes, from joystick locomotion	
12	No	
13	Yes	

Appendix F – Cognitive State Driven Transformations



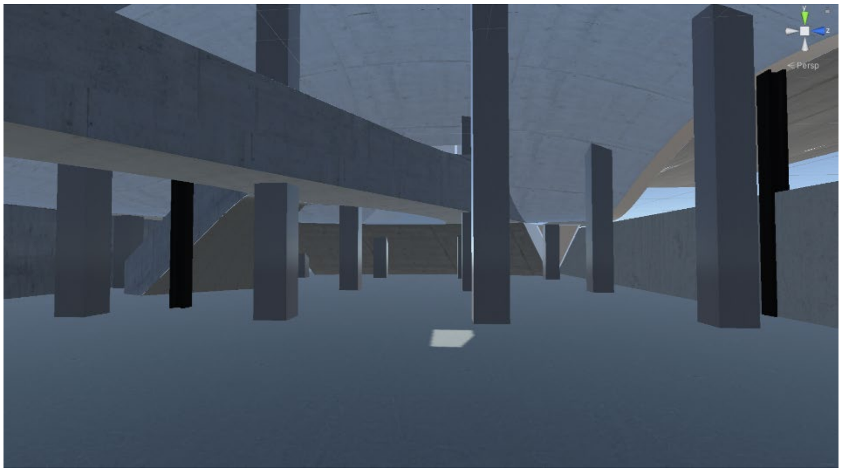
a). Apartment scene with low relaxation value

b). Apartment scene with medium relaxation value

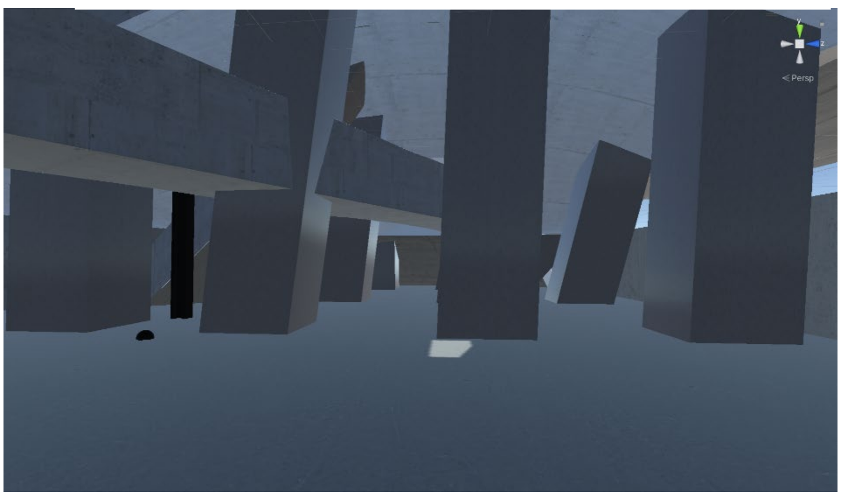


c). Apartment scene with high relaxation value

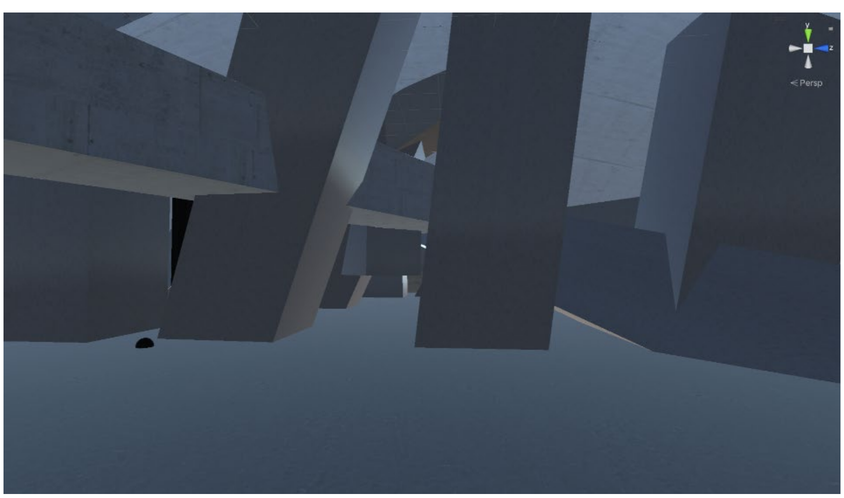
Appendix F – Cognitive State Driven Transformations



