Title
A Reactive Brain Computer Interface: a novel sonification and visualization approach evoked by illusions

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Publication Date
2021

Peer reviewed|Thesis/dissertation

University of California
Santa Barbara

A Reactive Brain Computer Interface: a novel sonification and visualization approach evoked by illusions

A dissertation submitted in partial satisfaction
of the requirements for the degree

Doctor of Philosophy
in
Media Arts and Technology

by

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Dedicated to my ancestors.

Acknowledgements

Writing this dissertation has been a tough, but satisfying journey filled with fascinating and at times incredibly frustrating problems. Through it all, I knew I could count on the support of friends and colleagues. I am first and foremost indebted to my advisor George Legrady. I am grateful for his support and for the times he helped me finish papers and proposals before deadlines. More than anything, I'm grateful for the confidence he placed in me and offered me the freedom to explore a subject that I am very passionate about. I am also thankful to Alenda Chang, Tobias Hollerer and Andres Cabrera for serving on the committee and giving me lots of feedback. Thanks to LaNette Lee for reading my papers and providing feedback. A special thank you goes to Marko Peljhan for stepping in to save the day many times. I would also like to thank my colleagues Gustavo Rincon and Mert Toka for always willing to help in any way, shape or form. Also thanks to Sihwa Park, Susie Green and Tornike Karchkhadze for their invaluable contribution to the projects and research. Thank you to all those who participated in my experiments. I am also deeply grateful to my Mom for her support throughout this journey.

Curriculum Vitæ

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Publications

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Mathew, M (2020). A Reactive Brain Computer Interface: a novel sonification and visualization approach evoked by illusions. Leonardo Abstract Service (LABS).

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Mathew, M., Cetinkaya, M., & Roginska, A. (2017). BSONIQ: A 3-D EEG Sound Installation. Georgia Institute of Technology.

Mathew, M., Grossman, J., & Andreopoulou, A. (2016). Women in audio: Contributions and challenges in music technology and production. In Audio Engineering Society Convention 141. Audio Engineering Society.

Exhibitions

IEEE Visap 2020, Virtual event.
Visum: beyond the physical eye (2020) - Installation

Altered Festival 2020, Chicago IL.
Visum: beyond the physical eye (2020) - Installation

Selected Compositions (public performance)
The Explorer (2019): Performed at the Diffrazioni Festival. (Italy)

Caminando (2015): Performed at the Center for research in Electronic Art Technology(CREATE) Concert 2018. (USA)

Abstract

A Reactive Brain Computer Interface: a novel sonification and visualization approach evoked by illusions

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The Brain Computer Interface (BCI) as a communication method has become very popular in the past several decades. This type of technology has also become more active in Human Computer Interaction for multimodal interaction and research. This research explores the intersection between art and neuroscience primarily from the perspective of a Media Artist. Neural activity generates electric and magnetic fields in the human brain and an Electro-encephalogram (EEG) device captures this activity. The captured neuronal activity can be used to control an application or environment. Reactive BCIs measure changes in a person's brain activity from external stimuli that someone needs to focus on.

BCI technology can give us a useful entry point into examining how biological data can create the aesthetic attributes of our personal and biomedical information and the significance communicated by an artwork that has a technical interface as an essential component. By embracing BCI technology as a methodology and using it in art practice, makes this type of work visible to a public that has little direct contact with the works of scientists. The scientific precision of artistic BCI has been scrutinized, but the key value of artists' use of this technology lies in the exploration of the emotive and educational impact of these types of technologies.

This research looks into the effects that art may have on the brain, looking into visual illusions also known as optical illusions. Optical illusions are distortions of the senses, which are caused by the visual system. Visual perception is the brain's ability to make sense of what the eyes see. Electroencephalography (EEG) is a non-invasive method used to measure and evaluate the electrical activity in the brain. Very few visual perception studies explore the link between neuroscience and the arts. Visual processing in the brain creates several types of visual evoked potentials (VEP) in our brainwaves. A VEP is an evoked potential caused by a visual stimulus, which is measured by the electrical response of the brain's primary visual cortex to a visual stimulus.

Another goal of this research is to develop a novel expressive interface using visual perceptive EEG data to create a computational language, that is, come up with a framework by converting VEP data into objects through specific algorithms and mappings that will provide sonic and/or visual output of this neurofeedback information. This is done primarily from an artist/composer (Art) standpoint using cognition and perception (Science). The proposed program utilizes brainwave data, by using VEP features triggered by optical illusions to manipulate audio/visuals. The research project exposes some significant considerations in the use of BCI technology for artistic purposes, like how to precisely collect and process EEG data aesthetically, as well as what license can be used with the data in order to create meaning or an environment for the audience themselves to bring meaning to the artwork. The interest lies in exploring how visual perception can inform and offer new forms of expression.

This dissertation looks at artistic explorations and narratives that result in the analysis of BCI data, drawing on insights from the fields of cognitive neuroscience, neurofeedback, biology, Brain Art and Op Art. It also presents a novel approach in creating media artworks using VEP features and multimodal interaction to explore visual and sonic output. It also documents development of Visum and Aspecta, two BCI artworks by concentrating on the conceptual design, approach, methods and challenges.

The overall goal is to offer pathways within the field of human computer interaction by creating art using visual sensory based methods of interfacing with computer systems that aim to amplify human qualities by creating art with them.

Contents

List of Figures

List of Tables

Part I

Chapter 1

Introduction

"The body is our general medium for having a world."

Maurice Merleau-Ponty

1.1 Motivation

Our biological output tells us something about what is going on in our bodies. These body functions could be heartbeats, muscular or cellular activity, or brainwaves. Any information within our body may be shown through biofeedback. Thus, these biological outputs or feedback can provide a way for us to understand our physical processes and explore personal narratives we use when articulating our own sensations. Brainwaves can tell us a lot about a person's mental state, physiological functions, etc. Can it tell us about how a person perceives an image or an optical illusion?

A Brain-Computer Interface (BCI) is useful in providing neurofeedback to the user or audience. Optical illusions give us insight into how the brain works. They can use patterns, light, and color that create images, which can be deceptive to our brains and reveal mechanisms of (Bach and Poloschek, 2006). Optical illusions occur because our brain is trying to interpret what we see and make sense of the world around us. Many artists use visual perceptive illusions in their works, for example, by applying specific colors to create a visual effect. Other artists have created optical illusion art or Op Art.

Most VEP research remains within the clinical or science world to diagnose vision issues such as retina/optic nerve issues. VEP research based on optical illusion stimuli has mostly been unexplored. VEP identification questions based on optical illusion have become a motivation to integrate science and art and become the focus of this research. The optical illusion phenomenon causes one to question if they are seeing what they think they are seeing.

Artistic approaches to the manipulation of visual perceptive data have the potential to give us insight into how someone perceives the illusion of art. In the media art fields, not many artworks have explored visual evoked potential data in an artistic context. This brainwave data can represent an individual's unique experience or temporally generated changes as input data in the BCI system. Most artworks involving EEG take the real-time output of a device and map it to sound or visual. Raw EEG signals contain a very high signal-to-noise ratio, which does not provide the most accurate data. Therefore, a media arts audience or BCI system user would not necessarily achieve the highest accuracy or output in creating art or system responsiveness.

As a media artist, I am very interested in manipulating and analyzing neural feedback data, so I can explore the different experiences of individuals based on their VEP data while learning about this process. The observer of the optical illusion becomes the observed. Vision information transformation is the primary goal of the artistic creation process in this research. Therefore, the main objectives of this research serve two purposes. The first is to investigate narratives created based on VEP data obtained through scientific methods and explore how this data can create a link between art and science by causing the latter to become intertwined with an artwork.

The second is looking from the media arts perspective. I believe that a sonification and visualization of VEP data can be a novel way of creating a person's expressive sonic and visual identity based on how they visually perceive. Signification is very good at handling complex information and triggering emotions. VEP data is converted to sound and visual objects, which will allow the audience to create compositions with them interactively.

1.2 Research Question/Problem Statement

Thesis Statement:

Visual stimuli can evoke activity in the vision center of the brain that can be recorded non-invasively. In science, our visual process is measured through visual evoked potentials at the occipital(image detection), and parietal lobe(image reaction/perception), which are changes in brainwaves after a stimulus is presented to an observer. Neuroscientific methods such as EEG data processing and averaging need to be applied to extract specific visual activity. A variety of information can come out of the sonification and visualization of this neurophysiological activity. Interactive or expressive interfaces can provide a creative environment of such data into audio/visual narratives. In this research, interfaces are proposed to create an artistic environment that uses visual evoked data based on optical illusions and examines narratives that can come out of the VEP data. It provides novel ways to create interactive BCI artworks using Gestalt principle models applied to the data with neuroscientific analysis and multimodal interaction.

BCI technology has been instrumental in non-verbal communication and assistive technology domains. With regards to using this technology for artistic performances, be it as an observer or artist, voluntary or involuntary evoked EEG can play a role in the process of creating, interacting, and experiencing artworks. Active, passive, or reactive paradigms can all be used in Brainwave performances. BCI can make a piece of art come alive and according to Nijholt (2019), the interactive changes could be virtual, real-time, or "off-line, that is, BCI experiences can be collected and used to decide about changes later, whether done by the artist or by the (digital) art itself".

What do BCI artists do?

In the Biofeedback Art fields, artists usually implement feedback systems that use bio data, using active paradigms and subjectivity in the artistic experience. BCI artists usually acquire signals in real-time and apply some mapping strategy to the signal for an audio and visual output.

VEP collection is an offline process since it involves trial segmenting and averaging the EEG data. VEP used in artworks very unusual. The research could embody the background research activity on which the artistic works are then created by exploring the challenges in retrieving visual evoked potential (VEP) data triggered by optical illusion stimuli and by doing this using scientific methods. The following questions could be asked:

- How can this VEP data provide a suitable platform for audio/visual output?
- Can a unique personalized and educational experience (interactive) or narrative be created for the audience?

This research aims to provide answers to these questions by designing mappings and algorithms as well as creating artworks based on them. This dissertation also looks at creative explorations discovered through illusion visual perception data, drawing on insights from several related fields and contributes new ways of creating a computational artwork based on data analysis and extraction. VEP data is unique, which means that it can create individually genuine and unique output for each user. Additionally, the process involved and narratives behind the VEP data features are very important aspects of this dissertation.

The Media Arts part of this dissertation project contains both a sonification and visualization element. The artworks will construct an aesthetic experience by using VEP feature analysis and data sonification and visualization based on scientific methods. An experiment is conducted to investigate the optical illusion visual perception process by having subjects look at different optical illusions while their brainwaves are recorded. Through this investigation, new avenues for further research can be suggested.

It is very rare to find prior works or research that involves the transformation of VEP data into audio and visuals using both artistic and scientific methods. In science research, in-depth analyses have been conducted on VEP data patterns, particularly Steady-State Visual Evoked Potential (SSVEP) and motion-onset VEP. However, a sonic or visual approach to using illusion-based VEP has never been used in the media arts context before.

The main contribution to this research is not just the building of an expressive system, but also the construction of models based on existing science, i.e., using models and placing them on top of the data. Therefore, this research is a novel approach for both VEP Sonification and Visualization.

1.3 Methodology

This dissertation will develop a computational/media artwork derived from scientific methodology to investigate the afore-mentioned questions regarding using VEP data. The artworks created in this dissertation are based on a reciprocal relationship between scientific research and media arts. Working with illusion-based VEP data requires a lot of knowledge such as cognitive neuroscience, biology, and BCI Art. Prior works in BCI, VEP scientific methods, and data analysis such as those conducted by (Creel, 2019) and sonification/visualization mapping strategies and aesthetics are discussed. In (Zeki, 2002); (Chatterjee, 2011) there is a parallel comparison made between nervous system functions and artistic explorations. In (Zeki, 2002), it also states that "no theory of aesthetics is complete without an understanding of its neural underpinnings". It should be noted that having expert scientific knowledge as well as good technical skills will not necessarily create great artworks. In-depth analysis and interpretation of the VEP data are necessary, and getting the ideal VEP signal is not guaranteed. Besides VEP data analysis, the in-depth analysis and understanding of the context and any VEP correlations are important. The proposed system's output will vary individually, which is linked to the subject's cognitive interpretation of the stimuli.

This research is specifically multi-disciplinary, looking into concepts of cognitive neuroscience, digital signal processing, HCI, data sonification, and visualization. A practical incentive to this research is to develop a new application/tool using BCI methods and transform them into creative output, which could be used in an interactive setting. Every user or observer of the application will have a unique experience. This dissertation presents a reactive BCI development through research, design, mapping strategies, and undertaking user experiments and evaluation. The system will be evaluated to test for accuracy and responsiveness.

1.4 Dissertation Structure

This dissertation attempts to investigate the representations used to intersect visual perception with an arts-based practice. Working in both auditory and visual modalities, this research's approach is to first build a conceptual understanding of how humans visually perceive and interact with the world. This framework will serve as an inspiration for the development of BCI artworks. These BCI artworks will be developed better to understand a computational model's challenges and accomplishments while opening a discussion around the nature of visual perception and human-computer interaction. Since designing a computational model revolving around any human perceptual system is a huge task, this research aims not to represent visual processing accurately but rather to focus on certain visual perception aspects. The approach here is to work from psychology, attempt to model aspects of the theory, and subsequently develop the arts practice to inform the theory and modeling.

There are eight chapters in this dissertation. Since it intersects art and science, it is divided into two parts. The first half covers the science background, including the brain and eye anatomy, history, and evolution of BCIs, EEG, previous artistic BCI works. The second half defines the artistic implementation through methodology, sonification and visualization strategies, system design, and evaluation. Chapter One describes the motivations and problems that led the author to investigate the topics in this dissertation. Chapter two delves into the background and evolution of BCIs, EEG, and VEP data analysis. Chapter Three covers visual perception. Chapter Four presents prior works in BCI and Art, including the author's own works in BCI sonification. Chapter

Five describes the methodology, artistic investigation, and mapping strategies in visualization and sonification and describes the development, framework, challenges, and strategies applied in the main artworks "Visum". Chapter Six presents the design and implementation of the BCI artwork "Aspecta". Chapter Seven covers the evaluation of Visum as well as Aspecta. Chapter Eight discusses the results and future works of this research.

Chapter 2

Background

> "Anything that could give rise to smarter-than-human intelligence - in the form of Artificial Intelligence, brain-computer interfaces, or neuroscience-based human intelligence enhancement - wins hands down beyond contest as doing the most to change the world. Nothing else is even in the same league."
>
> Eliezer Yudkowsky

Brain-Computer Interfaces have grown in popularity for the past several decades. They are used in both the clinical and artistic domains. This research uses a BCI for artistic output, and thus, this chapter presents a historical overview of BCIs. Brain-computer interfacing (BCI) is research or a system that captures a person's brain activity and uses it to control an environment or an application (Nijholt, 2019) or communication device. In these systems, users can explicitly manipulate their brain activity instead of using motor movements to produce signals that control computers or communication devices tan. It is also possible for a user's brain activity to be monitored to determine his/her mental state. Mental states can be translated into changes in a user's environment to better adjust to this particular mental state or change this mental state citepnijholt. BCI has also become a popular tool in advancing assistive technology, especially for those with severe physical disabilities, where control requires restricted or no motor abilities. The use of BCIs and the control of brainwaves is not anything new. Joseph Kamiya was among the first to conduct experiments and report voluntary alpha wave control discoveries in the 1960s (Kamiya, 1968); (Evans, 2002). However, it was not until decades later that BCI and its applications would become a reality through digital technologies' advancements. Jacques Vidal wrote a paper in 1973 that today is considered to be the beginning of BCI research (Vidal, 1973); (Nijholt, 2019). Interest, however, in BCI research faded during that time, and Vidal's paper did not impact the field during the late 1970s to 1990. The methods involved in brainwave behavior control can be divided into two categories, active and passive control. Active control refers to when a user exerts explicit control over his/her brainwave functions, typically by performing mental focusing tasks or attending to an external stimulus. This allows a user to exert control over a BCI system's output parameters. External stimuli for generating active BCI control are usually either visual, haptic, or auditory. Three of the most popular active BCI methods are the Steady State Visual Evokes Potential (SSVEP) response, the P300 response, and motor imagery. Passive control plays an essential role in systems that detect subconscious EEG patterns for control purposes (Eaton and Miranda, 2014), discussed in later chapters.

2.1 Brain-Computer Interface Categories

Neural or brainwave activity in our brain creates electric and magnetic fields and blood flow changes in our brain. These activity changes, which can be measured, also give information about the particular area involved in the brain. Different brain lobes or regions have other functions, which provide information about the cognitive and motor functions involved (Nijholt, 2019). Brain activity can either be voluntarily or involuntarily activated, i.e., endogenous or exogenous activation. The different brain areas show involuntary neural activity related to the senses, such as feeling, seeing, hearing, touching, and tasting. Affects such as excitement, frustration can also involuntarily create changes in our brain activity.

BCI research can be divided into active, passive, and reactive BCI (Zander et al., 2014). There may also be some overlap between them (Nijholt, 2019).

- With active BCI, a subject can manipulate his or her brain activity to issue commands to a brain-controlled device (Nijholt, 2019); (Zander et al., 2014). For example, a subject can meditate or relax his/her mind to evoke specific brainwaves. This subject can pretend to be angry to create an emotion imagery. If successful, this will show up in the subject's brain activity. Imagining body movements (e.g. hand/leg movements) can be detected by electrodes that acquire signals, in this example, from our motor cortex. These types of signals can control a wheelchair (Galán et al., 2008) an application or device (Graimann et al., 2009) like a robotic arm orthosis, which can assist in eating or drinking (Looned et al., 2014) and control a writing or spelling application (Perdikis et al., 2014); (Steinert et al., 2019).

- For reactive BCI, an application usually generates stimuli for the subject to focus on, which then activate changes in a subject's brain activity. This brain activity is modulated in reaction to an external stimulus given by the BCI system (Höhne et al., 2011); (Steinert et al., 2019). The subject needs to pay attention to and choose from artificially evocative stimuli (Nijholt, 2019). While doing this, their brain emits information about what they perceive. A stimulus is typically presented visually on a computer screen. It can sometimes be in the form of an auditory, haptic, or smell and taste stimulus. The user does not have the explicit task to control the application. A commonly used paradigm is P300-based selection, where stimuli, such as letters or symbols, flash in succession on a screen. It is further discussed in section 2.3. Using selective attention can create a range of controls, such as writing emails to control a TV (Sellers et al., 2010). P300 controlled systems enable locked-in patients to create artworks (Holz et al., 2015); (Steinert et al., 2019).

- With passive BCI, the subject is neither actively manipulating his/her brain activity nor looking at an external stimulus. The brain activity is measured and used to make changes to the environment or application. The user is monitored while performing a task. The user behaves in a natural way, not differently from not having his or her brain activity being measured (Nijholt, 2019). A popular application of passive BCI is monitoring a user's mental, e.g., arousal and workload. The passive BCIs can alert the user of dangerous situations at home or in the workplace by detecting lapses in attention (Martel et al., 2014). Passive BCI can improve human-computer interaction (Zander et al., 2014). For example, the system might adapt a task to be performed when a particular mental state is detected (excitement, frustration) by increasing or decreasing the difficulty level or by introducing more engaging elements (Steinert et al., 2019); (Mühl et al., 2014).

To summarize, users of active and reactive BCIs are usually expected to know about their role in controlling the system. This means voluntarily evoking specific brain activity or voluntarily paying attention to external stimuli, which evoke brainwave activity changes. A subject's active and reactive BCI performance depends on his/her mental state. Therefore, understanding a subject's mental state helps in interpreting active and reactive BCI communication and control. For the active BCI, a user has to actively control his or her brain activity through some mental process. With the reactive BCI, a user has to pay attention to stimuli presented, which lead to measurable changes in his/her brain activity. For the passive BCI, the user is not aware of being measured at all. There are several other ways a user's brain activity can be translated into intended communication and control commands. For example, in clinical BCI research environments, the typical paradigms used are motor imagery (active BCI) as well as event-related and evoked potentials (reactive BCI) (Nijholt, 2019). This research focuses on the latter, visually evoked potentials, covered in more detail later in this chapter.

2.2 Detecting Brainwaves

This section will cover the fundamentals and background of brainwaves and how to interpret them.

2.2.1 Introduction to Electroencephalography (EEG)

Recording brain activity in humans using electrodes attached to the scalp began with Hans Berger's experiments (1873-1941) in the early 1920s (Lutters and Koehler, 2016). Before that, these types of recordings had been done on the brains of animals. While recording brain wave patterns, Berger noticed that they were repetitive or rhythmic with a specific amplitude. These repetitions are measured in Hertz (Hz), where 1 Hz is one cycle per second. Berger discovered alpha waves (approximately 8-12 Hz) and distinguished them from other activity. He conducted experiments with subjects who were in a wakeful mental state. This way, he distinguished "alpha waves from waves with a higher frequency and smaller amplitude, the beta waves." Berger also noticed that Alpha activity usually increased when a subject closed his/her eyes. Beta activity increased when a subject opened his/her eyes. The most substantial alpha waves can be observed in the occipital lobe, which primarily deals with vision processing. Beta activity, when our attention is directed towards the outside world, is between 13 and 25 Hz and is most evident in the frontal lobes (Nijholt, 2019). Figure 2.1 further details the brainwave bandwidths and associated mental states.

