MINDFUL MANIFESTATION:

from EEG to Virtual Reality

by

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A 120-point thesis submitted to the Victoria University of
Wellington in partial fulfilment of the requirements for the
degree of Master of Architecture (Professional)

Victoria University of Wellington
School of Architecture

2019

Acknowledgements

For the completion of this Thesis:

- I would like to first and foremost thank my two wonderful supervisors, Tane Moleta and Marc Aurel Schnabel for the wonderful sessions, support, time & advice they had given me in the completion of this thesis.
- Following that, are the Virtual Augmented Studio Environment (V.A.S.E.) team, Cyrus Qureshi, Jessie Rogers & Brandon Wang for their advice and support.
- I would also further like to thank the experts who had helped me with the technical aspects of theoretical and implementations of EEG expertise and Neural Networks: Dr. Ibrahim Rahman, Dr. Simon McCallum, Dr. Yi Mei, Dr. Matt Crawford, Associate Professor Gina Grimshaw, Ph.D Candidate Konstantina Vasileva at Victoria University of Wellington from the department of Engineering and Computer Science (ECS). Appreciation for visiting Associate Professor Matias del Campo for the brief discussion surrounding artificial neural networks and detection library.
- I would like to thank William Judd, our esteemed V.A.S.E. research assistant with establishing networking connections between design softwares, and Byron Mallett, for the attempt in aid with establishing EEG data through Unity.
- Furthermore, I would like to thank my father, Hai Nguyen for his continual support throughout my life, least not mentioning the time, discussions and sponsorship in the completion of this thesis.
- To my cousin Phuong Anh Do, to whom had helped me through very dire times. To all my family members, who had been there for support.
- I am grateful to the remaining support from my friends with their assistance for the completion of this thesis; I shall always cherish this in my heart.
- Lastly, it would seem fitting to thank humanity for the coalescence of knowledge to which this research has based itself up on.

Abstract

Throughout millennia, the human mind has been attributed to the advancements of human society today. Architecture, likewise, a result of human wit and intelligence. This research takes a particular interest in the architecture that is, pre-conceived before its existence. From the inception of this research, it began with a particular interest in this design process, or creative. The objective, to develop a means for people to design using their mental imagination. The objective, while novel and realistic, demonstrate itself to be highly challenging in its enormous complexity. The investigation focuses now settles towards the development of an “integrated foundational” brain-computer interface (BCI) to design architecture through meaningful and intentional design interactions through human brain activities in real-time inside an immersive virtual environment.

The research methodology deploys the conglomeration of the following of hardware:

- 14-Channel EPOC+ electroencephalograph (EEG) headset (a brain electrical activity detector)
- High-end computer with VR capable graphics card
- HTC Vive Virtual Reality (VR) Headset

In terms of software, CortexUI, a cloud-based platform to stream live EEG data, Grasshopper (GH), a commonly used architectural visual scripting plugin software, followed by Unity, a commonly used tool to develop interactive VR/3D environment. The user shall be wearing both EEG and the HMD to interactive with the presented material.

The EEG is used to detect brain activities through its electrodes measuring variation in of electrical potential caused by passing signals sent within the brain's neurons. These raw data are transferred into Grasshopper in numerical forms, where these data are inputs to manipulate a series of pre-defined forms and interactions in Grasshopper, a plugin in Rhino software. The translation process involved data manipulation for desired design interaction, which altered the abstracted formal qualities of locations, scales, rotations, geometries and colours, with a minor implementation of certain artificial neural networks (ANN) within a design environment context. Virtual Reality consequently performs as a visualisation tool and immersing the user within that design interaction as well as become a design feedback tool. The user is stimulated to generate various design variations and able to capture that result in Rhino through baking the design in Grasshopper. The exported geometries act as an abstracted visualisation of the BCI system's user's mental state at that point in time.

The research outcome exceeded the aims & objectives from its "foundational" status in its ability to harbour multiple design interactive scenarios. However, there are considerable technical limitations and room for future research within this experiment, all of which shall be mentioned within the discussion section of this inquiry. A technical understanding and overall framework have been developed as a result of this study, tending towards creating a BCI-VR system to design architecture directly from the human imagination from the mind's eye.

HINDFUL MANIFESTATION

vertical
translation

enlarging

Keywords:

1. electroencephalography (EEG)
2. artificial neural networks (ANN)
3. virtual reality (VR)
4. brain-computer interface (BCI)
5. parametric design

**“I think
therefore it is”**

**(architecture into
being and becoming
through thought)**

Figure 1 (Author's Own): Summarised
Thesis Concept Design Poster

Designing architectural forms using electroencephalography (EEG), a brain activity detector inside a Virtual Reality Environment. The system created utilise three different design interactions, vertical translations, enlarging & self-organising map to generate a combined result.

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Other Publications

A part of this thesis has been accepted, published and presented at the INTELLIGENT & INFORMED, 24th International Conference of Computer Aided Design Research in Asia (CAADRIA) in 2019.

For reference, please follow:

- **Nguyen, D., Moleta, T. J., & Schnabel, M. A. (2019). Mindful Manifestation—A method for designing architectural forms using brain activities.** In M. H. Haeusler, M. A. Schnabel, & T. Fukuda (Eds.), Proceedings of the 24th CAADRIA Conference (Vol. 1, pp. 485–494). Retrieved from http://papers.cumincad.org/cgi-bin/works/paper/caadria2019_142

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“je pense, donc je suis”

“I think, therefore I am”

— René Descartes
1596-1650

extract from:
“Discourse on the Method”
1637

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— 0/0 : Introduction —

This section introduces the research area and topic, as much as discusses the initial ideas and inspirations that had informed the research. The discussed literatures within this section are brief and forms a background to the overall research paper, setting the context for greater discussion in further sections.

- 0/0/1: Research Motivation: Creativity
- 0/0/2: Research Background: Architecture & Neuroscience
- 0/0/3: Research Topic & Agenda: Designing Architecture through the Mental Imagination directly

0/0/1 : Research Motivation: Creativity

Creativity is but an intriguing yet elusive ability of the human mind. Its popularity in recent decades, from the researcher's observational point of view, belies within the critical reflection of its lack in the educational system (TED, 2007) - increase interest of 'intellectual geniuses' in presented popular media, for instance, the Big Bang Theory, The Accountant and The IT Crowd - and contemporary predicted sense in greater intellectual demands in the future workplace, a consequence brought on from increased automation. These events catalyse interests for this research project in gaining the insight to cultivate the human creative process. The research motivation establishes itself along the line of, providing the public with the gift of divine intellectual providence.

Contemporary pieces of evidence for its impact can be found within Temple Grandin's superb spatial visualisation skills. "When I [Temple Grandin] design livestock facilities, I can test run the equipment in my imagination, similar to a virtual reality computer program." (Grandin, 2009, p. 1437). Although such creative abilities are often found to be diverse through different kinds of literature (Singer, 2011; Robinson, 2011; Mahadevan, 2018). Creativity is not a matter of a singular categorisation by definition. Instead, the creative wonders from the exceptional individuals, such are, Albert Einstein, Isaac Newton, Marie Curie or Charles Darwin are all but different.

Perhaps, an interest in research and developments through a range of bodies

of research would transform what we regard as "genius" in our current context into a commonplace matter.

0/0/2: Research Background: Architecture & Neuroscience

From the initial interest into "creativity", the research has found itself situated within the field of Architecture and Neuroscience. Mallgrave's *The Architect's Brain* (2009), is reported to be the first text in drawing the bridge between these two disciplines, even though, Mallgrave in his book claimed

Richard Neutra as the first Neuroarchitect.

Consequent literature, drawing from the two fields can later be found within Architecture and Neuroscience (Pallasmaa et al., 2013), *Mind in Architecture* (Robinson & Pallasmaa, 2013), and *Neuroarchitecture* (Metzger, 2018). The consensus between these texts often discusses the interest between built forms and their impact on the human psyche through qualitative reflections in their

arguments rather than objective studied research. Certain terminologies come to mind when in the discussion of this research topic, e.g. Neuroarchitecture, Neuromorphic architecture or Neurodesign. However, the semantics which these terms refer to are vastly different across the literature. Through these ambiguities, perhaps, the outcome of this study would infuse definitions to these lexicons themselves.

0/0/3 : Research Topic & Agenda: Designing

Architecture with the Mental Imagination

"Reality is a
product of the
most august
imagination,"
(Pallasmaa, 2013,
p.19)

Figure 2 (Author's Own): Visualisation of Research Topic: Creating a tool for design architecture through the Mental Imagery

Through the myriads of the aforementioned body of research to which sets the general direction, there are a variety of paths to continue developing. A potential direction of research, designing an environment to bear a direct symbiotic relationship within the mind, following on Clarke & Chalmers' Extended Mind Thesis (1997). Just as Borges' Tower of Babel (Dade-Robertson, 2011, p. 3), is a metaphor for the universe, so too, can an environment be a metaphor, or an abstraction, of the human mind. Whether intentionally accurate or inaccurate to the theory of the human mind. A more intriguing research direction, the

captivation of architecture from the imagination came to mind as more intriguing. With past technologies, the attempt to capture the imagination in its sincerity has been attempted. Such a methodology can be exemplified through the realisation of the imagination through drawing. Personal experience would illustrate difficulties of depicting a visual mental image that decays as one begins describing part of the idea in terms of points, lines, curves, surfaces and geometries, or as one might say imaginative drawing. Such temporal delays between how we think, result in, "mimesis phantastike" (Hansli, 2008, p.15)

as Plato would say - the deceptive depiction of the architecture of idea. The result quite often becomes an externalised imaginative process within real space - a combination of the mental imagination, and the composition of non-representational aspects taking over. What result are shadow projections within "Plato's Cave" (Gleiniger, 2008, p. 41) – the loss of the mental architecture as Form. In reflection to Emmon's criticism, of the "[...] idea (or the metaphysical precedes the work (or the physical) in a triumph of idea over matter" (Emmons, 2015, p.89). Triumphant over the aspect of the "the medium is the message" (McLuhan, 1964, p.1).

In its realisation, its achievement would introduce greater accessibility, creativity and productivity to the architectural discipline. The research interest takes place in the designing of architecture *through* the human experience, rather than designing architecture *for* the human experience. Such research interest invites further inquiry into related topics such as Gardner's spatial & visual intelligence (Barry, 1997) from the psychological field of studies, such as the evidence in mental

rotation, or spatial recall, seen within taxi drivers' abilities to accurately navigate through space from the midst of their Mental Imagery.