d). Dome scene with low relaxation value



e). Dome scene with low relaxation value



f). Dome scene with high relaxation value

Bibliography

1. Bar, M., & Neta, M. (2006). Humans prefer curved visual objects. *Psychological science*, *17*(8), 645–648. https://doi.org/10.1111/j.1467-9280.2006.01759.x
2. Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. Qualitative research in psychology, 3(2), 77-101.
3. Clark, A., & Chalmers, D. (1998). The extended mind. analysis, 58(1), 7-19.
4. Ching, F. D. (2014). Architecture: Form, space, and order. John Wiley & Sons.
5. Corradi, G., Belman, M., Currò, T., Chuquichambi, E. G., Rey, C., & Nadal, M. (2019). Aesthetic sensitivity to curvature in real objects and abstract designs. *Acta psychologica*, *197*, 124–130. https://doi.org/10.1016/j.actpsy.2019.05.012
6. Gaver, W. W., Boucher, A., Pennington, S., & Walker, B. (2004). Cultural probes and the value of uncertainty. interactions, 11(5), 53-56.
7. Gibson, J. J. (1977). The theory of affordances. Hilldale, USA, 1(2), 67-82.
8. Inside reality labs research: Meet the team that's working to bring touch to the Digital World. Tech at Meta. (2022, March 22). Retrieved April 23, 2022, from https://tech.fb.com/ar-vr/2021/11/inside-reality-labs-meet-the-team-thats-bringing-touch-to-the-digital-world/
9. Kim, S., Park, H., & Choo, S. (2021). Effects of Changes to Architectural Elements on Human Relaxation-Arousal Responses: Based on VR and EEG. International Journal of Environmental Research and Public Health, 18(8), 4305. https://doi.org/10.3390/ijerph18084305
10. KLEPEIS, N., NELSON, W., OTT, W. et al. The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. J Expo Sci Environ Epidemiol 11, 231–252 (2001). https://doi.org/10.1038/sj.jea.7500165
11. Leder, H., Tinio, P. P., & Bar, M. (2011). Emotional valence modulates the preference for curved objects. *Perception*, *40*(6), 649–655. https://doi.org/10.1068/p6845
12. Neo, J. R. J., Won, A. S., & Shepley, M. M. (2021). Designing immersive virtual environments for human behavior research. Frontiers in Virtual Reality, 2, 603750.
13. Ozdemir, A. (2010). The effect of window views openness and naturalness on the perception of rooms spaciousness and brightness: A visual preference study. Scientific Research and Essays, 5(16), 2275-2287.
14. Škola, F., & Liarokapis, F. (2018). Embodied VR environment facilitates motor imagery brain–computer interface training. Computers & Graphics, 75, 59–71. https://doi.org/10.1016/j.cag.2018.05.024

15. Vourvopoulos, A., Bermudez i Badia, S., & Liarokapis, F. (2016). EEG correlates of video game experience and user profile in motor-imagery-based brain–computer interaction. *The Visual Computer*, *33*(4), 533–546. https://doi.org/10.1007/s00371-016-1304-2
16. Williams, N. S., McArthur, G. M., & Badcock, N. A. (2020). 10 years of EPOC: A scoping review of Emotiv's portable EEG device. https://doi.org/10.1101/2020.07.14.202085
17. Wallace, J., McCarthy, J., Wright, P. C., & Olivier, P. (2013, April). Making design probes work. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (pp. 3441-3450).