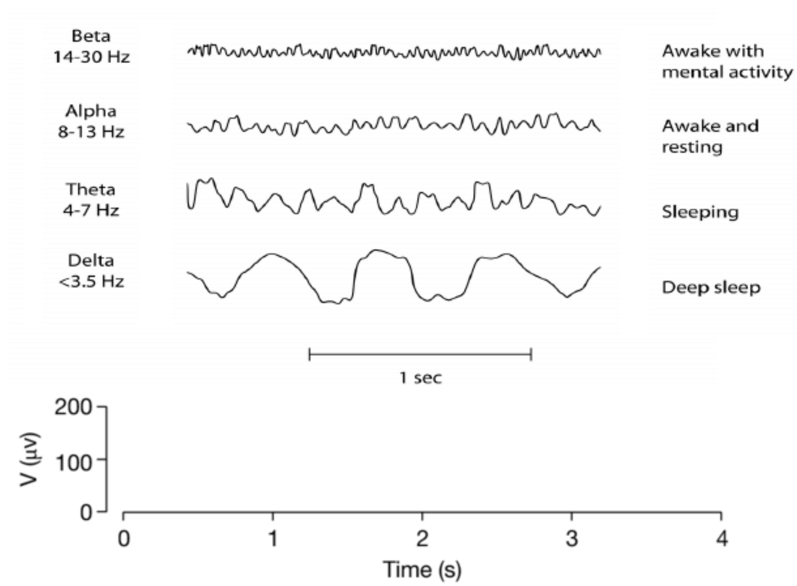


Figure 2.1: Brainwaves and associated mental states

2.2.2 Measuring EEG

It is essential to know where and when specific brain waves operate and dominate. How is brain activity measured in the various regions of our brain? The most common non-invasive methods used in laboratories involve electrodes placed on the scalp. The number of electrodes may vary; however, each of them provides brain activity information detected from different areas of the brain. Different brain areas are associated with different functions. Therefore, where electrodes are placed is very important. The non-invasive methods do not require surgery, that is, placing electrodes either on the surface of the brain itself or inside the brain. Methods like these require surgery to place electrodes under the scalp and are referred to as electrocorticography (ECoG) and intracortical measurement of brain activity (Nijholt, 2019). Electrical activity is recorded as a time-based signal by the EEG device. This makes it possible to study signal changes as a function of time or carry out spectral decompositions of the signals by looking at their frequency components and evolution over time. Since electrical activity is captured by several electrodes positioned over the scalp's surface, it is possible to view the spatial distribution of this activity and topographical changes over time (EEG, n.d.). Head shape and hair could be a disruptive factor depending on the headset's design (e.g. Emotiv Epoc). EEG devices use water (saline solution) or conductive gel to make the 'wet' electrodes work to more effectively pick up the brain's signals. Recent developments in EEG technology have also made it possible to use 'dry' electrodes that do not need gel and are faster to apply.

2.2.2.1 EEG Sensor Placement

Detecting brain signals, analyzing them, and extracting the relevant information is at the core of BCI research. Detecting, analyzing and extracting requires advanced methods of signal analysis, machine learning, and pattern recognition (Nam et al., 2018); (Lotte, 2014); (Nijholt, 2019). There are also other methods available that measure brain activity changes. A functional magnetic resonance imagining (fMRI) scanner detects changes in blood flow associated with neural activity. It has a high spatial resolution and low temporal resolution in comparison to EEG devices. The international 10/20 system has been the standard for electrode placement used in electroencephalography (EEG) for over 60 years. This system describes head surface locations via relative distances between cranial landmarks over the head surface. The primary purpose of the 10-20 system (Jasper, 1958); (Homan et al., 1987) was to provide a reproducible method for placing EEG electrodes over different studies, and‘ there was little need for high spatial resolution and accurate electrode placement (Jurcak et al., 2007). This has made the 10-20 international system a standard naming and positioning scheme for EEG applications. “It is based on an iterative subdivision of arcs on the scalp starting from craniometric reference points: Nasion (Ns), Inion (In), Left (PAL), and Right (PAR) pre-auricular points (Fig. 2.2 A). The intersection of the longitudinal (Ns-In) and lateral (PAL-PAR) is named the Vertex” (BCI2000, n.d.).

The original 10-20 system only included 19 electrodes (Figure 2.2 - B). Extensions were subsequently proposed to include over 70 electrodes in standard positions (Figure 2.2 - C). The extension also renamed four electrodes (indicated in black); the original names were: T3, T5, T4, and T6 for T7, P7, T8, and P8, respectively. One of the electrodes located in these positions is used as the reference channel, which is usually the ear lobe or mastoid (BCI2000, n.d.).

Odd numbers refer to the electrodes placed on the left hemisphere and even numbers on the right. A1 and A2 are on the ears. Z indicates midline electrodes.

F = frontal

C = central

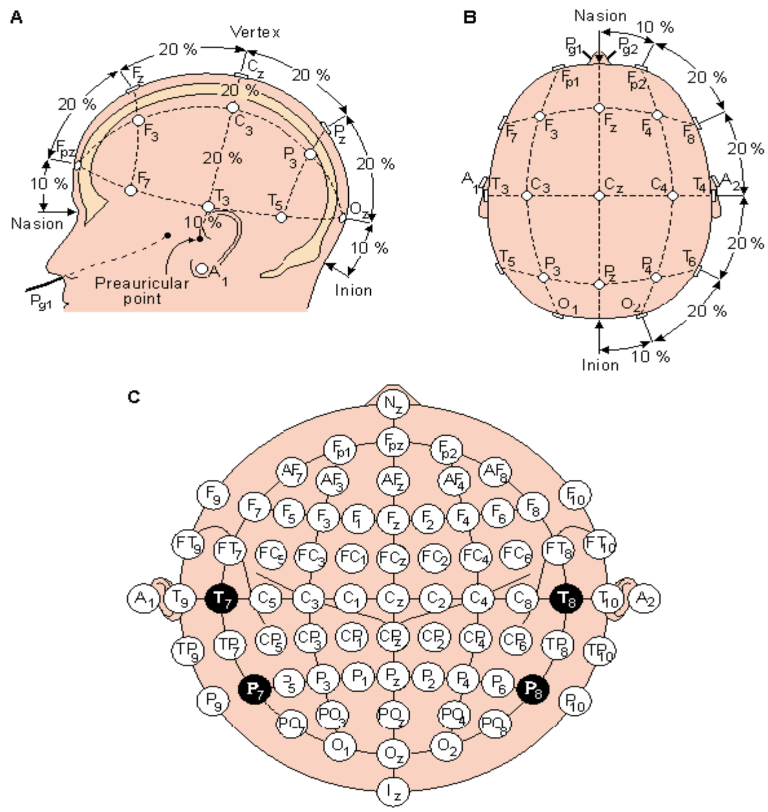


Figure 2.2: Layout of the EEG sensor placement is based on the 10-20 international system.- Credit: BCI2000.org

T = temporal

P = parietal

O = occipital

A= Auricle

To summarize, EEG allows for the measurement of electrical activity related to neuronal firing in our brain. Further analysis of the measured and filtered brain activity towards a specific goal can eventually “tell us or the application about an underlying aim” (Nijholt, 2019). The aim is achieving a particular mental state, brain damage, or body movement.

2.2.3 Issues When Measuring EEG

Recording low voltage electrical signals can produce issues, especially when looking for specific patterns inside the broader EEG activity. EEG signals can contain elements (e.g., artifacts) that can overlap within the particular target areas under investigation. Interference from conflicting brainwave patterns can also cover up the amplified target signal, for example, the visual evoked potential (discussed in detail in section 2.5.5.1 in this dissertation). Additionally, electrical noises (60Hz USA/50Hz other countries) from nearby powered machinery can also contribute to artifacts in the signal. Correct electrode setup and good contact for an optimal measuring environment are essential in acquiring a good signal. This increases the signal-to-noise ratio (SNR). The impedance of electrodes provides a measure of the quality of the contact. The higher the impedance of an electrode equates to smaller signal amplitude (Eaton and Miranda, 2014).

2.2.4 EEG Signal Processing

Raw EEG needs to go through specific processes for the data to be usable. Filtering is usually applied to remove noise and artifacts from the data. Other methods may involve feature or frequency extraction.

2.2.4.1 Filtering

The EEG signals are subject to noise and artifacts, such as eye blinks or muscle movements. Noise in EEGs, however, may be reduced using appropriate filtering methods. The EEG signals contain neuronal information below 100 Hz (in many applications, the information lies below 30 Hz), such as with the VEP. Frequency components above these frequencies can be removed by using a Lowpass filter. If the EEG data acquisition system is unable to cancel out the 50 or 60 Hz line frequency, a notch filter is applied. However, the characteristics of the internal and external noises affecting the EEG signals are often not known. The noise may be characterized if the signal and noise subspaces can be accurately separated.

2.2.4.2 Segmentation

Segmentation is the extraction of a signal between a particular start and end times. In this project, the data were segmented into 500 ms post-stimulus segments. Each image was presented five times in a non-consecutive fashion.

2.2.4.3 Trial Averaging

The segments were averaged to extract the VEP signal. EEG segments contain a lot of noise and mask the Evoked Related Potentials (ERP) signals. These are brainwave activity changes that occur post-stimulus, in this case, visual stimulus. ERPs are discussed in more detail in section 2.2.6. VEP waveforms are extracted from the electroencephalogram (EEG) through signal averaging, which adds electrical activity for specific periods (Odom et al., 2004). The averaging helps eliminate the noise contained in the EEG signal, leaving the visually evoked potential.

2.2.5 Interpreting EEG Signals

EEG signals are usually interpreted by associating them with mental states (Fig. 2.1). For example, brainwaves ranging from 8-13Hz are classified as alpha waves and are associated with a relaxed, eyes open mental state.

2.2.6 Evoked Potentials

Evoked potentials (EP), also referred to as an evoked response, is a potential in a specific pattern recorded from a specific part of the nervous system, especially the brain following the presentation of a stimulus such as a pure tone or a flash of light. Different types of potentials can result from stimuli of different types. EP is distinct from spontaneous potentials as detected by EEG or another physiologic recording device. EPs' amplitudes tend to be low, ranging from less than one microvolt (mv) to several microvolts, compared to tens of microvolts of an EEG.

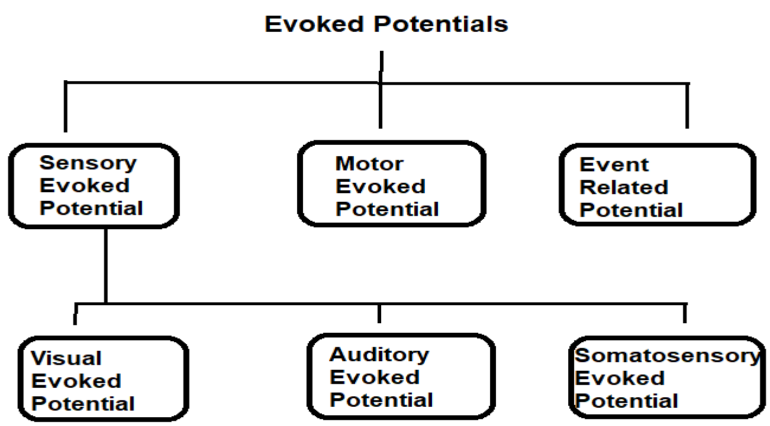


Figure 2.3: Evoked Potentials Classification

2.2.6.1 Visual-Evoked Potential (VEP)

The primary components of this research are the Visual Evoked Potentials (VEPs). These are cortical electrical potentials created by short visual stimuli that are recorded from the scalp overlying the visual cortex (Creel, 2019). These potentials are relatively large, positive polarity wave generated in the occipital cortex (Drislane, 2007). The terms visual evoked potential (VEP), visual evoked response (VER), and visual evoked cortical potential (VECP) are used interchangeably. The VEP measures the time that it takes for a visual stimulus to travel from the eye to the occipital cortex (VEP, 2017); (Odom et al., 2004) as well as to measure the functional integrity of the visual pathways from Retina via the optic nerves to the visual cortex of the brain, revealing any abnormalities in the visual pathway. Of primary interest is the latency of the positive wave at a midline occipital EEG electrode (discussed further in the next section), usually at about 100 ms, also referred to as the 'P100' post-stimulus (Drislane, 2007). VEP research also goes back to the 1930s, and VEPs were first noticed when a strobe flash created activity in the EEG. VEPs have been used quite often to study motion processing (Pitzalis et al., 2012).

2.2.6.2 VEP Sensor Location and Placement

VEPs evoked by flash stimuli can be recorded from many scalp locations in humans. Clinical VEPs are usually recorded from the occipital scalp. As previously noted, a standard EEG sensor placement system is the 10-20 International System, which is based on head size measurements (Jasper, 1958); (Creel, 2019). The mid-occipital electrode location (Oz) is on the midline. The distance above the inion is calculated as 10% of the distance between the inion and nasion (Fig.2.2). The inion is the most prominent projection of the occipital bone (Fig. 2.4) at the skull's lower rear part. According to (Creel, 2019), lateral occipital electrodes are a similar distance off the midline (Oz). VEP signal generators are not clearly defined. It is, however, suggested through various multichannel scalp recordings and visual MRI activity that the visual cortex is the source of the early components of the VEP (e.g. N1) prior to P1 (P100) (Slotnick et al., 1999). N1 is the first major negative deflection post-stimulus (see Fig. 2.5).

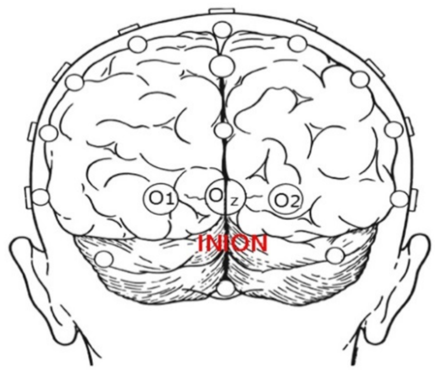


Figure 2.4: VEP Sensor Placement - Credit: Webvision.med.utah.edu

2.2.6.3 Recording Methods for VEP

Since EEG recording involves the use of electrodes, the reference electrodes' role will briefly be discussed. Reference electrodes are normally placed on the forehead, on the midline on top of the head, or the earlobe. A ground electrode can be placed at any location on the scalp, earlobe, or mastoid. The period analyzed for VEPs is usually between 200 and 500 milliseconds post-visual stimulus. The most common Bandpass frequency limits are 1 Hz and 100 Hz for VEP research. The visual stimuli that are commonly presented are strobe flashes, flashing light-emitting diodes (LEDs), transient and steady-state pattern reversal, and pattern onset/offset (Creel, 2019). Details on the placement of the electrodes in this research will be discussed later in this dissertation.

2.2.6.4 VEP Components

VEP components are peaks in the brainwave that occur post-stimulus. They usually have a prominent negative component at a peak time of approximately 70-75 ms (N1, a larger amplitude positive component at about 100 ms (P1), and a more variable negative component at about 135-140 ms (N2). The major component of a VEP is the large positive wave peaking at about 100 milliseconds, referred to as the "P100" or "P1". It tends to be very reliable between individuals and steady from about age five to sixty years (Creel, 2019). The "P300" or "P3" component, is an event-related potential (ERP) (Fig. 2.5) elicited in the process of understanding or decision making. It is considered to be a person's reaction to a stimulus. To be more specific, the P300 is thought to show processes involved in stimulus evaluation or perception (P300, n.d). When recorded by EEG, the P300 shows up as a positive deflection in voltage with a latency, that is, a delay between stimulus and response at approximately 250 to 500 ms. This signal is usually measured most strongly by the electrodes covering the parietal lobe (P sensors).

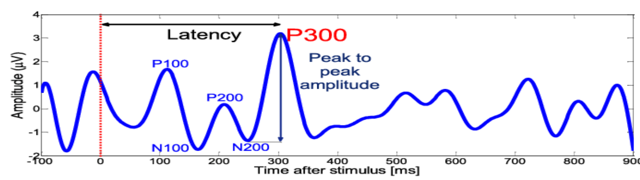


Figure 2.5: Event Related Potential Components

2.3 Popular BCI Paradigms

There have been many advancements in BCI research at the end of the last century and the beginning of the new one, where new BCI paradigms came into play. In clinical BCI research, the main paradigms for user's brain waves to be translated into intended commands for communication and control are motor imagery (active BCI) and event-related and evoked potentials (reactive BCI) (Nijholt, 2019).

SSVEP

Steady-state visual evoked potentials (SSVEPs) are paradigms that use light or object oscillating at a certain frequency. This oscillatory EEG activity's frequency is synchronized to that of a flickering visual stimulus, on which the user focuses. Using several stimuli, each with its own specific flickering frequency, the SSVEP response to each of them can be used to issue a specific BCI command (Nam et al., 2018), such as having a computer application do a particular task.

P300 Oddball

The oddball paradigm is a commonly used task for cognitive and attention measurement in ERP experiments. This is when subjects are shown several images or sounds. When the stimulus of interest presents itself (oddball) after an average of 300 milliseconds after this novel or "oddball" event, a positive deflection of voltage in the EEG (Nijholt, 2019) occurs across the parietal lobe. This P300 is useful for communicating via the computer like typing. Letters could be selected using this paradigm or notes to compose music.

Motor Imagery

Motor imagery (MI) has to do with body movements. Imagining body movements from the beginning to the end of the movements can lead to changes in the alpha (8-12 Hz) and beta frequency bands, measured in the motor cortex. These changes are referred to as event-related synchronization (ERS) and event-related desynchronization (ERD) (Nijholt, 2019). In conjunction with other cognitive tasks, this motor imagery approach can be used to control, for example, a cursor on a computer screen or a wheelchair without using the actual body.

2.4 Ethics and Privacy in BCI Research

Large amounts of brain data are being generated from research participants, including subdural, intracortical, and extracranial sources. Brain data are a vital resource for brain-computer interface (BCI) research. However, concerns have been raised about whether the collection and use of these data generate privacy risks. Besides, the nature of BCI research involves understanding and making inferences about device users' mental states, thoughts, and intentions (Klein and Rubel, 2018). Some assumptions explain the reasons why privacy in BCI research and development has not been addressed more extensively. First, there may be an implicit assumption that clinicians, researchers, and policy-makers lose privacy or increased risk to privacy is necessary or a trade-off for developing devices with enormous potential for health benefits. The possibility of a BCI device that would allow someone with locked-in syndrome to speak or someone who is quadriplegic to control a robotic limb is compelling and might seem to make privacy concerns trivial in comparison. Second, more BCI data are collected than is currently interpretable (Nijholt, 2019); (Finn et al., 2013). Until more is known about the information in BCI data, privacy concerns would seem premature (Hallinan et al., 2014). Third, implantable and non-implantable BCI research with human research participants takes place within academic institutions that have strict data protection policies and informed consent regulation that requires seeking prior consent or authorization of participants; this may lead some to believe that privacy risks are already addressed. This certainly applies to the research conducted in this dissertation, which also involves a human subject experiment conducted at a University.

2.5 Chapter 2 Discussion

The evolution and applications of BCI technology were presented. BCI technology is at the core of this research. Of the several types of BCIs, the reactive BCI paradigm is used in this research. Many references in this dissertation are made based on BCI technology and VEP, as well as understanding the basic theory of VEP is very important. The data explored in the BCI artworks developed in this research follows the scientific method of VEP data retrieval and explains why the data is collected the way it is. EEG is one of the most challenging biosignals to interpret mainly because human factors such as mental state, head size, equipment issues, etc., can affect the EEG and its interpretation. Besides that, EEG signals are also very noisy, requiring a lot of preprocessing. BCIs technology, however, has still improved over the years. Even though the BCI's primary function has been to help those with physical disabilities, some believe that BCIs will become more critical in our daily lives for even those who do not have any disability. Even in the artistic domain, it is becoming more common to have a BCI device used in a performance ensemble.

Chapter 3

Vision and Visual Perception

> "Neither camera, nor lens, nor film determine the quality of pictures; it is the visual perception of the man behind the mechanism which brings them to life. Art contains the allied ideas of making and begetting, of being master of one's craft and able to create. Without these properties no art exists and no photographic art can come into being."
>
> Helmut Gernsheim

This research primarily deals with visual perception and brain wave activity. Therefore, it is necessary to cover some fundamentals about the brain and vision. Visual perception is about seeing objects, surfaces, and events in the world around us (Bruce et al., 2003). It is what happens after a picture reaches the eyes (Baars and Gage,

2010) and the brain's ability to make sense of what the eyes see. However, this is not to be confused with visual acuity, which refers to how clearly a person sees, for example, 20/20 vision. So basically, someone can have 20/20 vision and still have visual perceptual processing issues. An illusion is a distortion of the senses, which can reveal how the brain typically organizes and interprets sensory information (Solso et al., 2005). This chapter will cover the various brain structures and their primary functions.

3.1 The Human Brain Structure and Function

This research primarily deals with visual perception and brain wave activity, and therefore it is necessary to cover some fundamentals about the brain and vision. Visual perception is about seeing objects, surfaces, and events in the world around us (Bruce et al., 2003). It happens after a picture reaches the eyes (Baars and Gage, 2010) and the brain's ability to make sense of what the eyes see. However, this is not to be confused with visual acuity, which refers to how clearly a person sees, for example, 20/20 vision. So basically, someone can have 20/20 vision and still have visual perceptual processing issues. An illusion is a distortion of the senses, revealing how the brain typically organizes and interprets sensory information (Solso et al., 2005). This chapter will cover the various brain structures and their primary functions.