Visual inspirations for this research direction can be found in Nolan's iconic movie Inception (Nolan et al., 2010), yet, the research is not satisfied simply being inspired and create novel fantasies. The research heavily focuses its interest heavily on a pragmatic direction, another precedent, Reconstructing Visual Experiences from Brain Activity Evoked by Natural Movies (Nishimoto et al., 2011), where human's blood oxygen level-dependent (BOLD) is measured using an fMRI machine. These data are used to reconstruct what the person is viewing. Furthermore, to this, short preliminary design research, including the use of electroencephalography (EEG), a brain electrical activity detector to navigate within a virtual environment, had been conducted previously. The topic is further discussed within section 0/3/0 Methodology of this research thesis. Through this premise, the research believing its practical realisation is achievable.

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Figure 3 (Gallant, 2011): Movie reconstruction from human brain activity. Retrieved from <https://www.youtube.com/watch?v=nsjDnYxJ0bo>. Footage from "Reconstructing Visual Experiences from Brain Activity Evoked by Natural Movies" (Nishimoto et al., 2011)

aims

objection

ves

— 0/1 : Aims, Objectives & Scope —

The research agenda as mentioned in the introduction set the tone and direction to which the research has conducted its research. However, from the discussions with several experts related to the research field and initial literature reviews, for the scope of this research project, instead of establishing the means of producing architecture as seen from the mental imagination outright. The research aims for the design process to be executed in more minute steps. This research project's objective is to facilitate a foundational BCI as a basis in gaining an understanding towards designing architecture through one's Mental Imagery (Farah, 2000). This foundational BCI would be a premise for further developments, which would otherwise enrich the system on many of its facets, much shall be explored within the 0/4 Discussion section of this thesis. This chapter is divided as follows:

- 0/1/1 : Scope of Research
- 0/1/2 : Aims & Objectives
- 0/1/3 : Research Questions

0/1/1 : Scope of Research

Throughout the research procedure, the project commenced with the expressed interest of designing of architecture from the imagination. This expressed interest is met with repeated misfortune as the scope of research is insurmountable to what would be possible within the given research time frame. Multiple fields of study, to name a few, neuroscience, psychology, philosophy and computer science, multidisciplinary PhD researchers would need to be pertained to close numerous gaps posed within the research agenda.

To further elaborate, let one assumes Vyshedskiy's under-empirically-examined contemporary theory of imagination (2017, p. 2) to be accurate, proposing 'the imagination as a result of the combination of stored mental artefacts in one's memory initialised by the prefrontal cortex (PFC)'. It is inferred that the understanding of human memory is necessary for developing a tool to translate it, which would also infer the essential understanding of the human visual process. Phenomenologically speaking, the human sensorial system can be simplified to five different sensory inputs. Comprehension in such topics extends only so far as what is seen to the point of that visual information reaching the human visual cortex. Coupled in this topic, is also the complexity of human vision itself, 'human saliency' (Rahman, 2018) an attribute of vision for instance, is a topic fitting of its own in-depth investigation; while, multiple of these thorough investigations would be necessary for the research to proceed.

Furthermore, compiled on top of these factors would be the philosophical arguments between the existence of the imagination and the Mental Imagery (Farah, 2000) (the mind's eye), and whether these aspects relate, or — are in fact differential to one another. One of the consulted experts had only initialised the investigation into visual memory and how these

shifts. The consideration of external stimuli, emotions, cultural backgrounds and past experience are all influencing components.

All these factors imply these topics are still ongoing, and currently bear loose theoretical foundation to which the research agenda would establish up on. The investigator of these inquiries would need to selectively plough through vast quantities of literature from such foreign disciplines from scratch, to then derive an engineering a means of communication these disciplines to the disciplinary background they are under, to allow for a discussion between these experts and construct a BCI system.

As a consequence, the thesis sought to construct a build a minute construct, partially sealing the immense gap proposed from the research topic agenda instead. The question of finding the means of designing architecture shall arise within future research.

0/1/2 : Aims & Objectives

A more refined and sensible research aim is, therefore, formulated, based on the findings outlined in the previous section. Instead of realising a system replicating forms in its exactitudes as seen within the person's mental imagery, a proposal in creating an *integrated foundational BCI system* to design architecture using brain activities in real-time is put forth instead. An aspiration of the removal of motor functions from the design process entirely is also attached, as these endeavours are found within all existing design processes. The "*integrated*" aspects can be seen in the linkage of various researched software and hardware; "*foundational*" can be understood as the system reaching minimum operational status without further considerations of its durability or accessibility. Though, the experience should be smooth without any cause for latencies or delays in real-time. The considered software should include Grasshopper, and Unity, native to the architectural design discipline given the temporal constraints of the research. Hardware components would entail the use of electroencephalography (EEG), a brain electrical activity detector, as BCI input, and a Head-Mounted Display (HMD), to immerse the user inside a Virtual Reality (VR) environment. Figure 3 visually illustrates such a connected workflow.

Nested within the BCI is a series of pre-designed architectural forms. These contents shall provide the basis for design interaction, to which the user can alter these forms following attributes: geometries, colour, scale, orientation & position. The design process or the interaction should ideally be a result of '*meaningful*' brain activities, engaged with a degree of intentionality from the system's user. *Meaningful* implies that the brain activities possess a level of cultural relationship, rather than mere numerical data, with no attribution to the human condition.

As well as its research aims and objectives & directions for future research from the initial base system. The intention of this research is not the mastery of a specific area in knowledge, but the mastery of the currently proposed BCI system, in its context, and produced content. Much akin to the architectural design process, the architect possesses a general base-level knowledge over the design process, but rarely, specialisation over a specific area of expertise. To perform this research procedure, the literature in its consideration should be interdisciplinary, drawing from the field of neuroscience, psychology to computer science, understandably, the previous statement can be perceived as extremely broad. Therefore, the aim is not to accrue expertise in one field of study; rather, the mastery over the knowledge in making the system. The research shall be selective in the literature to which it considers within its study. The developed BCI system shall be contextualised to the referenced literature within the 0/3 : Literature Review section of this research.

In the end, the '*integrated foundational*' BCI system should be the groundwork for further development - ideally towards a BCI for architectural design. Speculative glimpses of such a system shall be deliberated upon through chapter 0/4 : Discussion. This shall be evident in the knowledge accumulated to produce and during the process of its construction. This research strongly believes that the future in the design through visualising with the Mental Imagery is not far from reach. Incrementally, "*I think therefore it is*" shall be achieved.

Figure 4 (Author's Own): Research Concept Diagram: Illustration of the connected workflow

0/1/3 : Research Question

***“IS IT POSSIBLE TO
EXTERNALISE THE
ARCHITECTURE OF THE
IMAGINATION?”***

1. Initial Research Question

***“CAN WE USE
THOUGHTS TO DESIGN
ARCHITECTURE?”***

2. Refined research questions

***CAN WE
USE BRAIN
ACTIVITIES
TO DESIGN
ARCHITECTURE
?***

3. Final Research Question

LITERATURE REVIEW

URE

— 0/2 : Literature Review —

Although there is a great deal of literature referenced throughout this body of research. This '0/2 : Literature Review' section highlights the essential studies that have been referred to and used throughout the '0/3 : Methodology' section. As the relevant literature focuses on the technique of developing a tool, rather than a designed construct, the researcher thought it best to merge both the literature review aspects with the relevant projects in each category. These literature formulate a theoretical basis for the creation of the integrated foundational system. The chapter can be separated along the following sections, where each section shall include design precedents relevant to the research topic:

- 0/2/1 : Architectural Design Tools
- 0/2/2 : BCI & EEG
- 0/2/3 : Architecture and EEG Research.
- 0/2/4 : Artificial Neural Network within EEG Research

0/2/1 : Architectural Design Tools

Introduction: Rationale for Literature

As indicated within section 0/1/2: Aims & Objectives that an architectural tool is to be created through this design research, it is best to begin the first literature review section with a general overview over various architectural design tools. The undertaking in finding a singular text surrounding on the topic of the developments of architectural design tools had culminated with a void result, in the attempt to situate the researched BCI amongst a lineage of pre-existent architectural tools. These tools are, and not limited to, analogous design methods, such are traditional drawing, model-making, to the incorporated, videography, photography, print-making, or digital design tools, 3D printing, photogrammetry, virtual reality (VR), augmented reality, digital software.

There are essentially a vast amount of tools and techniques; all possess countless ways to which they can be combined to produce different design outcome. A recent compilation within Computational Design (Leach & Yuan, 2017) showcase a compilation of most recent computational design examples, though it would appear that such discussions have yet to make it to popular literature.

“Practice:ArchitectureTechnique+Representation” (Allen, 2009) discusses the inclusion of various essays and reflections on design techniques and methods, although, the interest of this research rests in the tool, not the technique, even though, it could be argued that the technique to design would be the development of the BCI.

Designing with VR:

Virtual reality is a tool for design and powerful in its ability to communicate architecture with rich and multiplicitous levels of design engagements, the ability to augment layers of both visual and audio interactions. Sitting in a tool as a post-image or

post cinematographic era (Manovich, 2003). Virtual reality, similar to a screen, provides live feedback - beneficial to the design process, for the user to reflect upon the inputs he/she has inserted. It is reflected by Manovich as the next development in the process of communication, extending beyond the idea of “virtual” to “virtual reality”.

The research look to the following two VR design precedents as context to this research thesis:

- Virtually Handcrafted (Innes, 2017) discusses the design of a tool for architectural design inside a Virtual Reality environment. The design work is outputted and manipulated through VR controllers. The experience provides an intuitive sense as if a person would be generating the forms inside a VR environment instead of real life. As with all design tools, human motor functions are a criterium to which is needed in the process of designing architecture. The design process from the given tool is additive, a result through continual addition and manipulation of forms inside VR. The tool possesses an interface to which the user can utilise to navigate and select different types of interaction within the design VR environment.
- Tiltbrush (Google, 2016) bears many similarities to Virtually Handcrafted, as both tools enable designing inside a VR environment using directed functionalities. The tool is extremely user-friendly, with an array of added functionalities to which a range of forms can be created from mesh augmented brushstrokes. The tool possesses a highly user-friendly interface with in-built quick, easy tutorial guides for new users. However, the tool is unfortunately short in its ability to present scales, even with a scalable ability, and best appropriated as best for conceptual design purposes, for the lack of fine controlled detailed.