The forebrain, which is the largest subdivision of the human brain, consists of the Cerebrum, also known as the cerebral cortex. It is a highly wrinkled surface of the cerebral hemisphere (Kandel, 1995) and is divided into two halves: the left and right hemispheres. The corpus callosum, a group of axons, connects the left and right cerebral hemispheres (Goldstein et al., 2017) The Cerebrum, which is associated with higher brain functions such as thinking, planning (Forebrain, 2018), perceiving, language, and sensory processing (Bailey, 2010). On the surface, white nerve fibers carry signals be-

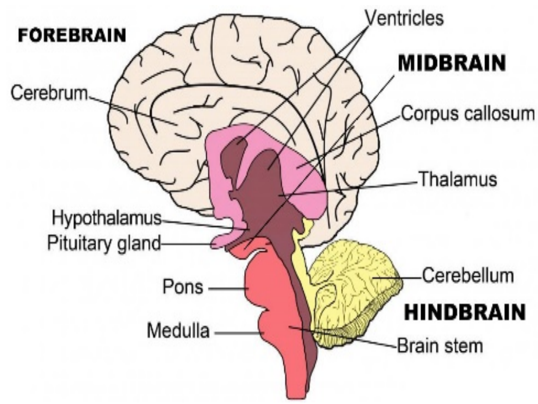


Figure 3.1: Brain structure - Credit: nbia.ca

tween nerve cells in other parts of the brain and the body. The gray surface or matter made up of nerve cells is divided into two hemispheres (Forebrain, 2018), which are divided into four parts referred to as lobes (Fig. 3.2) named after their underlying cranial bones (Kandel, 1995). They are the frontal lobe, which lies underneath the forehead, the parietal lobe, located at the upper rear of our brain, the occipital lobe, located at the back of our brain, and the temporal lobe, located by our ears. Table 3.1 lists the main functions associated with each lobe.

Frontal Lobe	**Temporal Lobe**	**Parietal Lobe**	**Parietal Lobe**
• Emotions • Behavioral control • Planning • Problem Solving	• Memory • Understanding Language • Speech	• Perception • Object classification	• Vision • Processing

Table 3.1: Brain lobes and associations

The midbrain lies beneath the cerebral cortex and is located near the center of the brain. It serves as an essential connection point between the other regions of the brain (Midbrain, 2018). The midbrain acts as a relay station for our auditory and visual

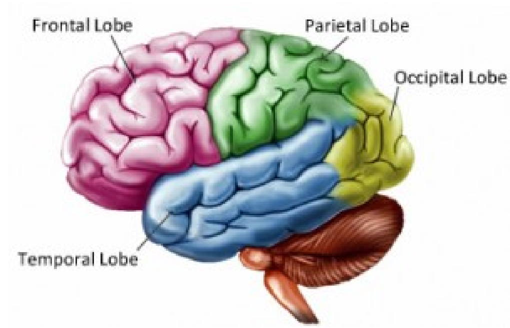


Figure 3.2: Brain lobes - Credit: nbia.ca

systems. It is also associated with modulating motor movement and reward functions (Sonne and Beato, 2018). Parts of the midbrain connects the cerebral cortex and spinal cord (Walter and Shaikh, 2014).

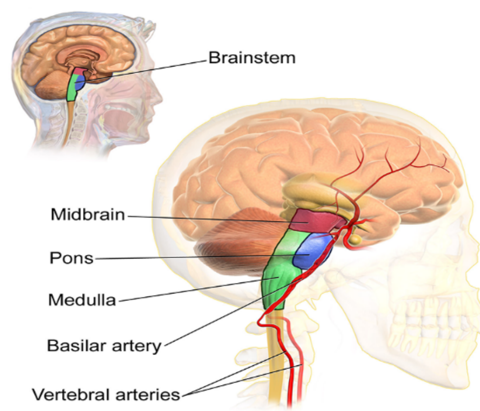


Figure 3.3: Mid Brain - Credit: Queensland Brain Institute

The hindbrain includes the spinal cord's upper part, the brain stem, and a wrinkled ball of tissue called the cerebellum. The hindbrain controls the body's vital functions such as respiration and heart rate (Brainbasics, n.d.).

The cerebellum, also known as "little brain", is like the Cerebrum and has two hemispheres and a highly folded surface. It is associated with the coordination and regulation of movement, balance, posture (Knierim, 2020), motion memory, respiratory and

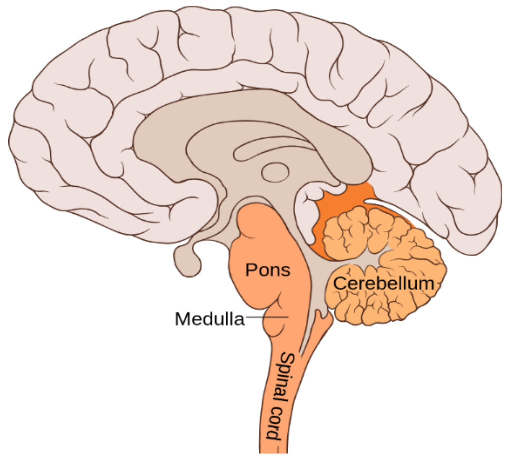


Figure 3.4: Hind brain - Credit: Queensland Brain Institute

vasomotor centers. Until recently, it is believed to also be is associated with cerebral networks involved in cognition (Buckner, 2013). The brain stem represents a transition between the brain and the spinal cord (Cech and Martin, 2011). The brain stem's function has to do with breathing, circulation, and digestion. The brain stem is also crucial in routing sensory nerve information in and motor nerve information out.

3.2 Neurons

What causes the electrical charge in our brainwaves? There are at least 85 billion neurons in the brain. Neurons, also referred to as nerve cells, are the brain's fundamental units (Kandel, 1995). The cells are responsible for receiving sensory input from the external world and sending motor commands to our muscles. Neurons communicate electrochemically to enable us to think, see, feel, and interact with the environment. The creation of new neurons in the brain is called neurogenesis and can occur even into adulthood (Underwood, 2019).

3.2.1 What Does a Neuron Look Like?

A good analogy is to think of a neuron like a tree. Neurons have three main parts: dendrites, an axon, and a cell body or soma (Fig. 3.5) (Kandel, 1995). These can be represented as the branches, roots, and trunk of a tree, respectively. A dendrite (tree branch) is where a neuron receives input from other cells. Dendrites branch out as they move towards their tips, and they even have leaf-like structures (post-synaptic contact sites) on them called spines. The axon (tree roots) is the long thin structure, which serves as the neuron's output; when a neuron wants to talk to another neuron, it sends an electrical message called an action potential throughout the entire axon to cause the release of neurotransmitters into a synapse. The soma (tree trunk) is where the nucleus lies, where the neuron's DNA is housed, and where proteins are made to be transported throughout the axon and dendrites.

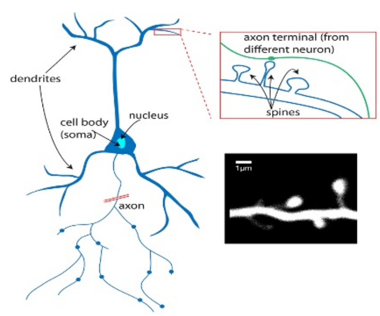


Figure 3.5: Neuron - Credit: qbi.uq.edu.au

In the spinal cord and the brain, various types of neurons are generally divided according to origin location, where they project to, and which neurotransmitters they use (neuron, 2019).

3.2.2 How Is Neuronal Activity Measured in an EEG

There are two main types of electrical activity associated with neurons: Action Potentials, which occur when a neuron sends information down an axon, away from the cell body (Chudler, n.d). Scalp electrodes cannot generally detect action potentials due to their timing and the axons' physical arrangement. Action Potentials can only be recorded if individual neurons fire simultaneously, causing the voltages of the action potentials to sum. Since neurons seldom fire simultaneously and because axons are relatively random in orientation, action potentials generally cancel each other out. Action potentials have a concise duration, approximately 1 Millisecond (ms).

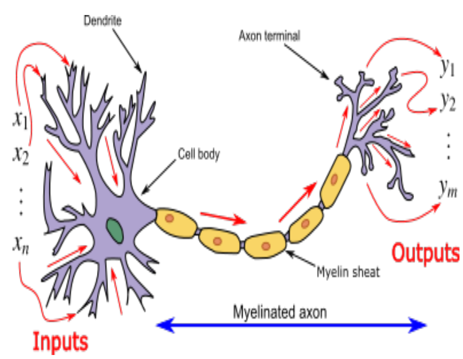


Figure 3.6: Neuron signal flow - Credit: en.wikemedia.org

The second, Postsynaptic Potentials (PSPs) occur when neurotransmitters bind to the receptors on the post-synaptic cell membrane. This causes ion channels to open or close, leading to a graded change in potential across the cell membrane.

EEG measures the aggregate spikes and synaptic currents generated by millions of cells. It measures the entire concert of activity, with signal amplitudes that roughly reflect the number of cells actively communicating at a specific moment or acting in concert with one another (eegmeasure, 2016). Since neurons communicate via electrical signals, using EEG would be best to record these signals. Cognition could happen at

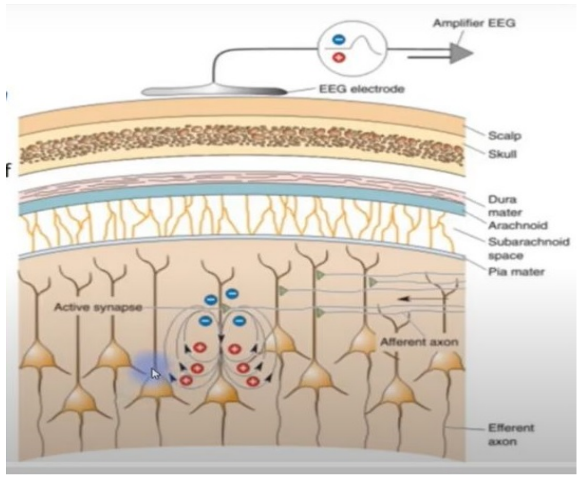


Figure 3.7: Neuronal activity measurement illustration - Credit: Mark X Cohen.

every millisecond, hundreds of milliseconds, or seconds. It is good to have a brain measuring method that records at the same speed as cognitive processes, and this is the main advantage that EEG has over other brain recording methods.

3.2.3 Brain Mapping

Topographical maps (Fig. 3.8) are a great way to visualize EEG signals. They show the spatial distribution of activity of the voltage potentials or quantified data and let us see the information in the data at a single or multiple time points (e.g., seconds or milliseconds). To interpret the data, one has to look down on the figure, representing the top of someone's head. The black dots represent the location of the nearest electrode/sensor place on the person's scalp. There are various colors between the electrodes placed on the scalp, representing scalar values for the electrical activity. The colors usually range from deep blue to deep red, representing low activity to high activity. Scalar values are discussed further in Chapter 5. There is an interpolation that occurs between the electrodes, that taking the voltage value between one sensor and the voltage value from another sensor and make the assumption that there is a smooth transition between the two sensors. The interpolation allows us to assume what the activity looks like from one electrode to the next. Topographical maps based on the data retrieved in this research are in Appendix B and described in more detail in Chapter 5.

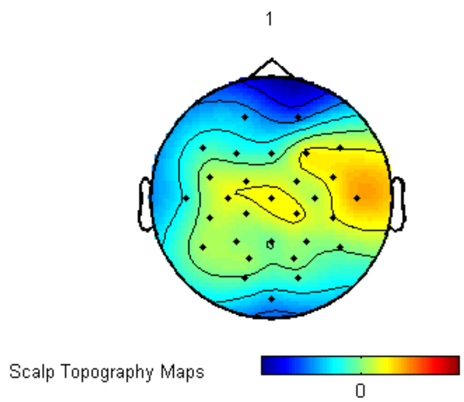


Figure 3.8: Brain topographical map - Credit: ieeexplore.ieee.org

3.2.4 Brain Function Discussion

The basics about the brain and neuronal function were presented. How the brain is structured (brain lobes) is vital in understanding why the human subject experiments conducted in this research were designed specifically. For example, why sensors were placed on a specific area of the head. EEG signals are very complex due to the complex nature of the neuronal activity. There is a lot of brain activity noise and are only limited to large scale potentials, meaning that brain activity could be measured when a certain amount of neurons fire simultaneously.

Given that there is a lot of noise in the data, filtering or other EEG pre-processing methods are required. These processes are further discussed in Chapter 5. Conducting EEG data analysis, statistics, and visualization could be time-consuming and even frustrating. Even though EEG has a high temporal resolution, which is good, it does not indicate exactly where something occurred (low spatial resolution). For example, suppose research participants have to perform a certain cognitive process such as thinking about something. In that case, it is not easy to see that in an EEG reading. However, EEG use in BCI artworks is still nonetheless very popular. Brain topographical mapping is also applied in this research that shows brain activity post-stimulus. The concept of brain mapping and how it is applied in one of the BCI artworks are discussed later in this dissertation.

3.3 Anatomy of the Eye

Humans use the sense of sight to interpret much of the world around them. What we as humans see is a small part of the entire 'electromagnetic spectrum'. Humans can see only the wavelengths of electromagnetic radiation between approximately 380 and 760 nanometers, referred to as 'light' (Chudler, n.d.).
The human eye is about 2.5 cm in length and weighs about 7 grams (Chudler, n.d.). It takes in light from the environment and converts it into an 'image'. The eye consists of several parts, which are not limited to the following (Fig. 3.9):

- The Cornea, which is a clear front window of the eye that transmits and focuses light into the eye.
- The Iris, the colored part of the eye helps control the amount of light that comes in the eye.
- The Pupil, a dark aperture in the iris that determines the amount of light that is let into the eye.
- The Lens, which is a transparent structure inside the eye that direct light rays to the Retina.

- The Retina, a nerve layer that lines the back of the eye, which senses light, and creates electrical impulses that travel through the optic nerve to the brain.
- The Macula is a small central area in the Retina that contains special light-sensitive cells and allows us to clearly see fine details.
- The Optic nerve serves as a connection between the eye and the brain, which carries electrical impulses formed by the Retina to the visual cortex of the brain.
- The Vitreous is a clear, jelly-like substance inside the middle of the eye.

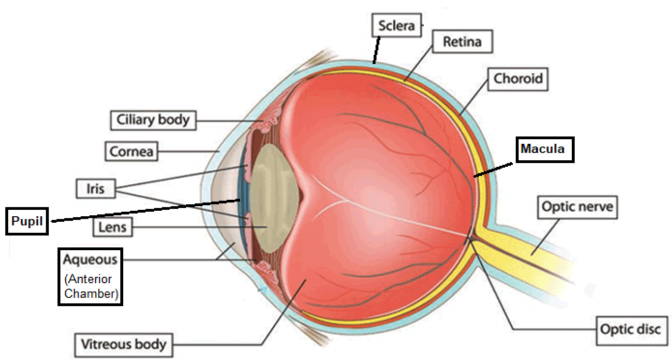


Figure 3.9: Eye anatomy - Credit: naturaleyecare.com

3.3.1 How Does Visual Perception Work Biologically?

The eye is analogous to a camera, in which the Retina would be the film. Photo-receptors are located inside the Retina, and the two types of photo-receptors involved in human vision are known as the Rods and Cones (Chudler, n.d.); (Rodscones, n.d.). There are about 120 million rods in the human eye and about 7 million cones (Bruce et al., 2003). They react to the energy of the light coming into the eyes and convert it into electrical signals. Some of these cells transmit a different amount of information that includes shape, color, and motion direction. Other cells process these electrical signals further like, for example, enhancing light/dark contrast while others oversee sharpening the image.

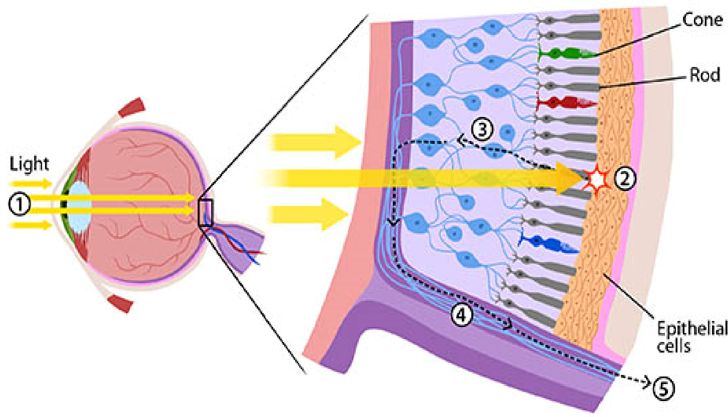


Figure 3.10: Eye Rods and Cones - Credit: askabiologist.asu.edu

Light comes into the eye via the pupil and traverses to the outermost layer of the Retina, which is the photoreceptor layer (Fig. 3.10), where the rods and cones are located (Lee et al., 2015). The rods work with low light levels (scotopic vision) (Rodscones, n.d.) and are useful for night vision (low spatial acuity). Since the Rods are activated with low light, they are not very helpful with color processing at night, which is why we see everything in grayscale at night. There are over 100 million rod cells in the human eye. On the other hand, Cones require a lot more light (photopic vision), which allows us to see color and have a high spatial acuity (Rodscones, n.d.). There are three types of cones: blue, green, and red. There are approximately 6 million cones in the human eye. Most of these are situated in the Fovea, a small pit in the back of the eye. Overlapping cones and how the brain integrates signals sent from them allows us to see millions of colors. The Primary Colors are Red, Green, and Blue, based on how rods and cones process light. They are the (additive) primary colors of light, which means that any other color can be created by mixing different amounts of the three.

3.3.1.1 Color Blindness

Color blindness is a reduced ability to distinguish between specific colors, so it means a person sees colors differently than most people. This condition is usually inherited from a parent. The most common type of color blindness is telling the difference between red and green. Another type is telling the difference between blue and yellow. Some people are completely color blind (colorblind, 2019). How one processes color can also affect how they process optical illusions, discussed in Chapter 5.

3.3.2 Primary Visual Cortex

The visual pathway is the anatomical pathway, where the Retina's electrical signals are sent to the brain (Armstrong and Cubbidge, 2014). The Optic nerve is where the bundle of nerve tails forms. Signals are transmitted through the optic nerve to the brain. Since humans have two eyes, there are two optic nerves. They cross paths and move from the inner brain through a substation (relay center) (Fig. 3.11) to the visual cortex.

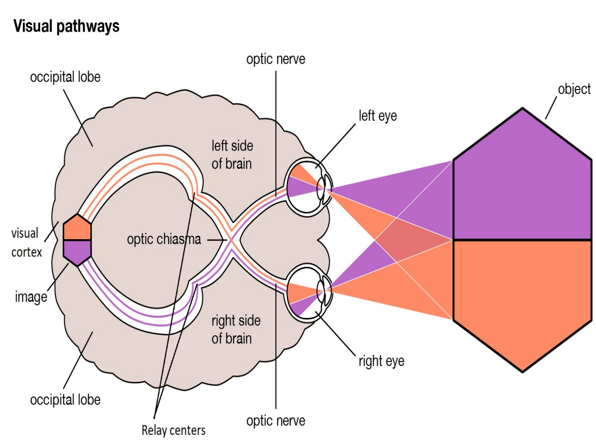


Figure 3.11: Visual pathway - Credit: Britannica.com

In the visual cortex, the information from both eyes gets filtered, processed, interpreted, and paired with existing patterns and then put back together into a full picture. The other parts of the brain associate these elements with experiences and emotions. Whatever is missing in the field of view is then filled in, which usually occurs unconsciously. The primary visual cortex, referred to as V1, is a brain structure that is important to the processing of visual stimuli. The importance of V1 to visual perception can be shown in cases where patients with damage to V1, experience disruptions in visual perception (vcortex, 2016), which can range from losing specific aspects of vision such as depth perception to blindness. When visual information is taken in through the eyes, it hits the Retina, goes through the optic nerve and the optic tract to a nucleus of the thalamus called the lateral geniculate nucleus (LGN). It then goes through a tract often called the optic radiation, which curves around the wall of the lateral ventricle in each cerebral hemisphere and reaches back to the occipital lobe (visual cortex). The axons inside the optic radiation end in the V1 by what is referred to as a retinotopic manner, meaning that the axons carrying information from a specific part of the visual field end at a location in V1 that corresponds to that location in the visual field (vcortex, 2016). V1 refers to the cortical regions that first receive and process information.

The areas of the occipital lobe surrounding the primary visual cortex are also primarily involved with vision. These are sometimes collectively known as the extra-striate cortex. These areas' function concerning the primary visual cortex is not fully understood; however, it is the belief that it plays a crucial role in visual processing (vcortex, 2016).

3.3.3 Visual Processing Discussion

The importance of the visual cortex was presented. Any defect in the anatomy of the eye or visual cortex affects how that observer visually perceives. Color perception also affects the visual cortex signal output. This is evident in VEP studies involving the checkerboard stimulus. This stimulus is when subjects look at alternating checkerboard squares that switch between white and black. This research does not go deeply into the processing of vision (such as the speed of visual processing) beyond its scope. However, it provides a general overview of the mechanisms involved in visual processing. Color blindness could affect visual perception, which could be a factor in how observers perceive optical illusions. This was considered in the optical illusion viewing experiment conducted in this research, where participants were asked if they were color blind. The overall theory behind vision was presented. How the brain processes visual information is what is in the VEP data and makes it complex. Also presented was the early psychological thought to visual perception. Helmholtz, considered the father of visual perception, viewed perception as “unconscious inference”, that is, representations or symbols of the physical world that can be disambiguated and interpreted through converging evidence from different senses. His main contribution was developing the Ophthalmoscope used for eye examinations (even to this very day) and the measurement of neural impulses’ speed. Even though Helmholtz made contributions in perception, the Gestalt school came after Helmholtz took a different approach to perception. Gestalt school is discussed further in the next section. Both the theory behind visual perception and Gestalt principles were considered in designing the BCI artworks interfaces, which are discussed later in this chapter.

3.3.4 Visual Perception

Visual perception is at the core of this research. The following section describes visual perception and the evolution of studies in this field. These studies range from the theoretical to the philosophical. Perception describes the way sensory information is organized, interpreted, and experienced. It is an interpretation of how we see the world around us by creating meaning from our senses and environmental experiences. Generally, the human perceptual system is designed for accuracy, and humans are good at using the vast amount of information available to them (Stoffregen and Bardy, 2001). For example, our eyes can distinguish between many colors. Our skin can sense different temperatures, and we can hear different types of sounds. Perception involves bottom-up and top-down processing. What comes through our senses would not mean much without our brain's ability to translate and organize the data into meaningful perceptions. With bottom-up processing our perceptions come from sensory input. In the case of visual processing, information travels in one direction, beginning with the Retina and proceeding to the visual cortex (Cherry, 2020). How sensory inputs are interpreted is affected by our experiences, culture, and thoughts, referred to as top-down processing.

3.3.4.1 Types of Visual Perception

The perceptual set is a psychological factor that determines how we perceive the environment. Several factors make up the perceptual set: expectation, culture, context, and emotion (Vernon, 1955). Usually, our perceptual sets tend to make us a certain aspect of a stimulus and ignore the others. This is the basis of many optical illusions. Some of the ways the mind brings external information together are by following Gestalt rules (discussed in detail in section 3.5) such as grouping, proximity, continuity, or closure. Depth perception is the ability to see objects in three dimensions (Boyd, 2018), although images that hit the Retina are two-dimensional. It helps us experience the depth, size, or shape of an object. We are able to perceive depth by using both binocular or monocular visual cues. Binocular cues help us perceive depth and require the use of both eyes. Because the eyes are apart, the retinas receive slightly different images. The closer the objects, the greater the difference between the two images, which is known as the retinal disparity. Monocular cues are depth cues, such as interposition, texture gradient and linear perspective, and these are available to either eye alone. Motion Perception is used to infer speed and moving objects. For example, shrinking objects are retreating, and enlarging objects are approaching. Motion objects can trick the brain; for example, larger objects are perceived to be moving slower than a smaller object moving at the same speed.

3.3.4.2 Early Studies in Visual Perception

Herman von Helmholtz (1821-1894), who is considered the father of visual perception, developed psychophysiology theories that pertain to the transduction of physical stimuli into nerve impulses and how qualitative stimulus information is coded into neural signals. The theory is the trichromatic theory of color vision (Levine and Shefner, 1981), which is vital to understanding Helmholtz's theory of perception (visual). Research into color vision suggests that when the primary color red, green, and blue were mixed, it became a subjective experience of any perceivable spectrum color. Helmholtz reasoned based on the law of primaries that there had to be receptor cells that are completely sensitive to one of the three primaries in the eye. The subjective experience of the non-primary colors was due to mixing different combinations of the wavelengths of red, green, and blue light (Piekkola, 2016).

Illusion shows that there might be a possibility there is an error in one's perception.

It is believed that Helmholtz thought that perception might involve experiential data that are not represented in the immediate stimulus, creating the false percept (Boring, 2008). Unconscious processes interpret the current stimulus upon the basis of prior experience, and that interpretation is the perception. According to Helmholtz our sensations are the result of the objective conditions of the environment beyond the senses. We do not have direct access to those conditions, and we are left in the position of deducing the cause of those sensations may be (Gibson, 1966); (Piekkola, 2016). The classical, empiricist perspective on depth perception is that the proximal stimulus, which immediately acts upon the receptors, does not contain a lot of information (Hershenson, 1999). Additional information needs to be provided by the senses. The sensory system responded to the proximal stimulus, that is, the physical stimulus acting upon the receptors (Piekkola, 2016). For example, with vision, light reflected off the distal stimulus, i.e., objects in the environment beyond the senses, is what the photoreceptors respond to. This and given the retinal image's impoverished nature, the perceptual process needs to get the information from the Retina and somehow interpret it to create a perception of our environment. Helmholtz believed that brain functions interpret sensory information before one has a subjective experience (Piekkola, 2016). Based on his empiricist knowledge and an attempt to explain the perception of three dimensions in vision, the unconscious inference theory is proposed. The treatise on Physiological Optics, introduced the standard, theory of perception— unconscious inference theory, a constructionist, representationalist, indirect realist theory (Southall, 2000). Increasing an experience allows the mind (brain process) to build up a set of expectations (Piekkola, 2016); (Southall, 2000). An example of expectation could be the recurrence of a previously experienced sensory collection that is most likely due to the same stimulating object producing those same impressions. This is the basis of these expectations that an imagined world of objects is constructed. The objects of experience to Helmholtz were simply an accumulation of sensations (Sahakian, 1975). According to Helmholtz, what one perceives is "due to unconscious inferences about what must have produced the present pattern of sensations" (Piekkola, 2016).

3.4 Gestalt School Principles

Sensory processing is a complex process. To understand this process, new research was brought forth to explain and understand this process in the Gestalt school principles in the early 1900s. The three prominent psychologists behind the Gestalt Theory are Max Wertheimer (1880-1943), Kurt Koffka (1886-1941), and Wolfgang Kohler (1887-1967). Unlike Helmholtz, Gestalt psychologists believed that humans do not perceive things in isolated pieces but in meaningful, intact configurations, referred to as Gestalt (Seel, 2012). In other words, they believe that the perceptual system follows organizational principles. The six principles of the Gestalt theory are:

- *Figure Ground*, which is the thought that when we look at a scene, we separate objects to focus or figure and others in the background.
- *Similarity* is based on the notion that we place objects with similar characteristics in a group. These could be color, font, size, texture, shape etc.
- *Proximity* is based on the belief that we group objects that are close to each other.
- *Closure*, based on the idea that our minds put objects together that are not necessarily together or complete to create a whole. e.g. *Kanisza triangle* (Fig. 3.12).
- *Continuity*, based on the theory that we continue to follow visually aligned objects until they are interrupted.

- *Order*, which is based on the belief that alignment and symmetry are attractive and essential design elements.

Gestalt psychology is still relevant today because it continues to "inspire contemporary scientific research" as well as "challenge some of the fundamental assumptions pf mainstream vision science and neuroscience" (Wagemans et al., 2012). It is also important for designers to create complete and compelling visuals. Usually, when these principles are ignored, designs tend to look out of place or incomplete, forcing our eyes to look at inconsistencies rather than the whole. One may not be able to pinpoint what seems off; however, the individual will certainly experience the feeling that something is out of place. Thus, for designers, the understanding of visual perception allows them "to make better design decisions based on a deeper understanding of how the brain interprets visual information" (Haina, 2016). Essentially what you see is within the realm of the mind, not the eye. This is not to be confused with visual acuity, which is how a person sees, for example, 20/20 vision.

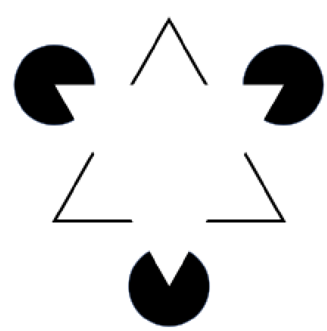


Figure 3.12: Kanizsa Triangle

Pre-attentive processing is a term that refers to the body's processing of sensory information (ambient temperature, light levels, etc.) that occurs before the conscious mind starts to pay attention to any specific objects in its vicinity.

3.4.1 Visual Illusions

In this section, the different types of visual illusions are presented along with the early research in this field, which spans more than a century and the major players involved. An optical illusion (also known as a visual illusion) is an illusion caused by the visual system and characterized by a visual percept that arguably differs from reality. Illusions can come in a wide variety; their categorization is difficult. The underlying cause is often not clear, but a classification proposed by Richard Gregory is useful as an orientation. There are three main classes: physical, physiological, and cognitive illusions, and in each class, there are four kinds: Ambiguities, distortions, paradoxes, and fictions (opillusion, 2020). Illusions sometimes expose the complex nature of the visual system. These are "stimuli that exist at the extremes of what our system has evolved to handle". Illusions are based on assumptions made by the visual system (Eagleman, 2001).

3.4.2 Types of Visual Illusions

In this section, three main types of optical illusions are presented and the significant works in this field of study. Optical illusions could be categorized as the following:

- *Literal optical illusions*, which create images that are different from the objects that make them. A good example is depicted in the figure 3.13.
- *Physiological Illusions*, which are effects on the eyes and brain of excessive stimulation of a specific type such as color, brightness, motion, and tilt. If one stares at the center of the figure below and move the head, it will seem like the circles are moving. The Rotating Snakes illusion (Figure 5.3), one of the optical illusions

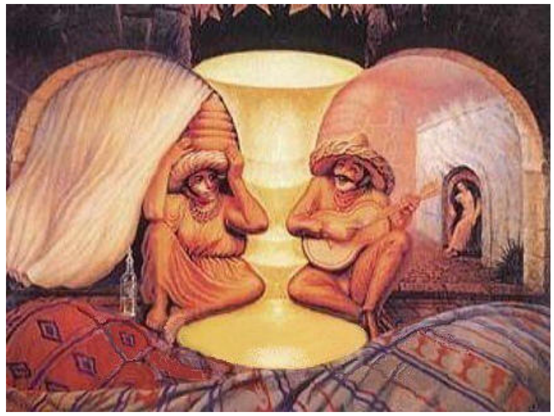


Figure 3.13: Example of Literal illusion - Credit: moillusions.com

used in this research, is also an example of physiological illusions and is discussed in more detail in Chapter 5.

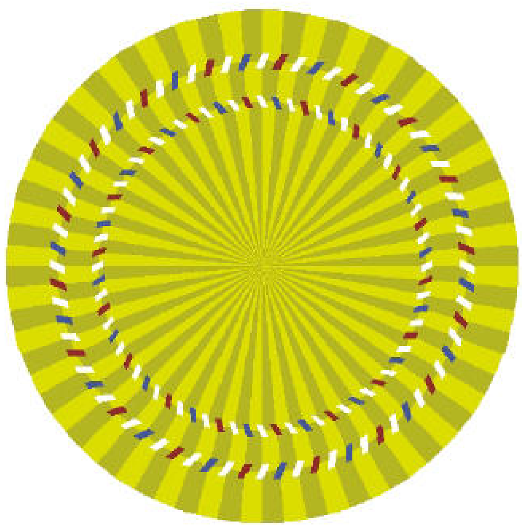


Figure 3.14: Example of physiological illusion

- *Cognitive Illusions* occur when the eye and brain make unconscious inferences about an image. These inferences include:

  After Effects: The motion after-effect (MAE) is a visual illusion experienced after viewing a moving visual stimulus for a time (seconds to minutes) with stationary eyes and then fixating a stationary stimulus. The stationary stimulus appears to move in the opposite direction to the original (physically moving) stimulus.

Illusory Contours: Subjective or *Illusory contours* are visual illusions that evoke the perception of an edge without a luminance or color change across that edge. Illusory brightness and depth ordering frequently accompany illusory contours.

Multistable Stimuli or Bistable Stimuli: *Multistable percepts* are illusions that stem from the ambiguity (impossible objects) of the presented image (the physical stimulus), which cannot be recognized with a unified interpretation by the human visual system. This ambiguity incorporated in the images causes a perceptual phenomenon in which the single image produces a set of different subjective perceptual states that can be alternated between (Schwartz et al., 2012). It is also referred to as 'Gestalt switch'. A popular example is the *Duck/Rabbit illusion*. An anonymous illustrator created this illusion in late 19th Century Germany (Donaldson, 2016). After being used by psychologist Joseph Jastrow, the image was made famous by Ludwig Wittgenstein, who included it in his Philosophical Investigations as a means of describing two different ways of seeing: "seeing that" versus "seeing as" (pinvestigate, 2020); (Howell, 1972).

3.4.3 Prior Works in Visual Illusion Study

This section briefly covers the previous research that was conducted in Visual Illusions. Research in optical illusions generates a lot of interest, especially from those studying cognitive sciences.

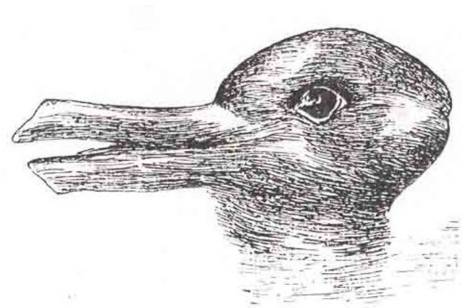


Figure 3.15: Duck/Rabbit illusion - Credit: Illusion Index

Work in visual perception and illusion has been going on for centuries. In 1668 Edme Mariotte discovered the human eye blind spot by chance in one of his studies. He was also the first one to determine the actual size of the blind spot. Mariotte found that the diameter of the biggest circle of paper that could disappear entirely from sight in the blind spot was about 1/9 to 1/10 of the distance at which the experiment was performed (Grzybowski and Aydin, 2007).

The *motion aftereffect* (MAE), a powerful illusion of motion in the visual image is caused by prior exposure in the opposite direction. For example, when looking at the rocks beside a waterfall, they may appear to drift upwards after viewing the flowing water for a short period, say about 60 seconds. This type of illusion originates in the visual cortex. It arises from selective adaptation in cells tuned to respond to movement direction. The MAE was first discovered by Aristotle (c. 330 BC) and rediscovered by the Czech physiologist Jan E. Purkinje (Anstis et al., 1998) in 1820.

Charles Wheatstone described and illustrated in 1838 how different stimuli could be viewed without a stereoscope under- and over convergence, by using two viewing tubes, or by a combination of over convergence and a septum between the eyes. Pictures that

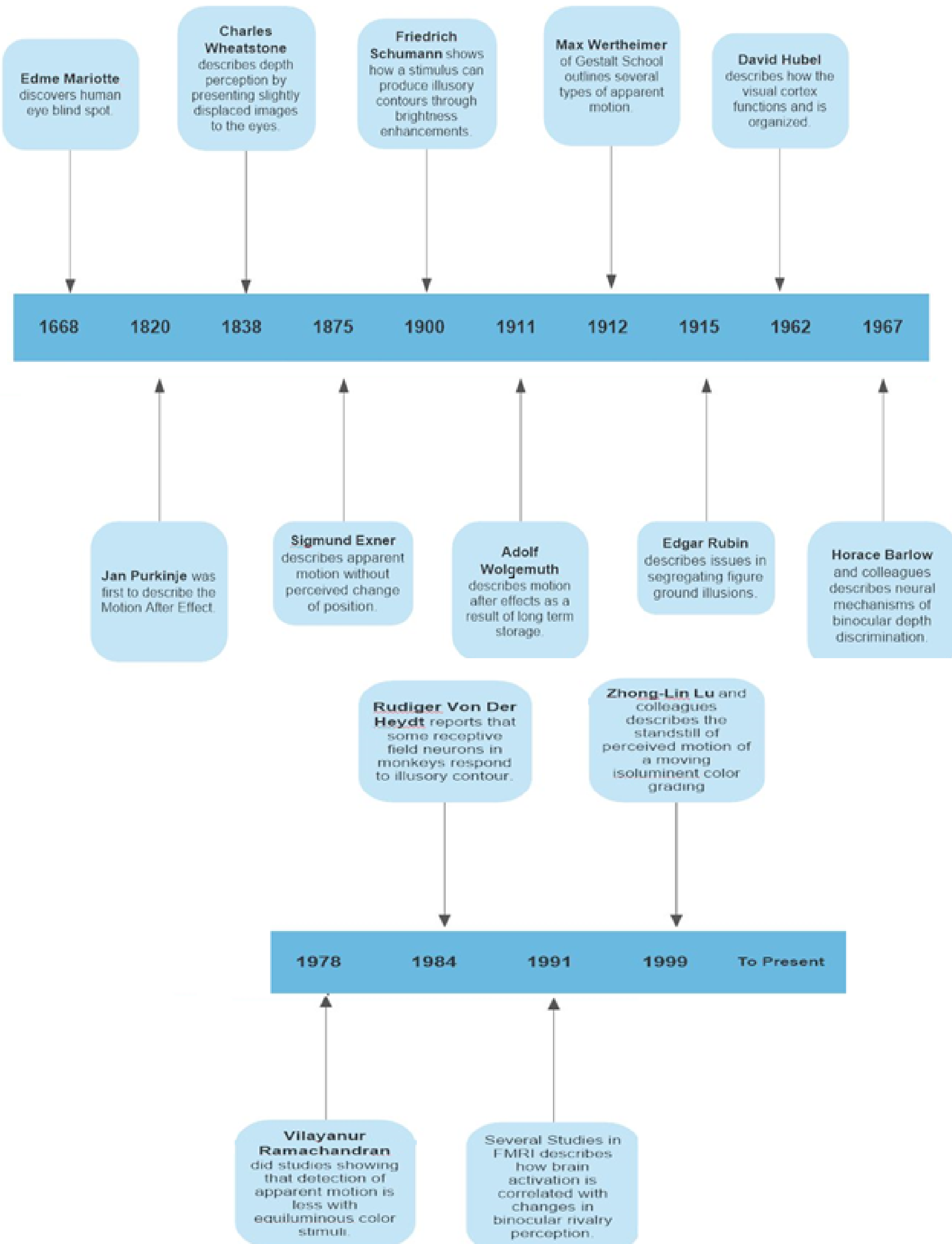


Figure 3.16: Visual perception research timeline

are not similar when viewed through a stereoscope, create the appearance of depth. As a result, Wheatstone conducted a series of systematic manipulations of the figures to discover the nature of the relationship (Wade et al., 1998). He also addressed the issue of motion parallax: he was confronted with the perception of depth by those who did not have binocular vision, addressing the question: how does an observer with only one eye see depth? (Ono and Wade, 2005).

The apparent motion has been divided into two classes: the first class, being a percept produced by viewing a continuously moving object, is referred to as real motion. The second class of motion, apparent motion, may result when stationary stimuli are presented in sequence to different retinal locations. In 1875, Sigmund Exner suggested that separate processes detect real and apparent motion. He also suggested that real motion is directly perceived while apparent motion is inferred from information about the change in position (Green, 1983).

Friederich Schumann introduced in 1904 a new class of visual stimuli known as illusory contours (also known as subjective contours, ambiguous contours, and cognitive contours) to psychology. Illusory contours are anomalous in that they do not satisfy the usual requirements for contour perception (Halpern, 1981). One of the main variables in understanding how and why illusory contours are perceived is how the stimulus is configured. For example, large dark inducing areas usually "create simultaneous contrast effects, and stimuli that provide monocular depth cues operate, at least in part, via Gestalt and interposition principles" (Halpern, 1987).
Adolf Wohlgemuth conducted research on long term storage of motion aftereffect in 1911 (Anstis et al., 1998).

In 1912 Max Wertheimer published a monograph entitled "Experimentelle Studien uber das Sehen von Bewegung", where Wertheimer described many experiments and demonstrations that touched upon many issues on research in motion perception. It is now very clear that his monograph was a seminal contribution (Sekuler, 1996) to motion perception. When a figure discretely and instantaneously changes its shape, observers do not normally perceive the abrupt transition between shapes that, in fact, takes place. A continuous shape change is perceived. Even though this illusory "transformational apparent motion (TAM) is a faulty construction of the visual system, it is not arbitrary" (Tse, 2006); (Steinman et al., 2000).
In 1915 Edgar Rubin's work in the theory of visual form-perception greatly contributed to the field. Here, he discovered the fundamental type of form-experience to consist of a figure standing upon a ground. The central feature of the perceptual experience being the figure and the recessive portion being the ground. A member of a whole cannot be considered alone; it can only exist in its reciprocal relation to the other members (Wever, 1927).

In 1962, David Hubel and Torsten Wiesel presented the first description of receptive fields in the primary visual cortex of mammals. They defined two classes of cortical cells, 'simple' and 'complex', that are based on neural responses to simple visual stimuli. They introduced the notion of a hierarchy of receptive fields, where increasingly complex receptive fields are constructed from more elementary ones (Ringach, 2004).

Vilayanur Ramachandran in 1978 noticed in his experiments a decreased detection of motion with the presence of equiluminous colored stimuli. A perplexing feature of primates' visual system is the occurrence of a multiplicity of separate 'maps' of the visual environment, each with its own independent set of afferent connections. Afferent neurons are sensory neurons that carry nerve impulses from a sensory stimulus toward the CNS and brain. These maps represent an early sate in the analysis of visual information by the brain. According to (Ramachandran and Gregory, 1978), color cues seem to have "a slightly detrimental effect on the perception of coherent apparent motion".

Since 1991, fMRI use for measurement of perception became more common (Belliveau et al., 1991). This may be because fMRI has excellent spatial resolution.
In (Lu et al., 1999) researched perceived motion standstill, i.e., when a quickly moving object appears to stand still, and its details are visible. It is proposed that motion standstill can occur when the spatiotemporal resolution of the shape and color systems exceeds that of the motion systems.