0/2/2 : Brain-Computer Interface & EEG

An introduction:

Following on from research on tools, from the previous section, it is crucial that we now delve deeper into the specific tools this thesis adopts for research. As previously mentioned within the research aims and objectives, the Brain-Computer Interface (BCI). It is essential to understand the context of the BCI, its history and the range of possible BCI, and interaction to which one can pertain to help contextualise the research.

BCI Background:

A development from the 1970s (Gonfalonieri, 2018) from the first-order cybernetics (Cutellic, 2019, p.2), and perhaps "BCIs were initially developed to help patients with very severe motor disabilities, who otherwise could not communicate." (Guger et al., 2017, p. 1). The application of BCI is evident within "Plug-and-Play Supervisory Control Using Muscle and Brain Signals for Real-Time Gesture and Error Detection" (DelPreto et al., 2018), where the human user would utilise the system to transmit corrective information, to the BCI to control robotic gestures. The BCI is part of a broader research agenda within of human-computer interface (HCI) where current day HCI are keyboards, mice and screens (Manovich, 2003). The large body of research on HCI can be found within "the proceedings of ACM's Conference on Human Factors in Computing Systems, CHI" (Dade-Robertson, 2011, p.28), where an ample demonstration of various type of HCI can be introduced. This is an incredibly large database, though, for this research scope, the thesis should inquire a look into specifically BCIs with the combination of EEGs in relations to architecture only.

It was also found that further extension of the Brain-Computer Interface (BCI), the inclusion of tongue input, such as the brain tongue computer

interface, is also a choice. However, as this research focuses on purely using brain activities, not much more shall be discussed in this topic.

Hardware for BCI: Rationale for EEG

There are various potential pieces of equipment for the implementation of brain-computer interaction. Brain activity detectors such are electroencephalography (EEG), magnetoencephalography (MEG), functional magnetic resonance imaging (fMRI), electrocorticography (ECoG), neural lacing and near-infrared spectroscopy (NIRS) are all available tools for extracting brain data (Cutellic, 2019) and used in brain-computer interaction. Each of these tools possesses certain advantages and disadvantages. However, EEG is suitable as an appropriate data acquisition method based on the high cost, complexity, weight and portability, which would be appropriate for both the project's research development and practical application as a professional and education architectural design tool. The research had discovered literature on recently developed on portable 3D printed MEG (Boto et al., 2018); thereby, MEGs could be an appropriate BCI in the future.

Amongst the choices of EEGs, one of the EEG experts had indicated different types of EEG created for specific research purposes - for instance, in the purpose of studying visual-spatial relations, or human cognitive processing. Custom-made EEGs are also available, and would perhaps reduce the amount of cost, in purchasing the hardware along with its subscriptions. Though, for this thesis proceeded with the intention of establishing a series of tested EEG sets.

Electroencephalography (EEG) in Practice:

Placements of the EEG electrodes are distributed across what is known as the 10-20 international

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system, one of the many universally agreed electrodes distribution across the cranium (Hari & Pucer, 2017, L1546) with the purpose of scientific reproducibility in experiments.

Consultation with EEG experts stated the preference to which EEG user should ideally be hairless to maximise detection of neural activities. There is also the concern of electrical interference caused by movements, electricity in the body. It was discussed, within the Victoria University of Wellington's Department of Psychology possess a specialist room, purely for raw EEG data extraction. The room's walls are clad with materials, preventing any external electrical interference, with the exception of WiFi signals, essential to the process are later removed within as part of the raw EEG data filtration process. The room itself becomes a very sensitive brain activity data detector. There is a need for minimal movement. Therefore experiments for EEG are usually set up as to avoid interference from motions, minimal finger movements away from the human body with simple closed questions routines have used in research experiments, following the consultation of one of the EEG experts. This somewhat defines the limitation of the tool itself to use it for designing architecture with brain activities.

EEG data would then require several filters; this is where meaningful extraction can take place. A variety of methods are outlined through the following literature (Drongelen, 2006; Lotte et al., 2007; Bashashati et al., 2007; Lotte et al., 2018a). These are essential in making and attributing raw EEG data, or brain electrical activities into meaningful data, as well as eliminate noises through various filters. The processes methods are divided into four following categories:

1. EEG Data Acquisition
2. Temporal & Spatial Filters
3. Feature Extractions
4. EEG Classification

However, for they sit beyond the research scope, as these are extremely technically challenging, in need of further resources in order to be realised. They are relevant to future research.

Figure 5 (Yeom et al., 2014): 10-20 International System The selected electrode locations of the International 10–20 system (29 EEG recording electrodes (black circles), one ground and one reference electrode (red circles) used in this paper). <https://doi.org/10.1371/journal.pone.0111157.g001>

Detection Device	Advantages	Disadvantages
EEG	Cheap, Light, Portable, Temporal Resolution	Lesser Spatial Resolution
MEG	Temporal Resolution	Heavy, Very Expensive, Stationary
fMRI	Spatial Resolution	Heavy, Very Expensive, Stationary
Neural Lace	Greater Signal Quality, Small, Portable	In Development, Invasive
ECoG	Greater Signal Quality	Invasive
NIRS	Less Sensitivity to Motion Interference	Lesser Temporal Resolution

Figure 6 (Author's Own): Advantages & Disadvantages between brain activity detection devices

0/2/3 : Architectural Research & EEG

Summary:

To the best of the researcher's knowledge regarding the topic of EEG studies within the architectural discipline, such collaboration has remained scarce, with interests in such studies coming as recent as six years in counting from the turn of the recent millenia. Only nine out of 9600 results were found inside the renowned CuminCAD academic resource, a source of multiple academic conferences in computer-aided architectural design. Some of these are present within this literature review section of this proposal. This type of research project as far it is concerned is, therefore, one of the very few research projects related to EEG. Based on research and conference submission feedback, the project is highly unique that it stands out with the triple EEG, Artificial Neural Networks (ANN) and VR combination.

What is an EEG?

EEG, a brain electrical activity detector, is often found within biomedical, psychological and neuroscientific applications (Mavros et al., 2016, p.195). Its application within research has often been found to resolve, with a history spanning as far back as 1929 beginning with the construction of the device by Hans Berger (LaVaque, 1999, p.1; Mavros et al., 2016, p. 195; Lotte et al., 2018b, p.1).

Architecture & Electroencephalography

As far as this research is aware, the conglomeration of EEG & architectural research had only been prevalent within the recent decade with the earliest cited source in 2006 (Huang, 2006). The few found recent studies (Mavros et al., 2012; Fraga et al., 2013; Shemesh et al., 2015; Mavros et al., 2016; Banaei et al., 2017; Coburn et al., 2017) are primarily concerned with EEG in its native biomedical & psychological context, an analytical tool aimed at analysing the

human mental state. As an architectural design tool, these they can be found in research such as *Augmented Iterations*, *Le Cube d'Apres* and *Towards Encoding Shape Features with visual event-related potential based brain-computer interface for generative design* (Cutellic & Lotte, 2013; Cutellic, 2014; Cutellic, 2019). The EEG detected P300 signals, "Positive increase of the EEG signal amplitude, which appears 300 ms after the user has perceived a rare and relevant stimulus" (Cutellic & Lotte, 2013). These tools, are highly sophisticated in their technicalities, and they require a highly experienced understanding and implementation of ANN data classification. Such understanding sits beyond the current scope of research; however, the formulate an understanding. A more sophisticated design tool (Cutellic, 2019), this study follows a prior study, *UCHRON* (Cutellic, 2018) by the same author.

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Figure 7 (Mangion & Zhang, 2014): Furl: Soft Pneumatic Pavilion. Retrieved April 2, 2019, from Interactive Architecture Lab website: <http://www.interactivearchitecture.org/lab-projects/furl-soft-pneumatic-pavilion>

Architectural Design Precedents with EEG:

Design precedents from both art and the architectural discipline, including *Cerebral Hut*, *Furl*, & *Neuroflower* (Ozel, 2013; Mangion & Zhang, 2014; Brick, 2015) were found the few examples found with the engagement of EEG to interact with designed artefacts.

- *Furl* (Mangion & Zhang, 2014) demonstrates how a physical piece of architecture that corresponds to changes based on neural activity to inflate and deflate the design/prototype installation.
- *Neuroflower* (Newton, 2015) blooms and unblooms as well as changes colour based on the neural activity as recorded using EEG.
- *Cerebral Hut* (Ozel, 2013) is a physical installation where the user with the EEG headset would otherwise have mechanical systems protruding in and out of the membrane of the design.

This form an example of the possible interaction that can be incorporated into the design. With both *Furl* and *Neuroflower* highly limited in scope, as the changes are mono-directional and that there are limited means to which the person can interact with the system using EEG. The response is binary, activated, and not activated. However, *Cerebral Hut* offers an extraneous layer of more sophisticated interaction with an additional interaction that is highly organic. Though, the visualised response from the initial mental input remains highly limited.

redacted due to copyrights

Figure 8 (Tracey, 2015): 'Neuroflowers' Sculpture Allows You to Make Robotic Flowers Blossom with Your Mind. Retrieved 9 November 2019, from Outer Places website: <https://www.outerplaces.com/science/item/8625-neuroflowers-sculpture-allows-you-to-make-robotic-flowers-blossom-with-your-mind>

redacted due to copyrights

Figure 9 (Archinect, 2012). ShowCase: Cerebral Hut by Guvenc Ozel. Retrieved 9 November 2019, from Archinect website: <https://archinect.com/features/article/60037941/showcase-cerebral-hut-by-guvenc-ozel>

redacted due to copyrights

Figure 10 (Archinect, 2012). ShowCase: Cerebral Hut by Guvenc Ozel. Retrieved 9 November 2019, from Archinect website: <https://archinect.com/features/article/60037941/showcase-cerebral-hut-by-guvenc-ozel>

0/2/4 : Artificial Neural Networks

Summary:

A rough overview of Artificial Neural Networks (ANN) would situate it as part of AI research and a mimicry against human neurons and a sub-branch of Machine Learning (ML) research within the field of computer science. Its application is vast and possesses multiple purposes. The most notable examples of ANN's utilisation is possibly the development of *Google DeepMind* (Rashid, 2016, p. 6) projects, such as *AlphaGo*, ML algorithms with the ability to defeat humans a highly sophisticated board game, Go. There are different types of ANN, each with different applications and purposes. For instance, Recurrent Neural Networks (RNN) neural networks offer an "internal memory" (Donges, 2018), bearing the ability to loop information back on to itself. Long Short Term Neural Network (LSTM) is the extension of such, with the ability to forget information, a mimicry of human memory. In terms of image classifications and generation, Convolutional Neural Network (CNN), as well as the Variational Autoencoder (VAE) are used respectively. Most well-known projects on these facets are *Google DeepDream* in AI's ability to merge, or data interpolate extracted features from images to formulate extraordinary looking image artefacts.