3.4.4 Visual Perception Discussion

The previous section presented those who made a big contribution to the field of visual perception. In the early works, the view on perception seemed more philosophical, and as time passed, it became more physical process based. There is still a lot to learn about visual perception. Very few early researchers in visual perception worked with BCI or EEG. Now with the emerging field of Neuroaesthetics and easier access to neuroimaging devices, there is a lot more being done to investigate how we perceive and especially connect to art.

3.5 Visual Science and Art

Artists and vision scientists pose similar questions and similar study phenomena; however, they examine them in different ways, with art being primarily evocative and science being mostly explanatory. Vision scientists want to explain how and why we see the way we do and have only started to approach art objects systematically. They are mainly concerned with vision and the neural mechanisms underlying the perception of color, depth, brightness, form, and motion in response to computer-controlled stimuli, i.e., bottom-up.

Few artists have exploited the potential of the neurobiology of seeing in their creations. Their aim is primarily a top-down approach to translating their perception of the outer world, like people and nature, onto the canvas. To be creative, an artist does not need scientific instruments or books. Visual illusions can serve as non-invasive tools to probe the workings of the brain. In exploring the relationship between art and science, (Ramachandran and Gregory, 1978) proposed eight principles of artistic experience rules that many artists consciously or unconsciously may apply to increase stimulation in the brain. These principles are mainly drawn from neurobiology, for example, distortion (false body proportions), exaggeration (caricature), peak shift (extraction of the essence), and sparse representation (sketch, outline). However, only a few of these techniques excite areas in the brain more strongly than when it occurs with natural stimuli (Ramachandran and Hirstein, 1999).

(Spillmann, 2007) lists several categories where art preceded visual science; color contrast, color assimilation, depth, lightness, perspective, surfaces, motion, contours, and scenes. The following section reviews some of the most famous works involving visual perception and art. Many visual artists use the principles of neuroscience in their art.

3.5.1 Prior Works Using Optical Illusions in Art

Though not usually trained psychologists or visual scientists, artists have been exploring how humans visually process and perceive the world in their artwork going back centuries. They did this by applying specific colors, for example, to produce a particular effect, such as the perception of depth to the observer of the art. This section reviews some artworks that contained optical illusions. Trompe-l'œil in the fine arts refers to the technique of visual illusion. The viewer's eye is tricked into believing that a painting is a three-dimensional object, rather than just a two-dimensional representation of it (Trompe, n.d.). This technique spans illusionary artistic devices across architecture, painting, decorative arts, and sculpture. A few examples of Trompe-l'oeil with artists exploring depth are shown in figure 3.17.

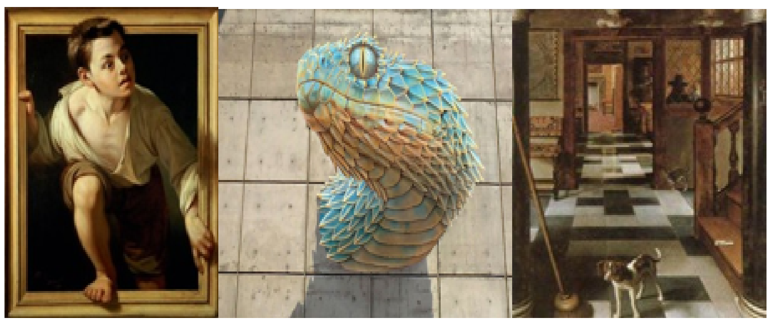


Figure 3.17: left: "Escaping Criticism" (1874) By Pere Borrell del Caso (1835-1910), center: "Quetzalcoatl" (2016) by John Pugh, right: "A View Down a Corridor" (1662) By Samuel van Hoogstraten (1627-78). Credit: http://www.visual-arts-cork.com/; www.thoughtco.com

Marcel Duchamp

Marcel Duchamp (1887-1968) explored depth-from-motion (Spillmann, 2007) and in 1935 published Rotoreliefs, which consisted of a set of 6 double-sided discs meant to be spun on a turntable at 40-60 rpm. Based on a manifestation of Duchamp's interest in optical illusions and mechanical art, Rotoreliefs (Fig. 3.18) create an illusion of depth when spun at the correct speed (Clark, 2016).

MC Escher

The mathematical art of Maurits Cornelis (MC) Escher (1898-1972) brought together

Figure 3.18: One of Duchamp's Rotorelief discs - Credit: moma.org

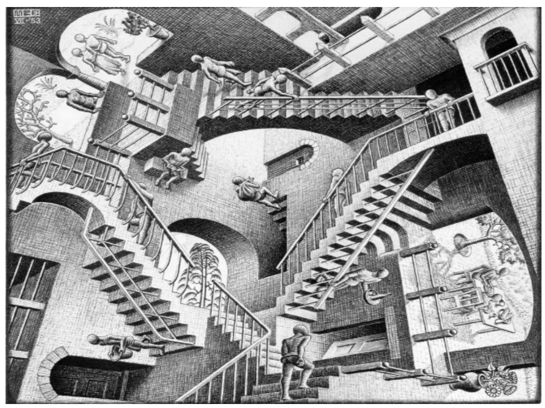


Figure 3.19: M.C. Escher's Relativity (1953) - Credit: totallyhistory.com

math and art as one, even though he was not a mathematician by training. He was very interested in tessellation, the process of covering (a plane surface) by repeated use of a single shape, without gaps or overlapping (Fig. 3.19). His most famous works involved optical illusions (ambiguous illustration). Escher was inspired by visual perception and how the brain does not always accurately interpret what we see. Escher wanted observers of his art to keep asking the question: what am I looking at?

Salvador Dali

Among the painters (modern) inspired by visual science, Salvador Dali (1904-1989) stands out. He knew how to produce genuine 3-D perceptions (Spillmann, 2007). Many

Figure 3.20: Arcimboldo's 'Bowl of Veggies or Face' c.1587-90 - Credit: guiseppe-arcimbodlo.org

of Salvador Dali's paintings use various pictorial techniques, photography, and holograms to further his exploration of visual perception and the ways that optical illusion affects our sense of reality. Giuseppe Arcimboldo made many paintings that contained optical illusions. The "Gardener" also known as "bowl of veggies" (Fig. 3.20), was one of his most famous paintings.

Bauhaus School

Gestalt psychology seems to have also influenced artists at the Bauhaus school, even though some believe that may be debatable. Students were taught that "Experiencing an object with all the senses was important, as was the combination of physical, sensual, spiritual and intellectual aspects if ideas were to take the shape of art" (Spillmann, 2007); (Shiner, 2001). Gestalt also suggests the scientific basis for Wassily Kandinsky (1866- 1944) and Paul Klee's (1879-1940) search for a universal visual script. Gestalt psychology became central to modern design theory after WWII, which promoted an ideology of vision as an autonomous and rational faculty (Lupton and Abbott Miller, 2006). Gyorgy Kepes's Language of Vision (1944), written at the New Bauhaus (now Institute of Design in Chicago), draws heavily upon Gestalt psychology.

Figure 3.21: Josef Albers' - Stacking Tables - Credit: ftn-blog.org

Another example that further shows the workings of these relational structures and principals of a perceptual organization is in Josef Albers' (1888-1976) Stacking Tables (1927) (Fig. 3.21). These tables, which are also functional, have the same constellated characteristics of horizontal and vertical groupings. However, they are also dynamic, meaning that we can arrange (and perceive) the groups according to the proximities that we control. The 'Gestalt switch' is shown through pictorial experimentation and in the functional design of the objects. These tables make up a constantly shifting set of groupings and motion perception due to the ascending/descending colored surfaces even though they are still.

Santiago Ramón y Cajal

Santiago Ramón y Cajal (1852–1934), considered the father of modern neuroscience (Smith, 2018), was a pioneering Spanish neuroanatomist, who combined scientific research with art to create drawings of the human brain and other nerve cells. Figure 3.22 shows one of his famous drawings of neurons and brain tissues.

Rodrigo Quian Quiroga

Rodrigo Quian Quiroga, a neuroscientist from the University of Leicester in the UK,

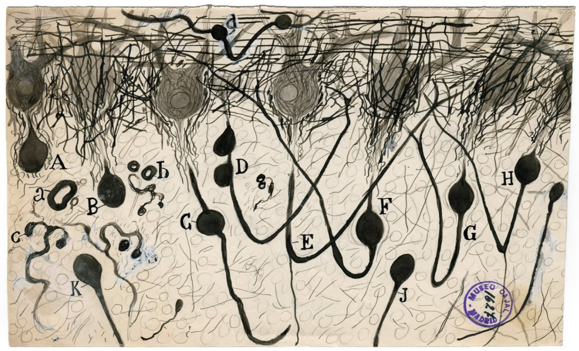


Figure 3.22: Ramon y Cajal's Axon of Purkinje neurons in the cerebellum of a drowned man," an ink and pencil drawing - Credit: nytimes.com

explores art and neuroscience, emphasizing *Binocular Rivalry* and *Occlusion*. Occlusion is when something covers something else. The first thing we see will be closer to us than the second thing. This creates the perception of depth. Binocular Rivalry is the information we get from both eyes converges in the brain. This is how we get 3D visualizations/pictures. If two different images are shown to each eye, it confuses the brain. The brain will switch from one image to the other. For example, in figure 3.23, the text will switch between blue and red when viewed with red-cyan 3D glasses.

Figure 3.23: Binocular Rivalry image - Credit: Wikipedia.org

3.5.2 Op-Art

Op Art, short for optical art or 'retinal art', is a style of visual art that uses optical illusions, that is, a style of abstract art (Opart, n.d.) that is usually composed of pat-

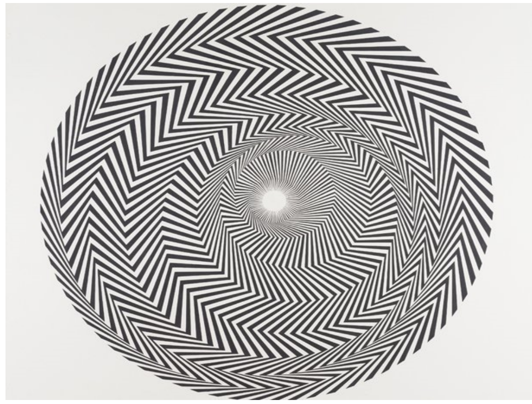


Figure 3.24: Bridget Riley's *Blaze 4* (1964) - Credit: artsy.net

Figure 3.25: Victor Vaserely's Zebra (1937) - Credit: wikiart.org

terns with strong contrast (usually black and white) of foreground and background, to create optical illusions that can either confuse or excite the eye. Op-Art, usually gives the viewer the impression of movement, warping, hidden images or flashing and vibrating patterns (Opart2, 2020). Historically, the Op-Art style may be said to have originated in the work of the kinetic artist Victor Vasarely (1908-97) as well as from Abstract Expressionism. Zebra, one of his best works, is shown in Fig 3.25. Another major Op artist is the British painter Bridget Riley (b.1931). By the end of the 1960s the Op-Art movement had faded.

3.5.2.1 How Does Op-Art Work?

Op-Art exploits the functional relationship between the eye's retina and the brain. Certain shapes cause confusion between these two organs, resulting in the perception of optical effects. These effects fall into two basic categories: first, movement caused by particular black and white geometric patterns, such as those in Bridget Riley's earlier works (Fig. 3.24), can confuse the eye even to the point of inducing physical dizziness. Op-Art's association with the effects of movement is why it is regarded as a Kinetic art division. Second, after-images appear after viewing pictures with specific colors or color-combinations. The interaction of differing colors in the painting-simultaneous contrast, successive contrast, and reverse contrast - may cause additional retinal effects.

3.6 Neuroaesthetics

In this chapter, *Neuroaesthetics* is briefly covered, a growing field for those interested in the intersection between art and science and has connections to this research. The word "aesthetic" (from the Greek aiesthesis, having to do with the senses) was first used in 1735 by Alexander Baumgarten, a German philosopher in a book on poetry. Since that time, it has been employed in two different, but not always distinct, ways. Even though the meaning of "aesthetic has strong historical connections with the arts and with artworks, a second usage has come to refer to any value system having to do with the appreciation of beauty, such as the beauty of nature" (Brown and Dissanayake, 2009). Enlightenment philosophers and their followers gradually developed the now elitist notion of "the aesthetic" — a special form of disinterested knowledge and appreciation—to describe the emotional response elicited by the perception of great works of art (Shiner, 2001); (Brown and Dissanayake, 2009).

Baumgarten coined the term 'aesthetics' to refer to the science of perception. Artists' formal methods can cull the structural features necessary for constructing precise perceptual representations from a dense flux of sensory information in conscious experience. Therefore, he further interpreted artists' formal methods as tools for studying the structure of art and perception as a field where the interests overlapped with aesthetics (Seeley, 2006). As it is referred to today, neuroaesthetics got its formal definition in 2002 (Nalbantian, 2008) and is an emerging field within cognitive neuroscience. It is concerned with the neural underpinnings of the aesthetic experience of beauty, particularly in visual art. Early neuroaesthetic writings in the late 1990s by Semir Zeki and neuroscientist Vilayanur Ramachandran identified parallels between an artist's approach to his or her visual world and the brain's visual information processing (Chatterjee and Vartanian, 2014). One key question for this field is whether art or aesthetic preferences are controlled by a set of scientific laws or principles.

Neuroscientific research has approached this area using imaging and neurophysiological techniques, such as *functional magnetic resonance* (fMRI), *magnetoencephalography* (MEG) and *electroencephalography* (EEG). The results produced so far are very heterogeneous (Cinzia and Vittorio, 2009). According to Suzanne Anker, a media artist, "Consciousness is layered by experience, education, and connoisseurship" (Buchholz, 2006), adding that these levels of awareness inform the way we look at images. "This is true of scientists looking at MRI scans as well as artists looking at a painting or a sculpture." The cerebral cortex, the hypothalamus, the Corpus Callosum (section 3.1) - each of these parts of the brain comes with its shape and essence, available to be probed by the artist. However, even the elusive brainwave has been making - well, waves - in the artistic world for some time (Buchholz, 2006). According to Chatterjee and Vartanian (2014), "because aesthetic encounters are common in everyday life, exploration of their biological bases can deepen our understanding of human behavior in important domains such as mate selection, consumer behavior, communication, and art". The discipline is at a historical inflection point and is poised to enter the mainstream of scientific inquiry.

3.7 Auditory Scene Analysis

Auditory Scene Analysis (ASA) is the aural equivalent for visual perception explored by Albert Bregman. It is a proposed model based on auditory perception. According to (Bregman, 1994) ASA is described as: "the process by which the auditory system separates the individual sounds in natural-world situations, in which these sounds are usually interleaved and overlapped in time and their components interleaved and overlapped in frequency". Thus, ASA can be understood as the process by which the human auditory system organizes sound into perceptually meaningful elements (ASA, n.d.).

This research primarily deals with visual perception. However, Gestalt Principles' application through the principles of grouping as well from a sonification standpoint is briefly discussed, in this case, the grouping of the sensors, which is discussed further in Chapter Five.

3.8 Chapter 3 Discussion

An overview of visual perception ranging from eye anatomy, psychology to artistic works involving optical illusions was presented. It is important to understand that what may confuse how humans perceive may not be just one reason but a myriad of reasons. Even though many artists are not trained in neuroscience, they still understand visual perception mechanisms and used them in their artworks. They knew how to use colors, for example, to create depth perception. It begs the question; can science learn from art and vice versa? The use of optical illusions in art is not new. However, the use of optical illusions in conjunction with BCI technology is very rare. The data used in this research was retrieved following scientific methods and based on visual perception resulting in looking at optical illusions.

Chapter 4

Previous BCI artworks

> "To develop a complete mind: Study the science of art; Study the art of science. Learn how to see. Realize that everything connects to everything else."
>
> Leonardo Da Vinci

As was previously discussed in section 2.1, Brain-Computer Interface (BCI) research classification is between active, reactive, and passive BCI. With the active and reactive BCIs, it is expected that the users know what their roles are in controlling the system. Additional ways in which a user's brain waves are converted into commands for intended communication and control are also possible. In clinical BCI research, the main paradigms (section 2.3) are motor imagery (active BCI) and event-related and evoked potentials (reactive BCI) (Nijholt, 2019). Passive BCI or translating passive BCI into active BCI has been used in many artistic interactive BCI applications even before clinical BCI research.

Artists make use of the possibilities BCI paradigms can offer to the design of an) application or artistic system (interactive). Instead of having a design based on a single paradigm, a multiple paradigm system can be used where brain wave information is merged with information from other sources (Nijholt, 2019). This means that brain wave input can be integrated into multimodal interactions (Gürkök and Nijholt, 2012), including other physiological information such as respiration or heartbeat.

Commercial grade BCI hardware and software also made it feasible that, even with very limited knowledge about BCI technology or commercial BCI software and hardware, one can still develop artistic BCI applications. Artists explore how BCI technology can contribute to their ideas about artistic expression (Nijholt, 2019) and how it can also influence their way of creating art.

The following sections of this chapter will cover more on BCI application in the artistic domain, including the author's previous works.

4.1 Brain-Computer Interfaces for Artistic Expression

As presented in Chapter 2, brain waves for artistic expression go back to the 1960s. During this time, BCI artists were inspired by neuroscientific research (alpha application) and looked for collaboration often with neuroscientists and gave brain waves a role in their installations. They discovered how to use the signals through real-time generation and control of sound and images. These artists came up with ideas that were away from the research; however, they could be considered 'artistic hypotheses'

(Nijholt, 2019) in their creative applications. The use of brain waves in interactive installations or performances was very challenging. It brought about new ways of experiencing art and the brain process involved in manipulating and evoking brain responses to performances and art installations. Many artists of the late 60s and 70s also believed that there could be interaction with two or more subjects and that subjects can become aware (through audio-visual feedback) of each other's brain activity. This artistic approach will be presented later in this chapter—most BCI artistic applications during this time control alpha activity.

4.1.1 Early Works in Brainwaves and Art

Alvin Lucier

In 1965 Edmond M. Dewan (1939-2009), a scientist, and Alvin Lucier, a composer, collaborated on experiments using alpha waves in musical compositions and performances. As a result, Alvin Lucier composed his *Music for Solo Performer* in 1965 (Fig. 4.1). He performed this composition sitting on a chair with electrodes attached to his head, not physically active except for his eyes' opening and closing. All this, while his amplified brain waves were routed to loudspeakers (See technical sketch Fig. 4.2 [1]).

Music for Solo Performer emerged from Lucier's artistic collaboration with biofeedback techniques and neuroscience research adopted from cybernetics, an interdisciplinary scientific field premised on technological paradigms of control and communication that was first articulated during the 1940s and 1950s (Barrett, 2017). Alvin Lucier's performance is regarded as the first BCI and art creation, which inspired many other artists at the time and even to this day.

[1] Novello, Alberto. "From invisible to visible, the EEG as a tool for music creation and control." Based on my Master's Thesis for the Institute of Sonology, Den Haag (2012).

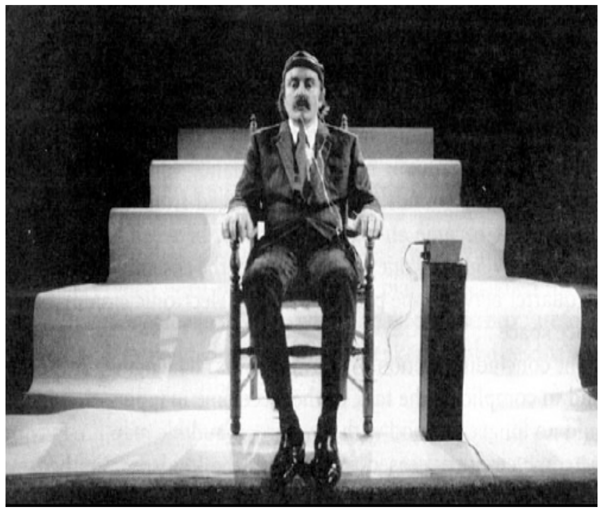


Figure 4.1: Alvin Lucier performing “Music for Solo performer - 1965 Credit: artbrain.org

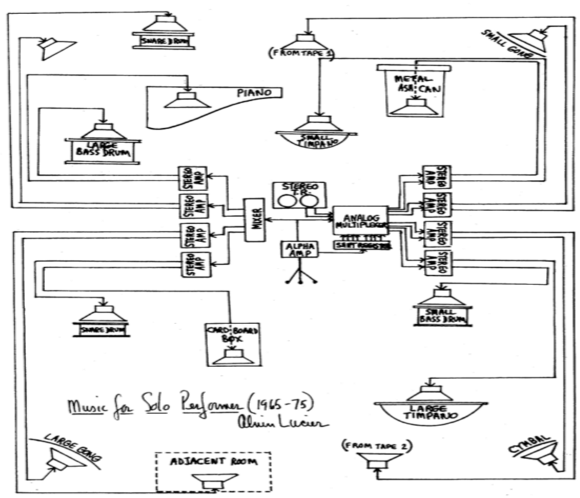


Figure 4.2: Technical layout for for Solo performer Credit: Novello, 2012

Richard Teitelbaum

Richard Teitelbaum (1939 - 2020), a composer and pioneer in brainwave sonification, explored using an amplified EEG signal to control a source for analog sound synthesis. Lucier wanted to communicate the natural frequencies of brain activity through acoustic sound sources. In contrast, Richard Teitelbaum started to incorporate biosignals into his electronic compositions using modular synthesizers. Inspired by Lucier and new advances in synthesis technology, Teitelbaum started integrating EEG signals in tandem with other bio-signals into his works. Here, the brain's electrical activities were electronically sonified in real time, providing a real-time bio-feedback loop for the performer (Teitelbaum, 1976). His work *Spacecraft* (1967) was a wholly improvised composition as it offered "a foundation for his later uses of brain waves that sought to investigate elements of control and musical interaction (Eaton, n.d.).

Manfred Eaton

Using adaptive biofeedback in music was explored by Manfred Eaton (Eaton 1971), who combined visual and auditory stimuli. He took a multimodal approach in his BCI art. He used EEG and other physiological input such as heartbeat, galvanic skin response, etc., to create what he called *Biomusic: sounds based on measured physiological signals*, which would reciprocally alter the sensory activities of participants, thus creating a feedback medium, in Eaton's terms, for "real-time," "multi-directional communication on a physiological level," a "spontaneous" form (Lysen, 2019) of communication (Eaton, 1974).

David Rosenboom

David Rosenboom, another pioneer in BCI and art, gathered many projects and experiments on brain waves, biofeedback, and the arts from the late sixties and early seventies (Nijholt, 2019); (Rosenboom, 1977). Most of his projects focused on the control of alpha waves; however, there is also mention of beta and theta and evoked responses in some of his works. Rosenboom conducted experiments that address the synchronization of brain waves, usually of two subjects having to perform a particular creative task. Beyond sonification is brain-controlled Music by David Rosenboom. According to Rosenboom, his piece *On Being Invisible* is an "attention-dependent sonic environment". This sonic environment is produced by a brain-controlled set of electronic sound modules acquired from several inputs: small instruments, voice, and brainwaves (Nijholt, 2019).

Nina Sobell

Figure 4.3: Nina Sobell's *Brainwave Drawings* (1973) Image credit: (ADA Digital Art Archive)

Nina Sobell, an installation artist, has been making art from brainwaves since the 1970s, when biofeedback, alpha machines, and video had been popular. Sobell's early installation in BCI art *Brainwave Drawing* hooked up two people at a time to an EEG machine and then connected the output to an oscilloscope. The oscilloscope images of the combined brainwaves were superimposed over live TV monitor images (Fig. 4.3) of the subjects' faces (Buchholz, 2006), with their brain wave drawings in the form of a Lissajous pattern that shows the two incoming frequencies (one representing each subject), and the pattern becomes an ellipse when the frequencies are identical (Nijholt, 2019).

Erkki Kurenniemi

Finnish artist Erkki Kurenniemi's was also experimenting with EEG in the 1960s-70s. His instrument *Dimi-T* used EEG to control an oscillator's pitch (Ojanen et al., 2007).

To summarize, in the early years of BCI art, artists explored new ways of creating interactive art that typically involved more than one participant in the art creation. They were often geared towards an audience that experienced how performers' brain waves affected the audio-visual performance. There was interest at that time in experimenting with the brain by meditating, using drugs, or being exposed to devices that evoked some visual hallucination (Geiger, 2003); (Haill, 2014); (Ter Meulen et al., 2009) using stroboscopic light, which affected the alpha waves. For example, the Dream Machine, later called the *Dreamachine*, was a machine that used light flickering to evoke alpha waves developed by Brion Gysin in the 1960s (Nijholt, 2019).

4.1.2 Recent Works Using EEG Sonification

There are many works out in the past 15 years there that use raw EEG signals to create artistic works. A few of these works are highlighted in this section. Each artist has his or her own style and artistic narrative for the EEG based work.

Lia Chavez

New York-based visual artist Lia Chavez has created a method by which viewers can witness the interrelation between their brainwaves and the vibrations that create sound and light. For her interactive and multidisciplinary installation, *The Octave of Visible Light: A Meditation Nightclub*, Chavez directs electrical impulses in the brain to engineer fully immersive sounds and fleeting light works.

Suzanne Dikker

Suzanne Dikker, a cognitive neuroscientist, and Matthias Oostrik, a computer artist and software developer who also specializes in interaction design, worked on projects together that use neuroscience to investigate the evasive nature of human interaction. Their collaboration, the *Mutual Wave Machine* (MWM), is an equal parts experiment and artistic installation, seeking to understand the mechanisms behind the successful synchronization between two people's sets of brainwaves.

Mariko Mori

Mariko Mori's *Wave UFO* (Fig. 4.4) brought together brainwave technology, real-time computer graphics architectural engineering and sound to create a dynamic interactive experience. "Wave UFO offers an alternative, non-reductionist way to understand the complex interplay between the biological and cultural mechanisms underlying human experience; it productively complicates and augments neuroscientific studies of human experience as well as their dissemination into other social and cultural arenas" (Mondloch, 2016).

Claudia Robles-Angel

Robles-Angel's work and research spans different aspects of visual and sound art, which

Figure 4.4: Mori's Wave UFO installation. Credit: www.medienkunstnetz.de/works/wave-ufo

"extend from audio-visual fixed media compositions to performances and installations interacting with biomedical signals via the usage of interfaces such as, for example, the BCI (Brain Computer Interface) measuring brain waves activity" (Robles-Angel, 2020). This is shown in her work "InsideOut Performance" [2].

4.2 Previous BCI Artworks Using Evoked Potentials

During the 1970s, other ways of stimulating and measuring brain activity were also discovered, such as event-related potentials (ERPs) and evoked potentials (EP). Jacques Vidal drew attention in his research to 'evoked responses' of the brain, embedded in ongoing electrical activity, because of exposure to sensory stimuli (visual, auditory, etc.). Influential papers that discussed explicit external stimuli and their impact on brain waves also appeared during that time. However, their reported research results were picked up by artists, and BCI-based clinical research interest had to wait two decades before it started to develop. Changes in potentials because of exposure to ex-

[2] http://s751373519.online.de/insideout

ternal stimuli were reported in (Picton et al., 1974); (Nunn, 1976); (Nijholt, 2019). The possible role of event-related potentials in music perception, composition, and performance was explored, especially aspects of expectancy and shifts in attention (Rosenboom, 1999). Rosenboom also made observations on brain waves evoked by imagining an event, an 'attention-dependent sonic environment' and in the ongoing development of his already existing composition *On Being Invisible* (Nijholt, 2019).

4.2.1 Previous Clinical BCI Works Using VEP

There was previous research conducted looking into optical illusions and their effect on brain waves. In (Hongsuo et al., 2011), an experiment was conducted to find the locations and mechanisms of brainwaves when human beings observed 2D optical illusion stimuli. They found that the response to the optical illusion had different response times and voltage with the different coarseness at the primary visual area (V1). They also concluded that their experiment results suggested that the band powers of the V1 were different. The Pz and POz locations' responses had negative peaks (N2) at 80 ms and 120 ms during the presentation of the stimuli. This suggests that the "illusion experiment and the identification experiment had similarities", because they saw a negative peak in about 250 ms.

(Zhe et al., 2016) conducted an experiment to analyze the brain's response to several optical illusion stimuli. The stimuli included cognitive, geometrical, and physiological illusions.They found that when participants observed cognitive illusions that more gamma waves were generated. They also found that when participants focused on physiological illusions that the brain caused more beta waves. They concluded that there was an increase in alpha waves in general with optical illusions and suggest that with optical illusions there is an increase in coherent brain signal transmission, resulting in "more intuition and imagination" compared to non-illusion patterns. Based on the conclusion of two previous studies listed above, there generally tends to be a change in brainwave activity that can occur when someone is looking at illusions. (Hongsuo et al., 2011) also called for more experiments to be conducted to confirm their findings.

4.2.2 SSVEP-Based BCI

The (Miranda, 2014) paper reports on the development of a proof-of-concept *brain-computer music interfacing system* (BCMI), which was tested on a patient with Locked-in Syndrome, described as a rare neurological disorder characterized by complete paralysis of voluntary muscles, except for those that control the eyes (Lockedin, n.d); (Rousseau et al., 2015). People with locked-in syndrome are conscious and can think and reason but are unable to speak or move. Communication is usually done with vertical eye movements and blinking (Lockedin, n.d); (Bruno, n.d.). The system uses the Steady-State Visual Evoked Potential (SSVEP) method, whereby targets are presented to a user on a computer monitor representing actions available to perform with the system (Miranda and Brouse, 2005). Each target is encoded by a flashing visual pattern vibrating at a specific frequency. If the users wanted to make a selection, then they must direct their gaze at the target corresponding to the action they would like to perform. This will then allow the user's brain to also vibrate at that specific frequency. When the device detects a particular frequency, it then translated that into a command. For example, move the cursor to the right when a frequency of 10 Hz is detected.

Figure 4.5: P300 Composer Interface - Credit: Grierson and Kiefer

4.2.3 Brain-Computer Music Interfaces

In (Grierson and Kiefer, 2014) research emphasizes the use of P300 event-related potentials (ERPs) in the development of brain-computer music interfaces (BCMIs). Grierson explores a recent study in the P300 BCI area, which may impact the usability of future BCI systems for Music. He and his team have developed the P300 composer, P300 DJ, and the P300 sequencer.

The P300 is based on the reactive BCI paradigm. The *P300 Composer* displays a grid of possible music note-names from A1 to G5, notes, and rests, as shown in Figure 4.5. Grid elements flash an equal number of times, in random order. The P300 averaging technique looks at the highest averaged amplitude signal. The user needs to attend to a specific grid element (reactive), by actively noticing when it flashes (Grierson and Kiefer, 2014).

Eduardo Miranda and his team in the UK develop BCMIs that take EEG signals and map them to musical parameters (Fig. 4.6). He works a lot with Locked-in patients to help them still be creative in some way. He developed a system to use EEG sig-

Figure 4.6: Miranda's Brain Computer Music Interface - Credit: newatlas.com

nals to "steer generative rules to compose and perform music" (Miranda, 2014). Different EEG features, such as the activation of various frequency bands and others, are mapped into the generative rules and control the performance's tempo and loudness.

(Knapp and Lusted, 1990) developed the *Biomuse*, a performance device that takes physiological data (EEG and EMG) and maps them to musical parameters. Adrian Attard Trevisan's research involves the sonification of EEG waves by designing BCI systems that convert these waves to Music (via MIDI) (Trevisan and Jones, 2010).

4.3 Design and Control of Artistic BCI

BCI can give us insight into how someone experiences Music and visual events and the responses to these events. Questions could be asked: are there changes to brainwave activity in reaction to auditory stimuli? Measuring evoked ERPs during a live performance can be used to decide how to continue with the performance. This gives the performers or audience members a way to control the performance. Unfortunately, ERPs usually require averaging over a number of trials, which creates a problem for live or real-time performance or interaction (Nijholt, 2019).

(Wadeson et al., 2015) identified four main control types of artistic BCIs:

- ***Passive***: Heavily reliant on preprogrammed artistic material. These systems are built to respond to certain brainwave signals, which do not require interaction or intention from the user to create the desired signals.
- ***Selective:*** Allow for the interaction of the user utilizing, controlling emotion, levels of relaxation or excitement, etc. to affect the end artistic result. However, the output depends on the application's pre-programmed artist material and not by the user's direct control.
- ***Direct:*** Users can choose a specific output from the toolbox-style application, such as musical notes, brush styles or shapes, etc.
- ***Collaborative:*** Allows multiple users to interact with each other or individually to create unique artistic experiences collectively.

4.3.1 BCI as Artistic Tool

Tools that create art need to be controlled by the artist. Therefore, the active and reactive control of a toolset is the first requirement. Interaction is the making or manipulation of an artwork. EEG detected voluntarily and involuntarily evoked brain waves can play a role in creating, experiencing, and interacting with a piece of art, whether it is from the artist or viewer. Artistic performances can be 'brainwave' interactive, where passive, reactive, and active BCI paradigms are involved. BCI can be used to create a piece of art or control a tool. It can measure how a piece of art is experienced, as well as interact with a piece of art, and via these interactions. It can make the piece of art come alive, so to speak. Changes can be virtual; they can be real-time while we are experiencing art, they can be off-line, that is, BCI experiences can be collected and used

Invasiveness	• Invasive • Semi-invasive • Non-invasive
Electrodes	• Type (Wet, Semi-dry or Dry) • Number • Placement
Sample Rate	
Output Data	• Raw • Brainwaves: alpha, beta etc. • Hybrid: Attention, Meditation etc.
Battery Type	
Price Range	
Commercial Name	

Table 4.1: Taxonomy of BCI Devices used in BCI Art

to decide about changes later, whether done by the artist or by the (digital) art itself (Nijholt, 2019).

4.4 Taxonomy of BCI in Art

To provide and understand BCI art, there has to be an overview of BCI approaches, ideas, and implementation. In this section, the state of the art in BCI use in modern-day art is presented. (Prpa and Pasquier, 2019) conducted research on BCI devices (Table 4.1) and how they were employed in BCI art for the past 53 years and presented a taxonomy of BCI artworks (Table 4.2).

Here, four subcategories of the input dimension are described: EEG classification approaches, agency paradigms, timeliness of the input, and modality of input. The definitions and types of EEG were already discussed in Chapter 2.

Input	EEG classification	Long-term coherent waves Short-term coherent wavesHybrid
	Agency	Active Reactive Passive
	Timeliness	Real-time Pre-recorded
	Modality	EEG Multimodal
Mapping	Direct Indirect Adaptive	
Output	Visual (visualization, painting, images) Sound (sonification, music) Audio-visualMoving images (generative) video Panorama Immersive (virtual/augmented reality) Physical object	
Format	Installation Performance Screen-based	
Audience	Active (interaction) Passive (observing)	

Table 4.2: Taxonomy of BCI Art Works

4.4.1 Input of BCI Artworks

Within BCI artworks, the following categories for input are presented: EEG classification, Agency, Timeliness, and Modality. We can separate the EEG into three subdivisions: the *Long-term coherent waves* (LTCW), *Short term coherent waves* (STCW), and *Hybrid*.

4.4.1.1 EEG Classification

Brainwaves that are recorded can be classified by their amplitudes, frequencies, location, and shape (Kumar and Bhuvaneswari, 2012). Raw, unprocessed data of the brain's electrical activity exposes background noise mixed in with brainwaves. Therefore, to better understand the relationship between brainwaves and the presented stimuli or cognitive processes, two distinct approaches are discussed. The first approach is the recording and analysis of LTCW, the second, STCW (Rosenboom, 1999), and the third approach, Hybrid, which emerged as a result of the progress in artificial intelligence and machine learning. The Hybrid builds upon LTCW and STCW by using all possible data combinations to train artificial models for feature extraction and prediction.

The LTCW approach, also known as neurofeedback, captures EEG activity and classifies it based on brainwave frequencies range from 1 to 30 Hz. It is believed that the prominence of different brainwaves varies in some parts of the brain more than others and that the probability of capturing a particular brainwave can be increased by positioning electrodes in the regions of the brain associated with it. SSTWs are the brain's responses to sensory, cognitive, or motor stimuli. They last between 300 ms to several seconds (Nijholt, 2019); (Stern et al., 2001) and are observable as cortical electrical activity changes after the stimulus. These *event-related potentials* (ERP) are time-locked

EEG activity, which means that they occur after a specific time following a sensory stimulus or cognitive process. The P300 is a good example of this since it stands for an ERP that occurs around 300 ms after the onset of an event that can be either a visual or audio stimulus (maybe both), or a thought (Nijholt, 2019); (Panoulas et al., 2010). Other than ERP, the different approach to input EEG classification builds upon *Steady-State Evoked Potentials* (SSEP). As discussed in Chapter 2, Steady-State Visual Evoked Potentials are brain responses evoked by visual stimuli at frequencies ranging from 3.5 to 75 Hz. When the Retina is visually stimulated, the brain generates an electrical response at the same frequency as the frequency of visual stimuli. Exposing the audience to visual stimulation of a particular frequency at the same time opens a design possibility to utilize as many input points as there are audience members, whose now altered brainwaves are synchronized.

Hybrid is the third and most recent approach allowed by the development in the machine learning domain. With the hybrid approach, the device's proprietary software employs machine learning models to capture EEG data to detect complex categories of affective or cognitive functioning. One example of such hybrid classification is *Emotiv*'s MyE-motive suite (previously known as EPOC Affectiv Suite), which allows participants to measure cognitive metrics such as interest, excitement, relaxation, engagement, etc. (emo, n.d.); (Nijholt, 2019). *NeuroSky*, another device that provides values such as attention, meditation, blink detection, mental effort (engagement), familiarity, cognitive preparedness, creativity, etc. (Nijholt, 2019); (neu, n.d.). *Interaxon*'s Muse headband is more limited in what they measure and only outputs levels of meditation (Nijholt, 2019). Since none of these commercial EEG devices provide insights as to how they derive their cognitive categories, how these levels are measured or extracted from the raw data creates speculation and ambiguity on their algorithms and processes.

4.4.1.2 Agency

In this section, three BCI agency paradigms are described along with some illustrations. For this input category,“agency” serves as a better reference than “control” for several reasons: first, in the context of BCI artworks, the participant-artwork interaction is not always built upon the control of the creative output. Usually, a participant’s brain activity is used in the artistic output without the participant’s awareness of their explicit “control” over the artwork. Second, the agency in the taxonomy concentrates on the degree of impact that the participant’s brain activity has within the artwork, thus, revealing “the capacity, condition, or state of acting or of exerting power” (Nijholt, 2019). This allows the artist to have creative control over the final output, by selecting interaction paradigms that restrict or support the degree of the impact that the participant’s brain activity can have on the creative output.

Active Input Agency-The purpose of BCI technology as assistive technology was to allow people with sensory-motor or cognitive impairments to perform otherwise inaccessible actions (Millán et al., 2010); (Nijholt, 2019). In the following examples, the participant has active control over the performed task. This approach’s disadvantage is the lengthy and tiring training process that the participant needs to go through before using the BCI device.

Reactive Input Agency-employs brain activity that is changed by an external stimulus. The participant is paying attention to the stimulus. The participant’s short-term transient waves then reveal the presence of the stimulus with an onset time, and those fluctuations in brainwaves are then used as a reactive input control (Nijholt, 2019); (Zander and Kothe, 2011).

The Passive Input Agency

With this paradigm, the participants are not required to explicitly perform any specific task to alter their brain activity explicitly. Passive BCI has been advocated as an adequate technology for open monitoring of ongoing brain processes that are not always easy to capture otherwise and convert. An example of passive BCI: adaptive automation, like when the participant's engagement levels decrease while driving, the system takes control over the driving or notifies the participant on his or her mental activity.

4.4.1.3 Timeliness

Timeliness of input data refers to when data is captured, which is subdivided into real-time and pre-recorded (data acquisition occurred some time ago). This artwork in this dissertation employs pre-recorded data and mapping those into the artwork.
Modality of input refers to the type or mode of input. Most BCI artworks are monomodal; that is, they employ EEG-data only. Multimodality refers to an approach in which EEG data is combined with another physiological input such as EKG (electrocardiography), heartbeat, EMG (electromyography - pertaining to muscle movement), or GSR (galvanic skin response).

4.4.2 Mapping Strategies

The analysis of how EEG data is mapped to the artworks' parameters and interaction variations revealed a big issue: a lack of documentation about the mapping details. Most artwork documentation does not disclose mapping details, making their analysis hard, which then calls for speculation (Nijholt, 2019). Based on BCI artworks presented, three mapping strategies can be identified: direct, indirect, and adaptive. With Direct Mapping the input EEG data is always mapped to the same parameters of the artwork, and the output is somewhat predictable. Indirect Mapping used in artworks maps EEG data to one set of parameters, which then influences the values of another set of parameters. Adaptive mapping came from artificial intelligence and machine learning models based on algorithm capable of listening and changing how and to what EEG data is mapped. Based on an algorithm. Adaptive mapping could play a role in the ever-changing nature of an artwork.

4.4.3 BCI Artwork - Output Type

(Nijholt, 2019) gives two reasons for BCI visual output classification. The first, "the media used in these artworks convey visual information. Second, the artworks are not context-dependent, they do not occupy the space beyond a canvas or a screen, and do not create a sense of spatial immersion". It seems like most artworks in this category are grounded around looking for an answer as to how we can visually represent something invisible to our eyes. In attempts to demystify the brain and find answers to these questions, many artists try to capture brain activity and transform brainwaves into screen visualizations, digital prints, and paintings. This is also the case in this dissertation.

Sonic Output: Brain Sonification, Music and Opera Cerebral Music, an example of this is the first recorded brain music performance by Alvin Lucier in Music for Solo Performer from 1965, reviewed in section 4.1.1.

Audio-Visual Output of BCI Artworks In this category, two formats for audio-visual BCI artworks are presented: BCI audio-visual installations and BCI audio-visual performances. Audio-Visual Installations— in these types of installations, the participants, one at a time, explore different mental states while usually their Alpha wave activity is mapped to interactive soundscape or visuals. With the audio-visual performances, a performer's agency and presence can vary significantly from one piece to another. For example, performance can be brainwave-generated music and visuals projected on the screen in which the performer's presence is minimal.

Moving Images as Output In this analysis, three kinds of moving images are possible: live video footage, brain-controlled movies, and screen-based virtual environments.

Installations of Physical Objects Here, artworks that employ brain activity to directly manipulate properties or states of physical objects, typically designed for one participant, are presented. The participant usually is centrally positioned in the installation.