ANN & Architecture:

ML's great potential for the architectural discipline is acknowledged, yet its prevailing disposition in the architectural field is reflected by Narridh Khean as "[...] "toying" is all that is currently happening" (2017, p.6). ML is remarked as "too complex for architects to embed within their workflow" (Meekings, 2017). However, with the recent developments of ready-made ANN in Grasshopper components, such as Dodo, Crow and Owl (Greco, 2015; Felbrich, 2016; Zwierzycki, 2018), advocate greater accessibility in its application to the discipline (Khean, 2017).

Examples of ANN's implementation into the architectural discipline can be found within *Trained Architectonics* (Algerciras-Rodriguez, 2016), where the Self Organising Map (SOM) ANN Architecture can be used to design architecture, through its continual iteration from a series of set coordinates set off. Perhaps the usefulness of the SOM is how its primitive analytical forms already possess a visual basis, for it to be easily used and translated across into visual utilisation. Stochastic Gradient Descent (SGD) application of SOMs to find the form from the previously constructed architectural forms through point-cloud and proceed to formal generation. The research uses Self-Organising Map as a method for iterating towards the point-cloud geometry from a range of "masterpiece" architectural form.

Biomimetic Robotic Construction Process (Cheng & Hou, 2016) demonstrates that ANNs can be applied within architecture through reinforcement learning algorithms. Robot arms can iteratively learn to pick different organic contents that are non-modularised of distinctly various forming geometries. Where, the robot is at the moment, as found within Gilles Retsin's robotic manufacturing from a singular modular approach to design (Leach & Yuan, 2017, p. 79-90). This demonstrates ANN's strength in being to solve complex problems without having to know the answer. However, the algorithm can learn and solve specific tasks on the spot, rather than having to possess all capabilities, approaching in tackling different problems through a universal algorithm possible.

One recent study (Khean, 2017), has proceeded as far as constructing ANN using pre-existing Grasshopper components. This example finds the basis in the approach to which, this study had attempted constructing Convolutional Neural

Network (CNN) within this research. *Brain2Image* (Kavasidis et al., 2017) outputs images similar to the photographs via EEG data gathered of participants viewing these photographs. The EEG data were inputted into a combination of LSTM brain classification networks to classify the raw EEG data, followed by two different neural network architectures, generative adversarial network (GANs) and the variational autoencoders (VAEs) to generate the images based on the classifications. Where this study is a reconstruction of a static imaging environment, the methodology as noted inside the research was developed based on fMRI scans of blood-oxygen-level dependent (BOLD) to reconstruct moving images through human’s stimulated brain data from watching movies (Nishimoto et al., 2011).

Figure 11 (Khean, 2017): From top to bottom, revised definitions for the net calculations, the hidden error contribution, and the updating of weights and biases.

Figure 12 (Algerciras-Rodriguez, 2016): Indices of Le Corbusier’s Chapel of Notre Dame du Haut in Ronchamp; Robert Venturi’s Vanna’s House; unbuilt Peter Eisenman’s Guardiola House; Mies Van Der Rohe’s Farnsworth’s House, produced by stochastic SOMs.

Figure 13 (Kavasidis et al., 2017, p.5, 6, 8): Brain2Image Image Reconstruction Methods

— 0/3 : Methodology —

The methodology section details the construction of the foundational BCI outlined within section 0/2/3 : aims & objectives of this research inquiry. The research framework follows a combination of both “applied: research through design and “clinical: research for design” (Frankel & Racine, 2010). The former would be the thesis development of technical knowledge surrounding the topic through the construction of the BCI for architecture through its construction, for example, the inclusion of ANN. The latter would be information in aid of developing the BCI. These include the implementation of certain design precedents, or developing the BCI in part from the literature provided. The computational hardware used within this research involves Origin Chronos PC with the following specification shall process all computational procedures: i7-7820X @3.60GHz CPU, GeForce GTX1080ti GPU and RAM DDR4x 2x16GB on a Windows 10 Pro 64-bit architecture.

The research methodology can be broken down into five sections, where each section shall be briefly explained within each section. They are divided as follows:

- 0/3/0 : Preliminary Research
- 0/3/1 : EEG Data Acquisition Methods
- 0/3/2 : Concept Design Experiment
- 0/3/3 : EEG & Design
- 0/3/4 : VR Incorporation

0/3/0 : Preliminary Research

Figure 14 (Author's Own): Emotiv Xavier Control Panel Training

Figure 15 (Author's Own) Emokey Software

First and foremost, it is essential to reiterate the preliminary design research, as previously mentioned in part 0/0/3: Research Topic. The preliminary research was a concise introductory investigation towards EEG research and architecture. The project aim was the creation of a game design environment and game mechanics to formulate subjectivity through both acts of playing the game and mentally interpreting the events taking place. The aim is for the player to formulate their own meaning and structure through the disarrayed contents that take place within the environment, based on human nature tendency towards apophenia.

The research implemented a 5-Channel EEG EMOTIV Insight headset. The interaction with EEG is executed through Mental Commands inside the EMOTIV Xavier Control Panel. The user can store a selected segment of their brain electrical activity over a set period of time. Whenever the player relapse to the same mental state that had transmitted that same stored segment, a command is sent forth. What consequently follows is the use of EMOTIV Emokey, to which augment that command into designated keyboard input. This research project, however, sought to develop a more in-depth technical understanding, more so from the provided software provided by the developers.

Figure 16 (Author's Own): Preliminary Research Designed Environment. A combination of reflective surfaces with ambiguous forms, with multiple cameras, opening up to the idea of subjectivities

Methodology Diagram

Figure 17 (Author's Own): Methodology
Diagram demonstrating the design workflow

```
using System;
using CortexAccess;
using System.Threading;
using System.Collections.Generic;
using System.IO;
using System.Collections;
using System.Text;

using System.Net;
using System.Net.Sockets;

namespace EEGLogger
{
    class Program
    {
        const string Username = "admin";
        const string Password = "12345678";
        const string LicenseId = "12345678";
        const int DebitNumber = 2; // default number of debit

        const string serverIP = "127.0.0.1";

        static void Main(string[] args)
        {
            Console.WriteLine("EEG LOGGER");
            Console.WriteLine("Please wear Headset with good signal!!!");

            Process p = new Process();

            // Register Event
            p.OnEEGDataReceived += OnEEGDataReceived;
            p.SessionCtrl.OnSubscribeEEGOK += OnEEGDataReceived;

            Thread.Sleep(2000); // for query to the server query to start
            if (String.IsNullOrEmpty(Username)) { }
            {
                p.Login(Username, Password);
                Thread.Sleep(1000); // for login
            }
            // Show username login
            Console.WriteLine("Username : " + GetUserLogin());

            if (p.AccessCtrl.IsLogin)
            {
                // Set session
                p.AuthCtrl.Authenticate();
                Thread.Sleep(1000); // for auth
            }
            if (!p.IsAuthenticated)
            {
                p.Query();
                Thread.Sleep(1000); // wait for querying headset and create session
            }
            if (!p.IsCreateSession)
            {
                p.CreateSession();
                Thread.Sleep(5000);
            }
            if (p.IsAuthenticated)
            {
                Console.WriteLine("Press Enter to exit");
                while (Console.ReadKey().Key != ConsoleKey.Enter) { }

                // Unsubscribe stream
                p.UnSubscribeData("eeg");
                Thread.Sleep(2000);
                // Close Out Stream
            }

            // static void OnDataReceived(object sender, ArrayList eegData)
            {
                // Create new Program
                Program p = new Program();
                Console.WriteLine(eegData.Count); // to display how much information is within the arraylist.
                string eegDataSent = "";
                foreach (var item in eegData)
                {
                    eegDataSent += (item + ",");
                }
                Console.WriteLine(eegDataSent); // to display what is within eegData.
                sendEEGData.udpsender(eegDataSent);
            }

            public void udpsender(string eegDataInput)
            {
                UdpClient udpclient = new UdpClient();

                try
                {
                    byte[] eegdata = Encoding.UTF8.GetBytes(eegDataInput);
                    udpclient.Send(eegdata, eegdata.Length, new IPEndPoint(IPAddress.Parse(serverIP), 100));
                }
            }
        }
    }
}
```

0/3/1 : EEG Data Acquisition

This section outlines the technicalities behind EEG data acquisition, the detection of brain electrical activities. They include the hypothetical and practical consideration of hardware and software to acquire EEG data both through recordings and in real-time.

Software & Hardware Considerations

Figure 18 (Author's Own): EEG Headsets tested for static and EEG live data acquisition

Of the three EEG headset tested, 14-Channel Emotiv EPOC EEG performed best, as the CortexUI cloud database did not recognise the EEG headsets. This is perhaps due to the tool being more popular and having existed for a more extended period of time. Software such as MATLAB's EEGLAB plugin (Mavros et al., 2016, p.196), OpenViBE, or BCI2000 are software many neuroscientists and computer scientists use to acquire and process EEG data. TensorFlow, Theano and Keras are commonly-used ML libraries in Python. However, as a foreign software to the architectural discipline, adopting these would be appropriate within a larger time frame.

Figure 19 (Author's Own): Diagram displaying the potential softwares as part of the design workflow

Static EEG Data Acquisition Method

The most direct means of gathering EEG data can be found through the use of EmotivPRO, EMOTIV's software, developed for the use of exporting EEG data. A test recording was executed and sent exported into .csv format, where gHowl Grasshopper plugins are used to import the file's information. EmotivPRO offers the capability for exporting four different types of information, raw EEG data, performance metrics (.pm), band power (.bp) and motion data (.md).

Raw EEG Data

The screenshot shows a spreadsheet of raw EEG data. The columns are labeled A through M, and the rows are numbered 1 through 35. The data is organized into columns for 'subject', 'label', 'channel', 'samples', and 'units'. The data is presented in a tabular format with numerical values.

Figure 21 (Author's Own) Raw EEG Data: data averaging at roughly 4000

.pm (Performance Metrics)

The screenshot shows a spreadsheet of performance metrics data. The columns are labeled A through M, and the rows are numbered 1 through 35. The data is organized into columns for 'subject', 'label', 'channel', 'samples', and 'units'. The data is presented in a tabular format with numerical values.

Figure 22 (Author's Own) Performance Metrics Data: data ranging from 0 to 1

Refined Developed Connections

CORTEX ACCESS METHODS	RESULTS
UNITY COMPILATION METHOD <p>Importing in-built NuGet package (external .dll libraries which are required to compile the given example script)</p> <p>CortexUI Registration Online for access information</p> <p>Unity compiling the example script as rewritten inside Unity</p>	UNRESOLVED <p>EMOTIV responded having resolved the bug which has been causing the issue. However, the method has not been tested since.</p>
UNITY ASSET (NEUROREHABLAB) <p>an online unity asset claims it provides the means to visualise and gather EEG data within Unity. the script appears to contain various self developed external libraries by the content uploader. it does however not work with EEG content appearing. it might seem that further tests may be required, otherwise, the method is now obsolete.</p>	NOT WORKING
EXPORTED .DLL METHOD <p>this method involves compiling the script into a .dll file instead of compiling inside Unity. this file is then assessed inside Unity where it can reference the method to which allows the data to be streamed. in this way, all the coding goes directly and managed by Unity (the design could then be used inside Unity. it would also require everything to work inside before it can be exported (although this would be tricky when it comes to designing).</p>	UNTESTED
GH WEBSOCKET METHOD <p>the method seems the most reliable, although the scripting may be the issue to grasp. there is a note of this method expiring by the end of this year.</p>	NOT WORKING
COMMUNITY SDK METHOD (EMOENGINE) <p>the method seems the most reliable as previous games had been developed, although the scripting may be the issue to grasp & modify to be used appropriately. there is a note of this method expiring by the end of this year.</p>	UNTESTED

Visual Studio

Script modified, edited & compiled using Visual Studio 2017 in C#

Figure 23 (Author's Own): A series of tested and non-tested EEG acquisition methods in real-time

Live EEG Data Acquisition Method

[illegible]

Through much trial and tribulations, a method of successfully transferring EEG data across is successful. The original example C# script was modified to instead of its original functionalities of exporting a spreadsheet, the incoming EEG data stream information into Grasshopper via a User Datagram Protocol Connection (UDP). The C# scripts were built into an .exe file with dynamic link libraries (.dll), containing namespaces for the program to access and function.

Figure 25 (Author's Own): Diagram demonstrating how EEG information are processes

Figure 24 (Author's Own): EEGLogger Script Example

0/3/2: Concept Design Experiment

software utilisation

The second stage, Concept Design Experiments were design concepts executed without the consideration of EEG data and what it has to offer. The idea was to test-view any developments of interest arising through this lack of knowledge. These various developments were built inside Grasshopper. Four unique design concepts are generated, where three were implemented into the system at later stages.

Figure 26 (Author's Own): Developments of Kaleidoscope Grasshopper design iterations

Figure 27 (Author's Own): Kaleidoscope Design Grasshopper Script

Kaleidoscope

The first design iteration, Kaleidoscope, intended for the user to immerse oneself inside a continually changing geometries. The design demonstrates sophisticated geometries and substantial computational processing power needed. The design possesses two different parameters where information can be passed through to interact with the design; these are:

- geometrical types
- quantity of geometrical segments

Figure 28 (Author's Own):
Series of other Geometries

mesh design.

colour overlaid
on to grids from
this original
photograph

Figure 29 (Author's Own): Under the assumption, that this would be the post-processing of images of EEG data is received

Figure 30 (Author's Own): Development of Image Spatialisation 1

The choice for image spatialisation, was based from earlier research interest in the attempt to integrate part of the *Brain2Image* (Kavasidis et al., 2017) image generation process into a BCI system, and spatialising the brain activity generated image content provided by the algorithm. The design concept would be the immersion of the human experience within the landscape of extruded brain generated photographic content.

Figure 31 (Author's Own): Image Spatialisation Grasshopper Script

Image Spatialisation

Image Spatialisation 1 would create an environment where the user can immerse themselves within the landscape. Image Spatialisation 2 creates a deepened space from the *Tour into the Picture* (TIP) method (Horry et al., 1997), then project grids with varied extruded boxes based on the colour values assigned to each of the projected grid.

Figure 32 (Author's Own):
Development of Image Spatialisation 2

extrusion.

As part of another series of design exploration, the interest of ANN in architecture is highlighted in section 0/2/4 of this research. Therefore, the intention of its implementation as part of the design workflow was essential in both the question of ANN's role as an analytical tool as well as a design tool within the architectural design process.

The Convolutional Neural Network (CNN) design iteration example is conceptually similar to found research (Khean, 2017) in its attempt to reconstruct ANN architecture algorithms in Grasshopper. The desire is to develop a CNN before transforming it into a Variational Autoencoder (VAE). The VAE would possess both image processing, and generative capabilities based on data interpolation of features extracted from the classification process. The algorithm was constructed and tested with matrix multiplication value of $[(1,0,-1), (1,0,-1), (1,0,-1)]$, an edge detection value, with the anticipated result of a black and white highlight over the image's edges. Such an intention so far has yet to happen but is considered as part of future studies.

Figure 33 (Author's Own): Convolutional Neural Networks Grasshopper Script

**convolving
edge detection
algorithm**

Figure 34 (Author's Own): Diagram explaining the "convolving" algorithmic procedure (Saha, 2018); a 3x3 filter moving at a stride of 1. Each new pixel is taking in consideration of contextual pixel information to abstract the image content.

Convolutional Neural Network (CNN)

What resulted in this design process, is a beautiful mistake with the height of the boxes moved in the vertical direction based on the boxes' brightness values. This would unequivocally create a three-dimensional geometrical form from two-dimensional objects.

Nevertheless, it is essential to emphasise that more resources in terms of time and expertise shall be required to achieve the full resolution. Altogether with the introduction of other segmentation algorithms such as image segmentation, and semantic segmentation can be added to operate as part of the image classification process within the BCI system.

The current algorithm currently possesses three parametric inputs:

- orientation of box to the user's position
- movement of box
- scale of box

Figure 35 (Author's Own): Image Processing Procedure in Grasshopper

artificial neural network.

Self Organising Maps (SOM)

Crow Plugins
(Felbrich, 2016)

Finally, within this section, in the attempt of incorporating a SOM algorithm through the Crow Plugin (Felbrich, 2016) inside Grasshopper. What this algorithm does is the generation of a grid to which would over time, adjust, and learn to fit its coordinates to a set of random seed coordinates. The amount of accuracy and time spent depends on the number of iterations that are specified. The two input parameters for this system are:

- The seed coordinates position
- The number of iterations can be modified

artificial neural network.

Static EEG Data

0/3/3 :
EEG & Design

software utilisation

Having established a series of design studies and the knowledge of EEG data received in real-time, this section elaborates on the fusion of these two aspects through a series of steps. They include static EEG data, to live EEG data, from its continual refinements, explorations and appropriation in development of geometric for interaction within the foundational BCI system.

Mindful Manifestation: from EEG to Virtual Reality

numerical data

A	B	C	D	E	F	G	H	I	J	K	L	M
title:ARC093	recorded:2	timestamp	subject:4	labels:COL	chan:12	samples:1	units:emotiv					
1	21	8244	8279	8168	4183	8058	8038	7870	8131	7929	5	890 1.53E+01
2	22	8239	8274	8168	4182	8485	8049	7870	8197	7930	5	905.3846 1.53E+01
3	23	8243	8274	8172	4184	8478	8042	7869	8196	7930	5	921.282 1.53E+01
4	24	8234	8285	8170	4180	8453	8052	7873	8133	7930	5	937.1794 1.53E+01
5	25	8230	8286	8178	4192	8444	8069	7872	8194	7930	5	952.5641 1.53E+01
6	26	8228	8287	8178	4190	8451	8054	7867	8194	7929	5	968.4615 1.53E+01
7	27	8226	8287	8178	4195	8476	8072	7870	8207	7936	5	984.3589 1.53E+01
8	28	8225	8291	8182	4191	8476	8058	7868	8196	7927	5	999.7436 1.53E+01
9	29	8226	8292	8182	4188	8483	8060	7870	8212	7930	6	15.64103 1.53E+01
10	30	8220	8293	8183	4184	8436	8037	7870	8152	7929	6	11.51846 1.53E+01
11	31	8221	8284	8184	4186	8474	8051	7871	8195	7928	6	46.92308 1.53E+01
12	32	8216	8287	8185	4188	8447	8070	7872	8195	7929	6	62.82052 1.53E+01
13	33	8219	8285	8185	4184	8444	8051	7867	8194	7927	6	78.71795 1.53E+01
14	34	8221	8281	8183	4199	8476	8085	7871	8195	7931	6	94.61539 1.53E+01
15	35	8219	8289	8191	4181	8467	8077	7871	8195	7927	6	110 1.53E+01
16	36	8222	8284	8195	4192	8473	8061	7875	8194	7931	6	125.8974 1.53E+01
17	37	8217	8294	8192	4180	8464	8070	7870	8196	7931	6	141.7949 1.53E+01
18	38	8222	8300	8190	4192	8461	8083	7870	8199	7931	6	157.8923 1.53E+01
19	39	8220	8298	8191	4185	8482	8097	7871	8202	7927	6	173.0769 1.53E+01
20	40	8224	8287	8190	4178	8468	8068	7872	8196	7927	6	188.9744 1.53E+01
21	41	8220	8290	8193	4178	8495	8041	7875	8188	7929	6	204.8718 1.53E+01
22	42	8215	8295	8197	4145	8447	8050	7871	8197	7930	6	220.2564 1.53E+01
23	43	8211	8298	8190	4150	8449	8044	7866	8195	7928	6	236.1538 1.53E+01
24	44	8212	8295	8189	4151	8461	8043	7873	8194	7929	6	252.0513 1.53E+01
25	45	8212	8292	8184	4182	8480	8062	7871	8198	7929	6	267.9487 1.53E+01
26	46	8213	8287	8184	4192	8472	8057	7873	8195	7928	6	283.3333 1.53E+01
27	47	8214	8283	8188	4198	8471	8050	7871	8198	7930	6	299.2208 1.53E+01
28	48	8217	8281	8185	4191	8454	8067	7869	8198	7932	6	315.1282 1.53E+01
29	49	8226	8288	8184	4196	8448	8068	7871	8196	7927	6	331.0256 1.53E+01
30	50	8226	8289	8188	4186	8481	8074	7878	8194	7929	6	346.4102 1.53E+01
31	51	8232	8287	8189	4188	8472	8064	7868	8198	7931	6	362.3077 1.53E+01
32	52	8237	8280	8185	4178	8470	8055	7865	8195	7927	6	378.2051 1.53E+01
33	53	8232	8276	8187	4169	8479	8032	7870	8206	7934	6	393.9897 1.53E+01
34	54	8234	8283	8183	4152	8448	8034	7873	8194	7931	6	409.4872 1.53E+01
35	55	8229	8287	8185	4163	8475	8037	7871	8187	7927	6	425.3846 1.53E+01
36	56	8222	8290	8184	4169	8471	8038	7873	8195	7930	6	441.282 1.53E+01
37	57	8217	8290	8187	4179	8464	8052	7876	8194	7928	6	456.6667 1.53E+01
38	58	8215	8290	8186	4226	8466	8052	7873	8207	7928	6	472.5641 1.53E+01
39	59	8211	8295	8188	4192	8469	8044	7873	8196	7926	6	488.4615 1.53E+01
40	60	8215	8293	8195	4179	8474	8029	7867	8193	7928	6	503.8461 1.53E+01