4.4.4 BCI Artwork - Presentation Format

BCI artworks usually come in three presentation formats. Screen-based, which are BCI artworks that are mobile or desktop-based applications. With the installation and performance formats, the artworks in both categories need human interaction, either real-time or recorded for the complete presentation. The performance format allows the artist to generate the output while the audience member plays the role of a passive observer. The installation format tends to open-ended where users/audience members can explore, usually with minimal guidance. These performances are more deterministic in what and how the artist wants to show.

4.4.5 BCI Artwork - Audience

Two roles of the audience member are described in this category. The first role: the active audience member wears the BCI equipment (real-time) while his or her brainwaves are directly sent to the artwork to control it. The second role is that of a passive observer, the spectator of the installation or performance.

4.5 Technical Challenges in BCI Art

Even though consumer BCIs tend to have a low spatial resolution and do not give a detailed picture of the entire brain process. Setup time before one can use the device is also another issue. Signals are also very noisy that require preprocessing, such as filtering. These disadvantages can affect BCI art that is created. Besides the BCI device issues, the BCI artworks themselves can come with their own set of problems such as:

- ***Irreplaceability***—The lack of documentation can lead to misunderstood ideas and concepts and failed attempts to replicate the project. In science, every research step has to be well-documented. With art-making it is just the opposite. Lack of documentation makes the artworks irreplaceable (Nijholt, 2019), which may well be the artist's intent. However, well-documented artworks can help the field grow by creating new creative output possibilities by limiting the unknown.

- ***Reliability***—EEG data acquired by the device is crucial to the BCI artwork process. Hence the type of electrode used is therefore also important. Wet electrodes are the preferred type of electrodes used in research labs. They require a wired connection and gel or paste application. Wireless is more popular with BCI artists because they allow for user mobility. Wireless headsets are also criticized for not being as accurate as wired headsets because of connectivity issues. Wireless data packets can be dropped during transmission. According to (Nijholt, 2019); (Davis et al., 2013), there is a need to address the importance of hybrid electrodes "for the democratization of affordable and reliable measuring tools that are easy to set up outside of labs".

- ***Open-sourcing and transparency***—Two limitations discussed here are the compatibilities of BCI systems across platforms and data transparency. If BCI application were also made for mobile devices like smartphones/tablets a broader range of applications that require greater mobility would be possible (Millán et al., 2010). As previously mentioned, most commercial BCI devices do not include free access to their raw data or provide and Software Development Kit (SDK). Interaxon, the creator of the Muse Headband used to provide a free SDK and decided to no longer do this. Emotiv, creator of Epoc+, used to provide an SDK and access to their raw waves with their research-grade EEG device and no longer does this. They now want to force users into a monthly subscription. OpenBCI, a New York-based company thus far, still provides access to the open-source raw data and SDK.

With these limitations, the artist is presented with two options, a) to use the available devices and trust their algorithms in how they sort out raw data and mental states and b) find a way to hack devices or DIY if they want to use raw data and apply open-source algorithms.

4.6 Author's Previous Works

In this chapter, the author's previous research and practice on creating various artworks related to BCI art are discussed. The practices explore various artistic experiments and methodologies on related topics such as biological art, EEG sonification, and how they lead to developing the objectives and goals of this current research. Those related topics have been critical parts of creating final artworks in both context and technical aspects in conjunction between art and technology. Brief descriptions, technical implementations, and results with images are provided.

4.6.1 NYU Grant Project

The author conducted research titled: "Using Electroencephalography (EEG) in Music Composition and Production", which received a Challenge Grant in 2014. This research involved designing a BCI system that extracts, filters, analyzes, and maps EEG signals (brain waves) into musical data. A hardware device will acquire the signals from the user's head, which is then sent to software written using Emotiv's EEG API and Max/MSP to filter and map the signals to musical output generated in real time. After training with the system, users can manipulate the program using their eye blinks and mental state. Testing and training the system will lead to further research on how and what type of brain waves are best suited for creative music applications. User studies of the system were documented to improve the accuracy of the system. This project's broader goal was to use the system for both academic (learning) and clinical purposes (practical). The system was ultimately designed with disabled people in mind, particularly those with limited to no mobility. The program would serve as an aid in helping these people express themselves creatively.

4.6.2 BSoniq

Another previous work of the author presented at the International Conference of Auditory Display (ICAD) in 2017 is *BSoniq*: a 3-D Sound Installation a multi-channel interactive neurofeedback installation which, allows for real-time sonification and visualization of electroencephalogram (EEG) data (Mathew et al., 2017). This EEG data provides multivariate information about human brain activity. Here, a multivariate event-based sonification is proposed using 3D spatial location to provide cues about these events. With *BSoniq*, users can listen to the various sounds (raw brain waves) emitted from their brain or parts of their brain and perceive their brainwave activities in a 3D spatialized surrounding, giving them a sense that they are inside their heads.

4.6.3 Master's Thesis

The author's NYU Master's thesis was titled: *A real-time Brain-Computer Music Interface,* a brain-computer interface (BCI) for Music that uses electroencephalogram (EEG) data to steer mapping rules to perform and compose music was introduced. A hardware device acquires the signals from the user's head, which will then be sent to software written using Emotiv's EEG API (Affectiv Suite) and Max/MSP to filter and map the mental states to musical output generated in real time. Numerous mapping methods analyzed human physiological signals to audio synthesis parameters to build biologically-driven musical instruments. Here a reusable and flexible framework for musical applications using biological information has been created and evaluated. Here, two interfaces are explored: *Brain Granulizer* and *Chord Changer*. The user can create sonic textures via granular synthesis with Brain Granulizer. The user's emotional states can be used to control various parameters to create sonic textures. Chord changer allows the user to change the chord qualities by changing mental states. These two systems both use the Emotiv Epoc affective algorithms to control the musical systems. Max/MSP is used to transform the affective data into musical output.

4.7 Chapter 4 Discussion

The artistic BCI performance application goes back to the mid-60s. The pioneers at the time all took different approaches to their EEG music creation. For instance, Alvin Lucier's approach directly connected amplified brain signals to loudspeakers to produce sound via a kinetic phenomenon. Richard Teitelbaum used EEG signals as voltage control the parameters on a synthesizer. David Rosenboom sought to understand and investigate features that underly brain signals to consciously control musical structure to a certain degree. Looking from a general overview in brainwave music, it seems that modern artists tend to choose Teitelbaum's approach due to its real-time, technological simplicity of creation, and ability to intrinsically evoke expectations in the audience. These artists tend to use commercial EEG devices such as the Emotiv[3] because they come with built-in software packages capable of sending control parameters via Open Sound Control. These composing/performing scenarios make it easy to perform with these devices; however, this can create a platform or tendency to allow performers to fall into these stereotypical performances.

When dealing with EEG data derived from an experiment (reactive) and designing a data-driven system, certain questions should be considered. Should there be any requirements when composing or performing to allow the audience to understand what is going on? Should the audience be involved? What type of control (mapping) should be embedded in the instrument? The output and the system construction should have a role in the artist's choice of the generated output during the performance.

4.8 Conclusion

This chapter presented artworks that work with BCI paradigms and taxonomy. The various mapping strategies used in previous BCI artworks are also presented. Understanding these strategies is very important to the development of the BCI artworks in this dissertation. It gives insight into what works best in BCI artworks. However, most of the works presented in this chapter used mental states or manufacturer algorithms for EEG devices that are unknown to users. Another issue is that Digital artworks, es-

[3] https://www.emotiv.com/

pecially those in BCI, are not usually structured and classified due to the lack of documentation. This is mainly because most artists may not want to make their code open-source or discuss their artmaking strategies. The works presented in this dissertation are discussed in detail.

Part II

Chapter 5

Methodology

> "Art and Science have their
> meeting point in method."
>
> Edward G. Bulwer-Lytton

5.1 Background

The previous chapters tracked a path in the development of BCI technology and the understanding of formation for the deeply-embodied nature of perception. This chapter emphasizes a pragmatist approach as it can be applied to sonification and visualization design. Sonification design being a generative activity where customized design skills are supported by scientific research in perception, biology, cognitive science, and aesthetics. It outlines essential features of a broad design methodology based on the understandings developed that could yield computational support. Going back to the formation of the Gestalt school of psychology, Chapter 3 provided an overview of Western civilization's understanding of the nature of perception and how humans use it to construct coherent meanings of the environment. Perceiving objects may seem to many as a trivial process, making it easy for us to ignore the complicated mechanisms involved in this process. Optical illusions are caused when the visual system makes assumptions. EEG data would be collected following scientific methods from a group of healthy subjects with normal (or corrected-to-normal) vision while they are presented with several illusions. This research's primary purpose would be to take the neural data and apply them in an arts-based practice.

In this part of the thesis, the design, implementation, and evaluation of two BCI artworks based on this neural data are presented. These artworks focus on the main aspects of sonification and visualization of the data, including data mapping and layout design. This evolving understanding created momentum in the development of the empirical method (Worrall, 2019). The past 65 years of scientific endeavor is based on this understanding, which continues to be the case today. The empirical method played an essential role in establishing psychology as its discipline, which led to establishing new fields, like artificial intelligence (AI) and neuroscience. Many research suggests that users' engagement with a stimulus can influence their cognition and perception of it and the information and understandings they derive from it when doing so (Gibson, 1966); (Worrall, 2019). This type of engagement allows for interaction or attention on several levels, including when done via interfaces.

The purpose of an auditory display is to convey meaningful information to a listener via sound. Knowledge of the cognitive and perceptual process that allows for their engagement is important to developing intelligible sonifications (Worrall, 2019). This is also implied in Sonification Report's definition of sonification as transforming data relations into perceived relations in an acoustic signal to facilitate communication or interpretation (Kramer et al., 2010). This is vital to sonic data representations or computational systems that model classes of design solutions that a layperson might use.

One of the Western thinking's main qualities is attempting to understand the nature of perception and how to use it to make sense of the world. This raises questions about the understanding of consciousness, particularly consciousness that has to do with the phenomenal perception of non-existing objects (Worrall, 2019). This is the central theme of this chapter, which is in both sonification and visualization design by combining both the practical and conceptual issues as well as a software sonification framework that needs to be considered. This allows listeners to situate themselves regarding a dataset, especially an EEG dataset, so they can retrieve information as much as possible from it as meaningfully as possible.

5.2 Why Visual Illusions?

Visual illusions can show visual perception mechanisms by using patterns, light, and color that create images, which can be deceptive to our brains. In this research, four optical illusions are used in this human subject experiment: The Stepping Feet, Rotating Snakes, Reverse Spokes wheel, and Cafe Wall illusion.

5.2.1 Visual Stimuli

This section will cover the four stimuli used in the experiment in detail. The following four illusions were used in this project because they use literal motion and static (illusion) motion. According to Michael Bach[4], who did much research in optical illusions, he described in an email conversation the following in terms of illusion type:
1) "Reverse Spoke Wheel" illusion, a local triangular luminance modulation, with different phase for each sector he described the type as 'Motion and Time'.

[4] https://michaelbach.de/index.html

2) The “Stepping feet” illusion is considered a motion illusion and described as ‘Motion and Time’.

3) The “Cafe Wall” illusion is considered static, which he labeled as ‘Geometric and angle’.

4) The “Rotating Snakes” illusion is considered motion - but it needs eye movements and is ‘Motion and Time’.

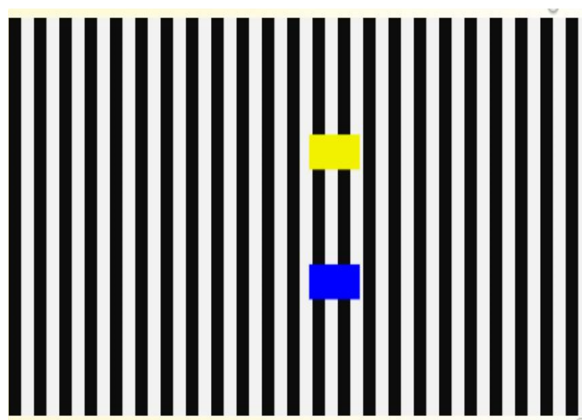


Figure 5.1: Stepping feet illusion - Credit: michaelbach.de

Stepping Feet

Two rectangles, one yellow and one blue, move horizontally across the display. When a specific type of background texture is present, the two rectangles seem to move in anti-phase. This creates an illusionary effect, which disappears when the background texture is changed or gone. These two rectangles resemble a pair of shuffling or stepping feet, hence the name: the stepping feet illusion (Mathot, 2012). Like any other illusions, this one also provides some insight into how our visual system works. The stepping feet illusion does not work with just any set of colors. There needs to be a luminance difference between them. One stimulus must be bright (the yellow rectangle in this case), and the other must be dark (the blue one). There also has to be a comparable luminance difference in the background, accomplished here through a pattern of alternating light and dark stripes. The blue and yellow rectangles move precisely in step, but they appear to speed up and slow down alternately when the background is striped. When the front and back edges of the blue rectangle lie on the black stripes, it lowers its contrast; therefore, the motion seems slower (Thompson, 1982). On the other hand, the blue rectangle edges have high contrast with the white stripes, so it appears as though the motion speeds up. The opposite holds true for the light yellow rectangle (Anstis, 2012).

Cafe Wall Illusion

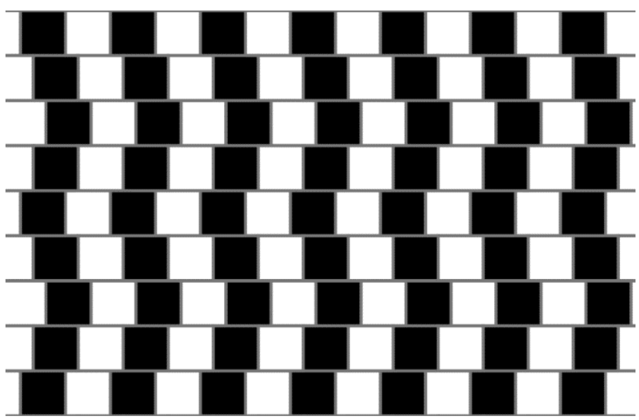


Figure 5.2: Cafe Wall illusion - Credit: wikipedia.org

The Café Wall illusion was first "noticed as a pattern in the brickwork of a café on St Michael's Hill in Bristol, by British psychologist Richard Gregory (1923-2010) (cafe-wall, n.d.). The Café Wall illusion is created with offset rows of tiles that alternate between dark and light ones surrounded by a visible line of grout. The grout is a shade somewhere between the two tile colors for the ideal effect. The tiles being offset by half a tile width makes the horizontal lines seem to slant diagonally, which creates wedges' appearance. Both the tiles' position and the grout's thickness and color in between them affect the illusion. When the grout lines are removed, there is no longer any illusion of diagonal lines. An explanation for this illusion is that "diagonal lines are perceived, because of how neurons in the brain interact. Different types of neurons react to the perception of dark and light colors and also due to the placement of the dark and light tiles, the different parts of the grout lines are dimmed or brightened in the retina. A brightness contrast across the grout line creates a small scale asymmetry where half the dark and light tiles move toward each other forming small wedges. These wedges are integrated into long wedges with the brain interpreting the grout line as a sloping line (cafewall2, n.d.).

Rotating Snakes

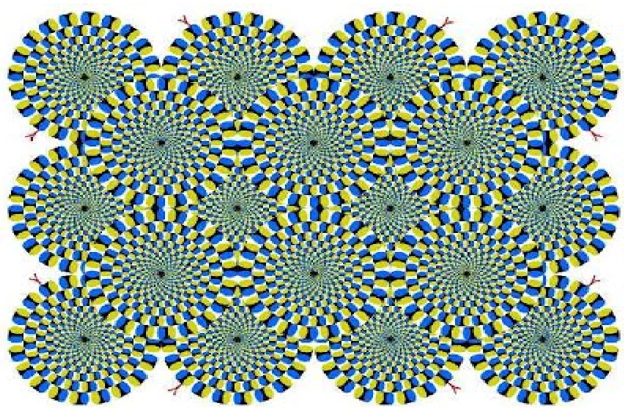


Figure 5.3: Rotating Snakes Illusion - Credit: http://www.ritsumei.ac.jp/ akitaoka

Different types of repetitive arrangements of luminance gradients can elicit the perception of illusory motion. The Rotating Snakes (Kitaoka and Ashida, 2003) is an example of this type of illusion (Fig. 5.3), which also sparked a lot of in the general public and the visual neurosciences (Otero-Millan et al., 2012). Repeated asymmetric patterns (RAPs) can make the visual system believe that there is motion.

Research suggests that tiny eye movements and blinking can make a geometric drawing

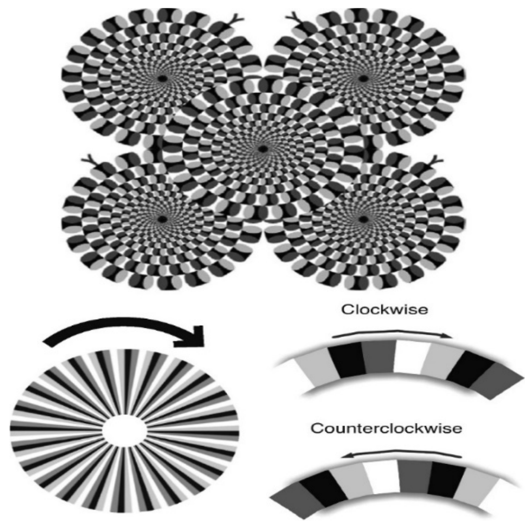


Figure 5.4: Rotating Snake motion direction based on luminance - Credit: A. Kitaoka

of “snakes” appear to move. Visual illusions can trick the brain into creating a mental representation that is different from the physical world. Illusion studies show the mechanisms by which the brain constructs our conscious experience of the world (Otero-Millan et al., 2012). Saccades, which are fast eye movements by the observer, drive the illusory motion. This type of illusion, usually referred to as peripheral drift illusion, was believed to occur due to slow drifting eye movements (Dobbs, 2017); (Backus and Oruç, 2005).

Reverse Spokes Wheel

Stuart Anstis developed this illusion in 2001 (Anstis and Rogers, 2011). The spokes (the grey lines separating the pie-slices) seem to rotate clockwise; however, this is not the case. There is a grayish color wave that travels counter-clockwise around the wheel in this illusion and the spokes get covered up by the pie slices. This occurs because two of the pizza slices are the same color as the spokes (Dean, 2012). The motion moves in the opposite direction of the movement that we perceive. Figure 5.6 shows a close-up of two pie-slices and a spoke. In step 1, the spoke is separated from the pie-slices.

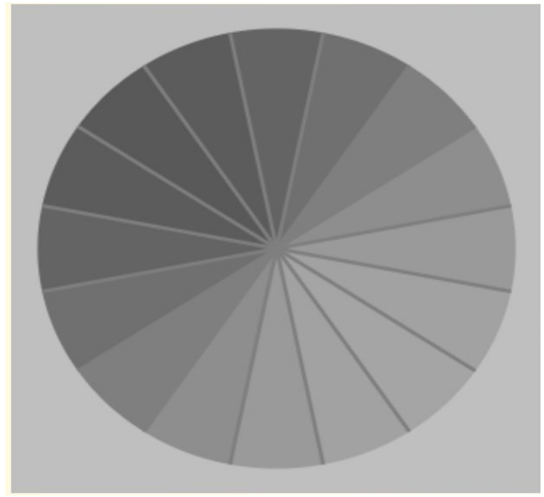


Figure 5.5: Reverse Spoke Wheel Illusion - michaelbach.de

When the pie-slices become brighter, the spoke also becomes the same color as the pie-slice on the right, meaning that the spoke becomes part of the right pie-slice. The boundary between the two pie-slices, as a result, is shifted to the left (step 2). In step 3, the spoke is the same color as the pie-slice on the left and which creates the appearance that the boundary between the pie-slices moved to the right, creating the illusion. The Gestalt principle of grouping is applied. The assumption that the viewer is grouping all of the spokes into a single object. Given that there are always exactly two spokes in motion (apparent), there is always a part of the object that makes it seem like the entire object appears to be in continuous motion (Mathot, 2010).

5.2.2 Visual Illusion Discussion

The illusions used in this research were presented and described. They were chosen to provide a variety of the types of illusion effect such as static, motion, and cognitive that should affect the VEP of the observer. The café wall illusion, for example, was chosen not only because of its motion but also for its checkerboard structure, which

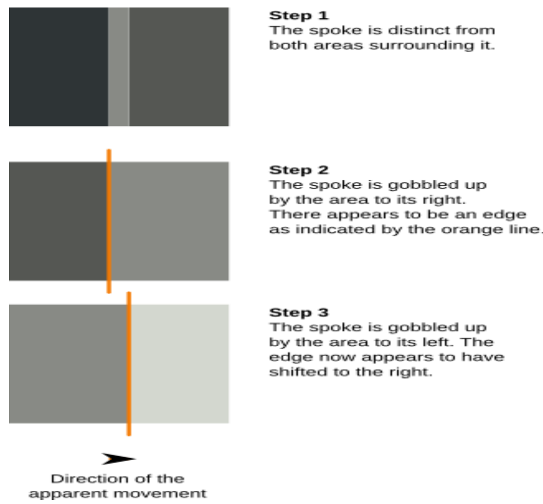


Figure 5.6: Reverse Spokes wheel illustration - Credit: S. Mathot
http://www.cogsci.nl/illusions/reverse-spokes

resembles the *checkerboard pattern reversal* [5]. This is the most widely used pattern stimulus given at clinical diagnostic VEP testing because of its simplicity and reliability. The Stepping feet illusion was chosen because it contains motion and contrasting colors. The Reverse spoke illusion was chosen because it contains subtle color contrasting. Most importantly, there is the Gestalt grouping principle at play (Bach, n.d.). Every spoke moves one small step per sector rotation but does this at a different time. Since all spokes are grouped, the entire spoke wheel is perceived as continuously rotating (grouping principle). So, based on this, it was interesting to see how the subjects would perceive this illusion. Rotating snakes were chosen, because of their color makeup and their popularity in other research. The details as to how the illusion was used in the experiment are discussed in the next section.