Following on from section 0/4/2 : EEG Data Acquisition of this design research. Static EEG is initially used for design investigations in the use of EEG data with formal design aspects. In assuring the design process possible, 384 lines of data,

Figure 38 (Author's Own): Importing Excel format files through Grasshopper Script

corresponding to three seconds worth of raw EEG data were extracted. Initially tested on an EMOTIV 5-Channel EEG Insight headset, the data is used to construct coordinates in space, this is ensued by translating these coordinates in series and undergo rotations.

position
(x, y, z)

RGB colour
(r, g, b)

scale
(x, y, z)

orientation
(x, y, z)

Static EEG Processing

Figure 39 (Author's Own): Demonstrations of EEG data manipulations

Figure 40 (Author's Own): Colour change induced by static EEG data

initial eeg design.


```
public static void OnEEGDataReceived(object sender, ArrayList eegData)
{
    Program sendEEGData = new Program();
    //Console.WriteLine(eegData.Count); // to display how many items are within each iteration of the array
    string eegDataSent = "";

    foreach (var item in eegData)
    {
        eegDataSent += (item + ";");
    }
    //Console.WriteLine(eegDataSent); // to display what is within eegData.
    sendEEGData.udpeegsender(eegDataSent);
}

public void udpeegsender(string eegDataInput)
{
    UdpClient udpclient = new UdpClient();

    try
    {
        byte[] eegdata = Encoding.UTF8.GetBytes(eegDataInput);
        udpclient.Send(eegdata, eegdata.Length, new IPEndPoint(IPAddress.Parse(serverIP), 100));
    }

    catch (Exception error)
    {
        Console.WriteLine(error.ToString());
    }
}
```

Figure 41 (Author's Own): EEG Logger C# Code

Figure 42 (Author's Own): Manipulation of geometric surface through raw EEG data

Figure 44 (Author's Own): Emotional Data colour test changes on the Boxes

Through what 'is provided by the company software developer, a command is used to extract emotional data in real-time, by the modification of the following pieces of information. The claimed 'emotions' data stream at roughly once every 10 seconds. Where there are supposedly seven possible emotion, long term excitement, interest, relaxation, focus, excitement, stress and engagement, only four values, interest, excitement, long term excitement and focus appeared to have data variation, and so, possibly used for interaction inside Grasshopper. This lack of information does have its benefits as the four values ranging between zero to one can conveniently be used as parametric inputs for ARGB colour components, of which are imposed on to the test-boxes. However, this process should be visited with ample scepticism as one of the experts has highlighted the received processed data as not accurately reflective of human affects, and hard to be "peer-reviewed due to their status as industrial intellectual property" (Mavros et al. 2016). The research assumes that it does, as this EEG processing method, demonstrate a proof-of-concept as to what would happen, given affect data can be deconstructed.

- 1.interest
- 2.excitement
- 3.long term excitement
- 4.focus

ARGB colour
(a, r, g ,b)

Emotional Data

Figure 45 Performance Logger C# Code

PERFORMANCELOGGER | AFFECT DATA

live interactive design.

Moving on to more sophisticated developments from Concept Design Experiment. The CNN experiment, now called “Glitch Box”, since the design was based on the algorithm, but does not possess its functionalities. The number of grids was downscaled from an amount of approximately 300 to only 100 boxes for a smooth live experience. The design series are separated into three different sections, initialising with “filterless”, where the received transmitted raw EEG data is sent directly to the geometric boxes. As the order of the boxes is ordered from left to right, top to bottom, the incoming numerical data has been found to interact, changing the boxes’ vertical positions in a similar fashion. EEG data therefore lingers, and so hinders the visibility of new incoming EEG data, resulting in a lack of live visual feedback for each response. To resolve this issue, the second design had the interaction of eight equally sequenced boxes to

Glitch Box

formerly: Convolutional Neural Network (CNN)

translate by the incoming data simultaneously vertically. The third design series proceeded in dampening the incoming magnitude of incoming EEG data induced by physical movements in relations with data when staying still. An exponential equation is multiplied after absolutising the value - hence, the lack of boxes moving in the negative direction.

live interactive design.

Figure 47 (Author's Own): Box Scaling Grasshopper Script

Figure 48 (Author's Own): Box Scaling Grasshopper Script

scale application
on CNN algorithm

reversed list
pattern

concentric
pattern

Box Scaling design iterations succeed the previously mentioned Glitch Box design iterations. Although, instead of moving the geometries along the Z-axis, the design was scaled instead. Scaling meant that there should be a larger span of negative spaces in between them.

A series of further investigations, including the reversal of the boxes' sequence order, as well as the concentric pattern design iteration of the Box Scaling geometric design concept, where the order of the boxes

Figure 49 (Author's Own): Box Scaling Animation

Box Scaling

was reordered to spiral outwards from the centre, were additionally implemented. The desire is to possess a live interaction, to which the design would have behaved similarly to a water droplet rippling outwards from the centre.

live interactive design.

As the last series of the EEG & Design section, the Self- Organising Map (SOM) example is brought forward. To avoid latencies in this real-time brain-computer interaction, SOM layer dimensions were reduced to 2,2,2,2 instead of the original 5,7,7,4 configurations. There are also further additions of thinned pink boxes to which resemble structural frameworks, bringing the design process to what could be within a brain-architectural interaction through ANN physicalised structural design response. The initial idea of design was to have the SOM continually iterating towards to coordinates consistently altered by incoming raw EEG data. Unfortunately, it would appear that Crow's SOM plugins are highly limited and would not iterate to new coordinate changes, but would only iterate to the seed coordinates at the instance of the algorithm's initialisation.

Consequently, in attempting to reinterpret all incoming EEG data under the found constraints of the Crow's SOM algorithm, the SOM algorithm would have to reinitialise its iterative process at 128Hz ideally. However, due to the practical limitation of both computational software and hardware, to the number of provided SOM networks, the fastest rate of SOM restart, would be every 0.2 seconds or 5Hz. The drawback of such fast reactivation rate would be the algorithm's

Figure 50 (Author's Own): Series of SOM transformation

Figure 51 (Author's Own): Grasshopper Script for the algorithm

Self Organising Map (SOM)

inability to formulate any noteworthy three-dimensional self-organising map to its target coordinates, for the results tend to be diminutive to differentiate itself from others. Therefore, a slight change was once modified to reinitialise at 0.5Hz instead. What is created is a balanced trade-off between the algorithm's accuracies to the target coordinates versus the amount of raw EEG data to which is geometricised by the SOM algorithm.

Run for 1800ms (1.8s)
Stops for 200ms
10000 Iterations to
reach final result

continually looping

Run for 180ms (0.18s)
Stops for 20ms
3000 Iterations to
reach final result

continually looping

interactive design +.

0/3/4 : Incorporating Virtual Reality

Having established a direct link in between EEG understanding together with the Concept Design Experiments, the addition of VR for immersive visual feedback is inserted into the system, initially concerning with transferring geometries from Grasshopper into Unity. Thereafter, having the entire process functioning BCI system, where it is further developed and refined. The advantages, disadvantages of each method, why they have been used and research findings throughout the process are generally discussed.

Moving forward, there are two processes to which were essential in bringing designs from section 0/3/3 : Concept Design Experiments from Grasshopper to Unity. The first method, the UDP method, once again establishes a UDP connection to transfer information of geometries from Grasshopper to Unity. Its drawbacks are the requirement for the geometries to be available in both Grasshopper and Unity. The position, colour, scale & orientation of these geometries are processed, sent and parsed inside UnityVR. This process remains the crux of the BCI under development, as implemented as it requires lesser computational processing, and thus appropriated a live connection without latencies. How the algorithm operates, involve the reconstruction of meshes inside Unity from a series of gathered coordinates from Grasshopper.

Figure 52 (Author's Own): parameters of changes of boxes that are affected by changes inside Grasshopper

UDP Method

Figure 53 (Author's Own): Grasshopper to Unity UDP Data Transference Method

Grasshopper to Unity.

The alternative method, to which the UDP method is currently lacking, the transfer of complex geometries, would be the MeshStreaming method (Horikawa, 2017a), transmitting Meshes from Grasshopper to Unity via a WebSocket connection as the UDP method had demonstrated to be unreliable. Data was not reliably sent from one place to the other, a WebSocket connection, similar to a Transmission Control Protocol (TCP) would ensure the data packet is received before sending more information over. MeshStreaming method indicates itself to be slow & unreliable — unsuitable for a complex system with many software need to work, and so is not incorporated into the system.

MeshStreaming

Figure 54 (Author's Own): VR Controller with indicators of assigned functionalities for a series of buttons

Figure 55 (Author's Own): Demonstration of different design scenarios incorporated to the full incorporated system, with different human interaction to generate a range of design results in combination with the baking functionalities

Virtual Reality Enhancement

Figure 56 (Author's Own): Diagram displaying the backflow of data from Unity to Grasshopper, indicated through the backflow via a WebSocket port connection.

Through the development of both UDP and Mesh Streaming connections, a full system is established with particular adaptations. Such implications would be the further reduction in the number of boxes in Glitch Box Design Scenario Two. Further additions to the system, the “baking geometries” function, and the design “togglng” all executed through WebSocket for the same reason as explained within the Mesh Streaming method.

Figure 57 (Author's Own): VR Controller with indicators of assigned functionalities for a series of buttons

Virtual Reality Enhancements.

The system was found to be highly fragile. There is a requirement for a high number of programs to be initialised, which tends to cause frustration in the pursuit of initialising the system. A particular sequence of software & hardware initialisations are also necessary in order to avoid system failure; the order is as follows:

1. Unity
2. Grasshopper
3. Unity to Grasshopper WebSocket Connection
4. HTC Vive Headset in UnityVR environment
5. EMOTIV 14-Channel EEG Headset
6. Cortex UI EEG Data Stream

Failure to adhere to this process, as found within the research, for instance, undertaking the sixth task then the second would lead to a vast quantity of data is being transmitted

at a point where Grasshopper is just initialising. The result would be the program's failure to launch or respond. This inadvertently results in immediate system crash as one of the components in the BCI-VR system fails to operate. Generally speaking, the system's life span stretches from 10 seconds to 5 minutes.

Figure 58 (Author's Own): Diagram demonstrating the process of processing EEG data for this design purpose.

Full Connected System

Fully Incorporated System.

onstrating the various technical stages in
poses throughout the scripted BCI system

Figure 59 (Author's Own): Complete Refined Grasshopper Script, with annotation of the components

Grasshopper Script

Fully Incorporated System.

Figure 60 (Author's Own) Screenshots of a recording of a user inside the developed BCI system

Virtual Reality Experience

Whilst, the research aims to remove human motor function in the design process altogether, utilisation with the VR controller does introduce a level of motor inputs into the design process. Still, the interaction is only limited to the choice of switching between possible design scenario types, not, the engagement in alterations of design geometries throughout each scenario themselves.

Fully Incorporated System.

VR EXPERIENCE

The research discovered a correlation between the person's restfulness and the magnitude of the EEG data's values. This is to say that the system's user's mind while in a restful state emits lesser brain electrical activities in comparison as to when the mind is restless. Such correlations were visible while interacting with design

VR EXPERIENCE

Virtual Reality Experience

Continued...

scenario two, glitch box experiments, which demonstrate more significant fluctuations in the translation of each box in the Z-direction depending on whether they were thinking peaceful or non-peaceful thoughts. Such a relationship demonstrates evidence for the developed BCI's capability in its ability in modifying architectural forms through electrical brain activities.

Figure 61 (Author's Own):
Successive screenshots
of user using the BCI
within a VR environment

Fully Incorporated System.

Design Tool Outcome

Fully Incorporated System.

As with any design processes, the actual design outputs in comparison to the original design intent before it is crafted tends to deviate as the actual design is finalised. Where the initial aim is to create a foundational BCI to design using brain activities, the study was able to achieve more. On the mere basis, of reconfiguring the hardware and workflow in how the current BCI system on offer is used, an entirely different meaning behind these design interactions would arise altogether.

It has been mentioned in the 0/3/1 : EEG data acquisition section, how designing with static EEG data has been advised against, based on the EEG data acquisition technique used - through the import of EmotivPRO .csv file export via the gHowl component into Grasshopper being sluggish. However, since these EEG data are static, the data can be copied onto the clipboard, and pasted directly into a Grasshopper Panel component. This maintains the large quantity of EEG data, and at the same time, allow Grasshopper to process through this vast quantity of data smoothly. The data can be either replayed within the developed BCI system, to which system's user would be experiencing geometric interpretations of another person's brain activities - potentially an abstracted architectural interpretation of a person's memory. The user could otherwise curate and pick out specific segments to which they would bake geometries into Rhino, an active process in revising geometric design information found to be interesting. Alternatively, the recording can be manipulated, edited, altered - reversed, jittered, which would otherwise associate with the idea of actively manipulating and altering the interpretation of memories and events, experiencing records of memory backwards. The potentiality for exploration in this direction is endless and ripe for future research.

Furthermore, the investigation has discovered an electrical interference induced by the VR headset on to the EEG headset as cautioned by an EEG expert. The disruption is found to additionally amplify the electrical signals by a factor of 1.5x the original amount. As a result, for the immediate circumstance, advisable in having two users, one using the EEG headset, and the other within a VR headset. This alteration would inadvertently the system as a tool for designing architectural through the interaction of pre-existent forms, to the immersive visualisation of other's brain recorded data in real-time, or a potential novel interpretation of peering into another human mind. To which, each of the two users would presumably feel a great deal more comfortable, having only to deal with a single device each at a given moment. The user in VR, can once again, cherry-pick to bake geometries at the junctures to the user's preferences. As it is certain, the combinational use and shuffles introduce limitless meanings.

Alternative Design Methods

Figure 63 (Author's Own): Seed Coordinates for Design Scenario One: Self Organising Maps (SOM), being applied

— 0/4 : Discussion —

This section discusses the technical limitations, potential upgrades the current system possess and potentially undergoes. The section also situates the developed BCI system within the context of other systems as highlighted in the 0:2 : Literature Review section. The section concludes with reference to the original research agenda, indicated in section 0/0/3 Research Topic & Agenda and discussed in section 0/1/1 : Scope of Research. The topics under discussions are listed as follows:

- 0/4/1 : System's Design Intentionality
- 0/4/2 : Further EEG Design Interactions
- 0/4/3 : Further System Modifications
- 0/4/4 : A speculative BCI using the Mental Imagery to Design Architecture

0/4/1 : System's Design Intentionality

Much criticism and concern over the system's lack of design intentionality has been noted, and often reflected by peers surrounding the factor that the workflow was merely a random number generator. Such criticisms may be appropriate for Design Scenario One SOM, as raw EEG data has only been directed to alter the seed coordinates randomly. However, they are unfounded in reflection to Design Scenario Two Glitch Box and Design Scenario Three Box Scaling. Through using the BCI system, the differentiation between thinking of "restful" or "restless" thoughts have an impact on the magnitude of raw EEG data, and thus the geometric outcome substantially. One method of intentionally interact within this system is, therefore, to think of "restless" or "restful" thoughts. This is also applicable to the SOM algorithm should the seed coordinates position be modified along the same line as design scenario two and three. A further extension of intentionality would be the incorporation of the eye-tracking devices to the current BCI system. The eye-tracking device can be used to coordinate the location of geometric instantiation, and its instantiation to either generate or not generate can be attributed binarily of certain recorded EEG data through Mental Commands.

To further extend this discussion, one should remember that the developed BCI system's design creation hinge upon the input of three minds: the system's user, the system's designer (the principal researcher) and the implemented ANN. We should ask the question as to whose intentionality should we be concerned with? To begin unravelling this question, it would be fair to say that the implemented ANN's algorithm, as not sophisticated enough to be considered as having intentionality. The system's designer has largely preordained that intentionality to the ANN. Therefore, the intentionality to which one should be concerned about should merely be between the system designer and the system user. There are two ends of the spectrum to which this research belies, the development of a BCI that

can automate a series of design results through raw received EEG data, or the emphasis on the system's user's intention in generating a series of design. Depending on the degree of design engagement, the system can be developed along either direction or to specific scenarios where a different level of design engagements can be adjusted, as to how much input is required by the user on to the design outcome. On the scale of intentionality in comparison to the two VR design tool case studies, *Google Tiltbrush* (Google, 2016) and *Virtually Handcrafted* (Innes, 2017) with the developed BCI-VR system, as design tools, both of the two case studies inside VR, and other conventional CAD design tools, such as *Revit*, *SketchUp* or *Rhino* would begin the design procedure through generation of form from a blank canvas, possessing a degree of intentionality that the user is fully aware of. This is mostly due to the history of developments of the tool for design, and the accustomed mastery of the user on the system.

0/4/2 : Further EEG Design Interactions

In furthering the system's design interactions through EEG data, the process can be separated into two components, the technical EEG data processing procedure, and how the response of architectural forms to the incoming EEG data.

The CortexUI EEG cloud database offers five different types of data stream, raw EEG data, emotion data, motion data, mental commands & facial commands. As the research aims to investigate the use of brain activities, only raw EEG data, emotion data and mental commands are appropriate for this research; the research had only implemented raw EEG data and emotion data. Mental commands are yet to have been incorporated into the system. Having mentioned this functionality in section 0/3/0 : Preliminary Design Research, the user can record a section of their brain activities, where the system, given the user can recall that mental state, shall detect the signal output numerical data based on how similar to those patterns are. This numerical value can be used to trigger an event, such as generating

certain types of geometries or enact basic scaling, rotating and translating transformations and colour changes to the design.

Other meaningful design inputs would require the construction of filters, feature extraction & analytical methods. Frequency bands (Mahler, 2018), a commonly discussed features, found within the Emotiv's static data extraction method. Such as the inverse relationship between alpha and beta frequency bands, from the range of 8-12Hz and 12-25Hz; the presence of data with alpha frequency bands correlation with "mental and physical relaxation" (Mahler, 2018, p.21), where beta correlates with "active, busy or anxious thinking and active concentration" (Mahler, 2018, p.22). Other EEG features, such are the N400, N170 and P300 signals (Mahler, 2018, p.40) (the P300 is marked as "positive increase of the EEG signal amplitude which appears 300 ms after the user perceived a rare and relevant stimulus" (Cutellic & Lotte, 2013)), or the use of steady-state visually evoked potential (SSVEP) (Schwartz, 1999, p. 348-349; Lotte et al., 2018b, p. 4) can also be implemented, giving the pre-existent designed content more meaning. These methods would require ANNs to extract these features and would demonstrate itself to be computationally heavy.

In addition, it is advised that the layering of these extraneous interactions on to the current BCI to consider the user's ease to design in mind. Overburdening multiple certain types of interactions on a given design scenario, may not only crash the system due to the computational processing power required from multiple ANNs required to extract these features, but also the overcomplication for the user to design with their intention effectively. The learning curve would be demonstrably steep.

Moreover, the current integrated foundational BCI system only utilises a single electrode, out of the fourteen available EEG electrodes to send signals to manipulate the pre-existent architectural geometries. Basic research based

on neuroscience reveals how specific brain lobes are correlated with different human functionalities (Cherry, 2018); for instance, "temporal organization of behavior is primarily a function of the frontal cortex" (Vyshedskiy, 2017, p.2). However, with the rise of "multivariate neuroscience", the "conjunctive consideration of multiple measurements at the same time" (Cohen, 2018) would suggest a revision of reductionist segmentation of brain lobe areas into specific functionalities, as multiple areas in the brain are necessary to carry specific functionalities.

0/4/3 : Situating within Literature Reviews

In relations to past studies, physicalised EEG induced design installations, *Cerebral Hut*, *Furl* and *NeuroFlower* (Ovec, 2013; Mangion & Zhang, 2014; Brick, 2015), the level of design interactions, the current system through its design scenario two and three demonstrate to be a more sophisticated design interaction. Where, instead of existence between boolean states, the interaction possess a continuous range to which it can exist in. Perhaps such comparison is difficult, as the installations are physicalised. Therefore, further considerations of real environmental constraints, cost, labour, structural considerations may contribute to the lack that is found within the examples.

In relations to a series of other EEG architectural design system, the systems proposed within *Augmented Iterations*, *Le Cube d'Après* and *Towards encoding shape features with visual event-related potential based brain-computer interface for generative design* (Cutellic & Lotte, 2013; Cutellic, 2014; Cutellic, 2019), the current developed BCI system do not possess sophisticated ANN to which it would use to classify EEG data. What it does possess, would be where the current design strategy follows parametric design principles through connected workflows of input and output data mechanically between human and computer. The design strategies in *owards encoding shape features with visual event-related potential based brain-computer*

interface for generative design (Cutellic, 2019), does, however, possess an additional layer of generative design strategies, to which the research would like to adopt in the future.

It is also worth mentioning that through all the design precedents, it poses as the first and only system that possess both EEG and VR with the purpose of designing architecture within the architectural discipline. Furthermore, one of the very few EEG-VR systems architectural discipline with the other system is found within the study of *Walking through Architectural Spaces...* (Banaei et al., 2017).

0/4/4: Further System Modification

Whilst the question of improving the system's performance, such as its 'durability' can be generally handled through the following three modifications:

- changing the software platform that is used for generating architectural geometries.
- modification with better scripting methods (efficient code writing)
- upgrading the hardware used within the computational process.

Extensive modifications could help to improve the system's intended purposes. This section includes the discussion surrounding eye-tracking tools, as mentioned in section 0/4/1 : System's Design Intentionality.

- *Serialisation*, a process which allows saving information inside the VR environment. This would help the user to gain real-time visual feedback on the geometric baking process as they are inside the VR environment.
- *Physicalisation*, a process that can be developed through the developed bake geometries functionality allows the selective capturing, with a metaphor close to that of a low-shutter speed camera capture of the interpretation of the human cognitive process,

The fact that these geometries are overlapping one another, means that they are not, further development of an algorithm which would boolean unionise the overlapping objects, to form one cohesive geometric object. The result can be analogised as the translation from 'soft' architecture to 'hard' architecture, where the BCI system would extend to that of interacting architecture within a real environment in real-time - moving closer towards conventional understanding in the architectural discipline.

- *Multi-user Engagements*: The system, moving away from merely a single user within the system can expand its capabilities to possess multiple users within multiple constructed BCI system, interacting with one another in a shared space through more sophisticated network connections. The process would be a collaborative process and a collection of minds, all interacting and negotiating with one another simultaneously.
- *Virtual Interface*: A user-friendly virtual interface, similar to found precedents in *Tiltbrush* and *Virtually Handcrafted* (Google, 2016; Innes, 2017), would improve the system's accessibility overall.

0/4/5 : Speculative BCI using the Mental Imagery to Design Architecture

Despite the fact the research into this venue has ceased due to earlier technical difficulties, the aims and objectives in section 0/2/1 seek the opportunity for this system to develop the ability to design architecture with the Mental Imagery. It is, therefore, important that this topic is mentioned in this discussion chapter.

Retrospectively speaking, on par with the initial aims and objectives, this research began based on *Brain2Image* (Kavasidis et al., 2017) a proposed technical system of inter-related software and hardware, contained algorithms with the intention of producing VR immersive experience, based on the image generated from the brain activities (see

Figure 64 on page 98-99). It was hypothesised that the end results of would be a Larsen effect, the effect found placing a microphone in front of a speaker. However, in this case, it is a result from the continual loop of perceiving noise by the brain, and the algorithm generating further noises based on the EEG data it detects.

Where the evidence between these two aspects can be found within Vitrano's scientific studies of EEG signals in situations of (2012), and Kirchoff's *Predictive Processing, Perceiving and Imagining* essay (2017) in support of the two concepts' relationship. The participation of aphantasiacs, subjects without the ability for mental visualisation (Clemens, 2018) as suggested by one of the experts, would be useful in discerning whether the visual process is in fact attributed to the idea of "mental visualisation", and therefore, fertile ground for further developments.

A fresher alternative perspective, a more direct method in response to the original question of developing a design system of lesser mediation, would involve the abstraction of the system's user's creative process through ANN. The more similar the process to the person based on EEG data, the more successful the system.

As theoretical explanations are undoubtedly abstractions of reality, Such theories formulate a strong basis towards building algorithms that are creative based on the mimicry of the human creative and imaginative process. Such theories can be found in recent compilations (Robinson, 2011; Singer, 2011; Mahadevan, 2018) transcribing various creative processes of different individuals through various lenses of theoretical abstractions. Machine-learning algorithms can then be developed to adopt that particular person's creative process. Another approach would also be to develop an ML algorithm learning more from a general outlook towards human creativity. Such instances can be found through revisiting of Vyshedskiy's *Mental Synthesis Theory* (2017), an algorithm

mimicking the ideas stored within the memory, and thereafter merged to formulate a new design type. The further addition of "Bayesian inference" (Kirchoff, 2017, p. 754) would formulate a model of brain visual perception, to abstract the brain's ability to perceive and interpret information. Bearing in mind, that for such incorporation into the current foundational BCI system, should the process be achieved, would have to take into account of the computational calculation cost, which had made several design ideas within appropriate given the context of utilised software. The developed algorithm, should it bear a resemblance to any ANN constructions, should be referred to as a Creative Adversarial Network (CAN) mentioned in *Imagination Machines* (Mahadevan, 2018, p. 2), a term to describe ANN mimicking the human creative process.

This process, can, of course, extend to the creative mental design process of other architectural designers, such as moving away from mere SOM formal analysis of 'masterpiece' architecture as found within *Trained Architectonics* (Algerciras-Rodriguez, 2016).

However, it is important to emphasise that these remain speculative until a pragmatic system is established; otherwise, the discussion would still remains hypothetical.

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Figure 64 (Author's Own): Further Interview Recruitment Posters

Figure 65 (Author's Own): Original Research Methodology Diagram:

Process based on Brain2Image research. The aim of this system is to develop a means of generating architecture through a process which would relate to the creative process. This is linked between the idea of perception as imagination, therefore, the act of reconstructing images using EEG signals, which are content captured whilst the brain is perceiving a content, act as a possible hypothesis, for this trained network used for people to generate visual contents alone, purely from their imagination.

An interactive Multi-user Mind-Sharing Experience can be Introduced... The question is how to segment which part a person could design... or a merging of both?

NEUROIMAGING ARCHITECTURE: FROM EEG TO VIRTUAL REALITY

FULL DESIGN METHODOLOGY (01/07/2018)

CLUSION.
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— 0/5 : Conclusion —

To conclude the research thesis, section reiterates the motivation which ensued the undertaking of this thesis. The aspiration, designing from one's mental imagination, is but a highly provocative and intriguing idea. Its supposed success would imply in theory, a more efficient design process, and a re-examination of the architectural design skillset. However, throughout this research, multiple gaps, as well as further refinement in the system's development, demonstrate that not only is the journey far and arduous, it would require a great deal of reflection and fine-tuning, before this aspirational method can take hold.

In reference to the design aims & objectives in section 0/1/3, the research had mastered the development of a Brain-Computer Interface (BCI) to design architecture through the real-time interaction of pre-existent design forms using brain activities through EEG in VR. The interactions are to manipulate geometries according to their attributes of scale, colour, position and orientation. Additionally, compelling graphical to communicate the project has been developed through a variety of media and format: slide presentations, videography large format posters and book.

It has also exceeded the aims & objectives set out within this project, extending beyond than just the construction of a foundational system. Such extension comprises the availability to design with three different interaction scenarios, designing architecture with static brain activities as well as the introduction of the 'bake geometries' functionality. Not to mention, as each of these interactions can be combined in varying successions to produce different design outcomes rich both formally and meaningfully. Besides, although the developed BCI-VR system is found to be less sophisticated in its technical capabilities and design strategies with other design systems in the O/2 Literature Review section, the system, to the best of the author's knowledge, is substantial in being the first functional BCI using EEG with VR to design architecture.

As with anything, impediments within the construction are unavoidable. For the BCI-VR constructed system, it was the system's high fragility, shortcomings in 'meaningful' data interaction, and a limited range of design intentionalities. These impediments, given greater resources, in time, labour and expertise shall be resolved, where all the solutions have been highlighted within the O/4/ Discussion section.

Through designing the BCI, the researcher had accrued technical knowledge to which can be implemented in designing this research original research intention, which would be the development of the architecture from the imagination. The actualisation of this speculative tool would implicate a revolution in how one regards the architectural discipline. Questions challenging the conventional understanding of architecture, such arise. To name a few, they could be along the line of "what is an architect's required skillset?", or "is architecture is but a consequence of neurological construction?".

Mindful Manifestation: from EEG to Virtual Reality

Figure 66, 67, 68, 69 (Author's Own): analogous conceptual drawings for developing a more sophisticated developed design based on the given current BCI's system formal

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List of Figures

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- **Figure 5:** Yeom, S.-K., Fazli, S., Müller, K.-R., & Lee, S.-W. (2014, November 10). The selected electrode locations of the International 10–20 system (29 EEG recording electrodes (black circles), one ground and one reference electrode (red circles) used in this paper). <https://doi.org/10.1371/journal.pone.0111157.g001>
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- **Figure 13:** Kavasidis, I., Palazzo, S., Spampinato, C., Giordano, D., & Shah, M. (2017). Brain2Image: Converting Brain Signals into Images. 1809–1817. <https://doi.org/10.1145/3123266.3127907>

Videos of Design Interactions

These are the links to the videos demonstrating the content in motion within this thesis

- **Video 1:** Figure 28 & 32: ARCI593 Design Experiment Video 1. (2019). Retrieved from <https://www.youtube.com/watch?v=UEqWZxDLZbg&feature=youtu.be>
- **Video 2:** Figure 35 & 37: ARCI593 Design Experiment Video 2. (2019). Retrieved from https://www.youtube.com/watch?v=aQ_daC2mH60&feature=youtu.be
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- **Video 4:** Figure 49: ARCI593 CNN Scaling. (2019). Retrieved from <https://www.youtube.com/watch?v=SJIV577Cqgw&feature=youtu.be>
- **Video 5:** Figure 51: ARCI593 Self Organising Maps (SOM) & EEG. (2019). Retrieved from <https://www.youtube.com/watch?v=AeZ0J8VAIGA&feature=youtu.be>
- **Video 6:** Figure 60 & 61: ARCI593 Grasshopper & UnityVR Experience. (2019). Retrieved from <https://www.youtube.com/watch?v=VVUS-VjOq6g&feature=youtu.be>

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