[5] https://webvision.med.utah.edu/wp-content/uploads/2011/11/VEPFig4.*jpg*

5.3 Experiment

This work builds on VEP research and the impact optical illusion may have on it. In this EEG Visual perception study experiment, sixteen participants' brainwaves are measured during the perception of images and optical illusions. This experiment's main goal is to see if there are changes in brainwave activity when the user perceives motion in the provided images. This experiment was UCSB IRB (Ohas) approved (No. 44-19-0410), and no video recording was done. Documentation for this experiment is in written form only. In this experiment, the OpenBCI Ultramark IV EEG device was used to record subjects' brainwaves over eight channels. The four cognitive illusion images described in section 5.2.1 are used in this experiment.

5.3.1 Experiment Setup

Visual stimuli were displayed on a 17-inch LCD monitor with a 60Hz refresh rate and 1920 x 1200 resolution, viewed from a distance of 50 cm.

Hardware: OpenBCI UltraMark IV EEG device [6]

OpenBCI 32bit Board:

- 8 differential, high gain, low noise input channel
- Compatible with active and passive electrodes
- 24-bit channel data resolution

Software:

- OpenBCI GUI and custom built GUI (experiment)
- Python/MATLAB for Data Analysis/Segmentation/trial averaging

[6] https://openbci.com/

5.3.2 Subjects and EEG Data Recording

Sixteen healthy volunteers (eight females and eight males), aged 20 to 49 participated in this experiment, with a mean age of 31.9 years. Each subject showed normal to corrected vision. Fourteen were right-handed, and two were left-handed. All subjects gave informed consent. Subjects were facing a display screen on which static and illusory images were displayed as visual stimuli.

The multi-channel EEG was recorded on the OpenBCI UltraMark IV device's GUI at a 250-Hz sampling rate with eight electrodes and two reference electrodes placed at standard positions of the 10-20 international system. Reference and ground electrodes were placed on the auricle. EEG data were collected continuously and analyzed off-line.

Channel	**Sensor**
1	Fp1
2	Fp2
3	P3
4	PZ
5	P4
6	O1
7	OZ
8	O2

Table 5.1: Sensors and corresponding channels

5.3.3 Experiment Design

Static images (no motion and no illusion) were used to establish baseline brainwave readings in this experiment. Optical illusion images (motion and non-motion) are used. There were three stages in this experiment. Each stage had a certain amount of trials in it. A trial is defined as any image (illusion, non-illusion, blank, fixation). All trials are at least 1000 ms in duration. There were ten trials for Stage 1, twenty-four trials

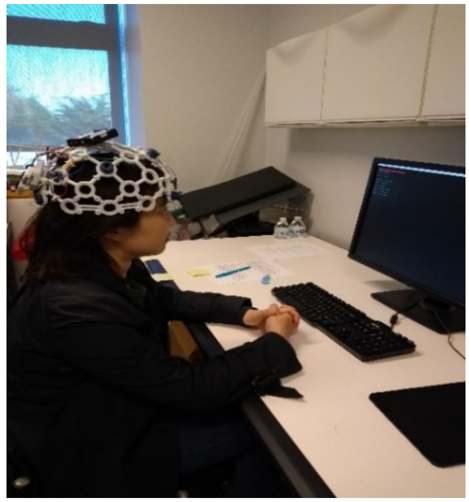


Figure 5.7: Subject participating in experiment.

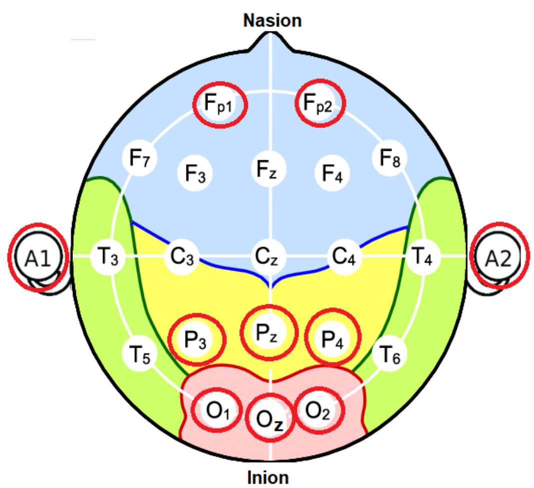


Figure 5.8: Sensor placement used in experiment.

for Stage 2, and sixteen trials for Stage 3 for a total of 50 trials.

First stage: Still images were used to set a baseline. Here the amount of trials is set to 10. A trial consisting of Fixation (2000 ms), Non-illusion image (5000 ms), and Blank screen (3000 ms). The fixation was to get the subject to focus on the + on the screen. The non-illusion image was displayed to get a baseline EEG reading of the subject when a visual stimulus was presented. A blank screen was to serve as a transition phase before the next visual stimulus.

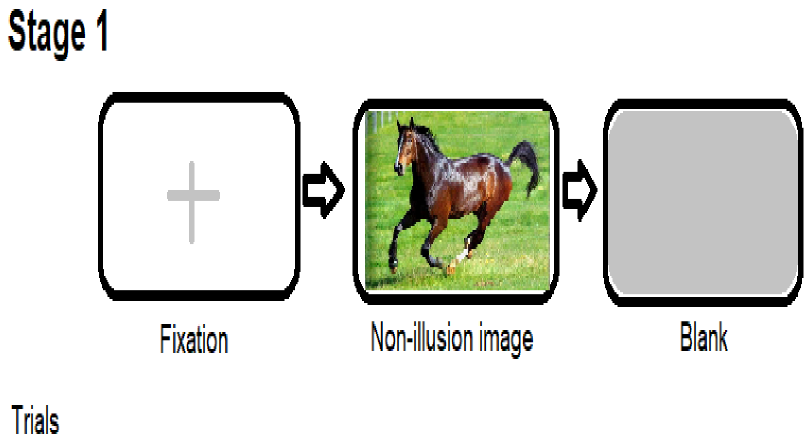


Figure 5.9: Stage 1 trial diagram.

Second stage: Observing optical illusions. The amount of trials used here is 24, indicating that the four optical illusions were shown to the participants six times, not in a row. The purpose was to get EEG readings of optical illusions visual stimuli. The trial duration for stage 2 is as follows: Fixation (2000 ms), illusion image (5000 ms) and Blank (3000 ms).

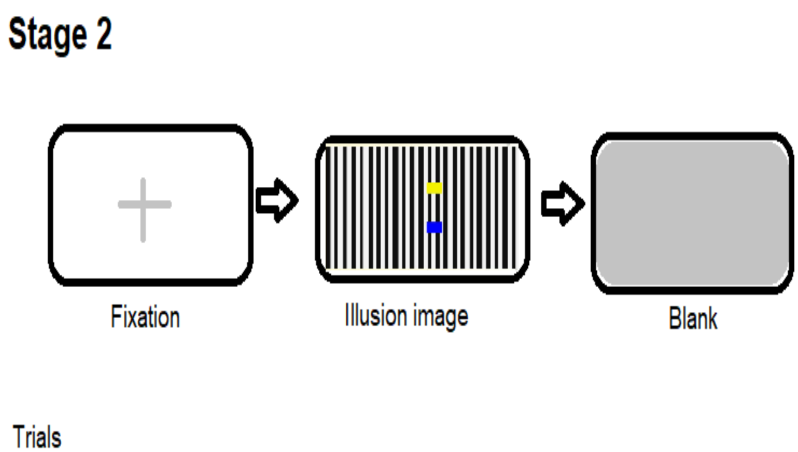


Figure 5.10: Stage 2 trial diagram.

Third stage: In this stage sixteen trials were used.

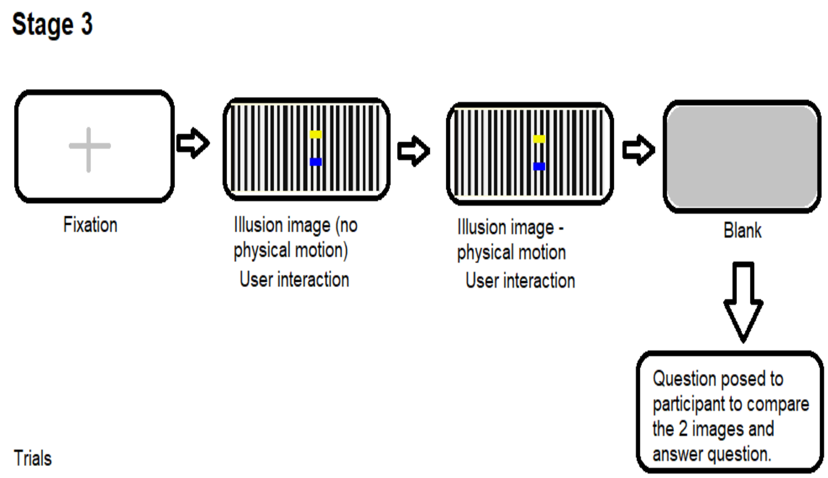


Figure 5.11: Trial diagram for the 3^{rd} stage.

The purpose of stage 3 is to see if the subject can distinguish between optical illusions (static) and physical motion (an altered version of the optical illusion).

5.3.4 Experiment Discussion

An experiment was conducted to retrieve VEP data from subjects looking at optical illusions. The experiment was designed in three stages. The first stage displays still images, and these are images with no optical or animation in them. They were used to set the baseline for EEG brainwave readings. Stage two shows the optical illusion several times to the participant. The reason for showing the images several times to the participant is to get an averaged signal for each optical illusion trial. Trial averaging is a scientific approach applied to remove background noise and extract the visual evoked potential signal. The third stage presented the participants with two images: the optical illusion and an altered version of that optical illusion. They were asked if they could tell specific differences between the images and their answers were logged. The experiment structure is to compare and analyze the three stages to look for brainwave differences caused by observing optical illusions.

5.3.5 Data Structure and Description

In this section, the details of the data set used in this dissertation are described. The data set used in this dissertation is hosted at : https://drive.google.com/drive/folders/1CJJKZp6gNbwKt4-lRwz_zj9mgkckCwrG?usp=sharing

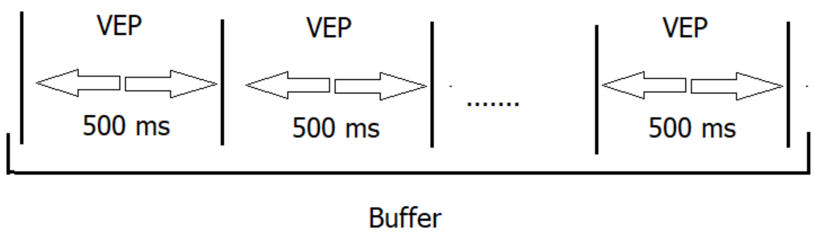


Figure 5.12: VEP Data Structure

As previously described, the VEPs are in 500 ms segments, which are 125 samples (rows) at a 250Hz sample rate. This is the format in which the data is imported into the buffer in Max/MSP to create audio/visuals used the BCI artworks, discussed in further detail later in this chapter.
The VEP data as shown in the Table 5.2 range from -1 to 1, which is very low for human hearing. Therefor, the VEP data has to be scaled and specific sonification algorithms applied to them in order to extract musical features or create sound objects. The users can use the sound objects to create compositions with them.

Fp1	Fp2	P3	Pz	P4	O1	Oz	O2
0.05347	-0.00808	-0.01156	0.024907	0.033837	0.018405	0.014885	-0.06353
-0.04746	0.031553	-0.07764	0.024232	0.031397	0.03015	0.037258	-0.13607
-0.05217	0.037768	-0.07225	-0.00274	0.010132	0.014351	0.027131	-0.09985
-0.08986	0.002296	-0.12588	-0.02537	-0.02268	-0.00504	-0.00224	-0.09333
-0.19465	0.013544	-0.20771	-0.00847	-0.01806	0.027366	0.024087	-0.16725
-0.18791	0.05851	-0.13396	0.029462	0.025	0.069594	0.074418	-0.14695
-0.01672	0.01572	0.065398	0.011912	0.012923	0.014866	0.015458	0.035102
0.120452	-0.05666	0.162249	-0.04124	-0.04704	-0.07034	-0.08158	0.170378
0.079912	-0.02178	0.099004	-0.03001	-0.03533	-0.04912	-0.05791	0.120627

Table 5.2: Data header and a few rows of a subject's VEP data

5.4 Sonification

The important data features for sonification are the size, range, variability, dimensionality, format, location (source), and accessibility, ranging from small finite datasets that can easily be maintained on a portable computer (Worrall, 2019). Sonification is the practice of mapping aspects of the data to produce sound signals, provided that certain conditions are met. According to (Hermann et al., 2011), these include reproducibility, that is, the same data can be transformed the same ways by others and produce the same results, as well as intelligibility, i.e., the 'objective' elements of the original data, are reflected systematically in the resulting sound. A common use of data sonification is: "the process of acoustically presenting a time-data series." Sonification can also be combined with traditional visualizations to expand the dimensionality of the representation (Hermann, 2008). This is very important to the development and framework of the artworks developed in this research. The following sections will cover data sonification and its use in this research in more detail.

5.4.1 Sonification and its Practical Application

In the past several decades, sonification received much attention from the scientific community (Lutters and Koehler, 2016). Although the sense of vision continues to dominate over the other senses, auditory data representation has been increasingly recognized as a legitimate technique to complement existing data display modes (Supper, 2012); (Lutters and Koehler, 2016). Sonification can be applied in both scientific and experimental music domains. The five main functions of sonification are alerting functions, status and progress indication, data exploration, entertainment, and art (Hermann et al., 2011). Sonification in art explores aesthetic meanings in a subtle distinction between sonification and music compared to the other four functions, which mainly investigate the purpose of information delivery.

The interplay between art and science is best shown by the sonification of the EEG (Lutters and Koehler, 2016), which has led to an increase in medical and artistic applications. For example, in neurophysiology, sonification has been used to complement visual EEG analysis, a complex process.

Components can be altered to change the user's perception of the sound, which portrays the underlying information's perception. An increase or decrease at some point in this information is shown by an increase or decrease in amplitude, tempo, or pitch; however, it could also be indicated by varying other less commonly used components. Many studies are being done to find the best methods to present various types of information, and still, no conclusive set of methods has been produced. According to (Väljamäe et al., 2013); (Sonification, n.d.), several different techniques for the auditory rendering of data can be classified:

- Audification - in this technique, variations in EEG data values are directly treated as a soundwave. It is often applied to time-compressed EEG data by shifting the

EEG frequencies to audible spectra.

- Parameter Mapping - the most popular form of sonifying the EEG signal involves the EEG mapping activity to a particular sound parameter, e.g., mapping EEG alpha band to an intensity level of a sound.
- Acoustic Sonification - creating data forms (physical objects constructed from digital datasets) (Barrass, 2012) with acoustic properties that provide useful information about the data—for example, creating a bell-shaped object that represents the HRTF (data) of an individual. Thus, acoustic sonification maps a data set onto the shape of a 3D acoustic object acousticsonifi (2019).

In this dissertation, sonification is used to transform data; in this case, VEP data into audio facilitates the understanding of this data and intersects it with art practices. The primary method for sonification used in this research is parameter mapping sonification. Mapping refers to receiving real-time data from controllers and sensors and using them as control parameters that drive sound synthesis processes (Filatriau et al., 2006). Parameter mapping sonification links changes in some data dimensions with changes in an acoustic dimension to produce the sonification. Model-based sonification requires a virtual model driven by the data-driven model's reactions to the user's actions (Hermann et al., 2011). Users can interactively manipulate the sonification by changing and controling the results.

The process of designing sonification requires active feedback between the system and its users. A close-looped interaction enhances a listener's engagement with the artworks. This is the approach being taken with the BCI Artworks described in this dissertation.

5.4.2 Sonification Design Strategies: representation-literal or conceptual?

As previously stated, data sonification functions as an external, independent, or abstracted representation of data in order to retrieve information from it. The purpose of using it as a perceptualization process is to divulge information in a data set to a listener at least as effectively as any other form of presentation Worrall (2019), such as animated visualizations or graphs. For sonification to meaningfully represent information, this information needs to be part of the representation experience, i.e., the sonification should be experienced in terms of what it represents (Worrall, 2019). The experience and representation connection between the data set and sonification could vary greatly depending on its purpose. For example, in an artistic sonification, that connection might be open-ended, even in the form of a cultural commentary on the data source's environmental impact. In scientific data sonification, the connection between experience and representation needs to be very close. According to (Hermann et al., 2011); (Worrall, 2019) if this is the case, then it is crucial that the following is applied:

1. The sound should reflect objective properties or relations in the input data.
2. The sonification is reproducible: the same data and identical interactions produce a resulting sound that is perceptually the same.
3. The transformation should be systematic, meaning that there is a precise definition provided of how the data causes the sound to change (e.g., formulas).
4. The system can intentionally be used with both different data as well as in repetition with the same data.

5.4.2.1 Establishing an Artistic Data Sonifcation Design Framework

Many tools are being developed that have various degrees of flexibility and power to integrate sound synthesis and data processing. This section outlines the requirements for such a framework. It proposes an integration of independent components such as those for data acquisition and analysis, together with a means to include new works on cognitive and perceptual mappings and user interface and control by encapsulating or controlling them.

5.4.3 VEP as Sonic Object

VEPs provide rich and detailed input data suitable for expression via musical parameters. Presenting the data in an immersive, multimodal way allows for a more simplified understanding of this complex data. Audience members who experience and interact with the BCI artwork *Visum* (described in section 5.10) can create musical compositions or listen/view the output.

In a gallery setting, the audience can listen to the spatialized sound objects and look at the visual projections. This gives the sense that they are in someone's brain listening to sounds that they may not necessarily be aware of. They can also interact with the installation by using the VEP data to create their compositions.

5.4.4 Auditory Display and Testing

There are various methods humans use to determine where a sound is coming from. The most basic methods are interaural time differences (ITDs) and interaural level differences (ILDs) (Fig. 5.13). The interaural time difference occurs when there is an additional amount of time for the sound to arrive at the more distant ear (Röttger et al., 2007). For example, sounds waves coming from a sound source located at an azimuth of 45 degrees will reach the right ear faster than the left ear. With the ILD, there is an attenuation of the sound when it travels to the more distant ear.

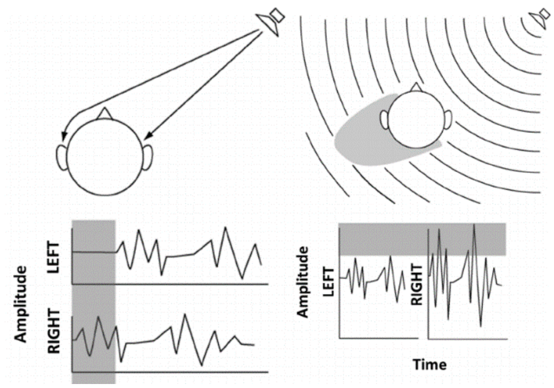


Figure 5.13: ITD Figure - Credit: (Sun et al., 2015)

Creating a sound spatialization system based on ITDs and ILDs alone is possible. However, specific issues arise when only using these two localization cues. ILDs are not linear with respect to frequency. This is because sound waves with frequencies approximately 1500 Hz have wavelengths about the size of the diameter of the human head. Frequencies less than 1500 Hz, as a result, are not attenuated as much by the head. On the other hand, frequencies above 1500 Hz are attenuated a lot. ILDs are the best cues at high frequencies.

Elevations create an additional set of problems. Usually, sounds coming from sources at elevations similar to each other will have the same ITDs and ILDs also referred to as "cone-of-confusion" (Kapralos et al., 2008). This is when the sound source cannot be accurately determined. Sound signals processed using only ITDs and ILDs appear to originate from inside the listener's head, creating a problem. Besides ITDs and ILDs, there are other mechanisms used to provide sound cues. Incoming sound waves tend to have their spectral content altered by reflections from the listener's head, shoulders, and torso, which the human brain processes to extract more localization cues. This process is known as the Head-Related Transfer Function (HRTF). HRTF is a "function used in acoustics that characterizes how a particular ear (left or right) receives sound from a point in space. A pair of two transfer functions, one for each ear, is used for sound localization, which is very important for humans" (Potisk and Svenšek, 2015). Essentially, HRTF measures sound changes when they come from different directions around a person. The auditory system uses these changes to locate where a sound is coming from (acousticsonifi, 2019). Every person's ear shape and body dimensions are different, which leads to a specific set of HRTFs that the brain needs to accommodate. HRTFs contain spectral filtering effects as well as both ITD and ILD cues. This means that HRTF needs to be provided for each individual, which is not possible for this research. The Media Lab at MIT has made a multitude of HRTF measurements[7] using a KEMAR dummy. KEMAR represents a head, ear, and human torso, where different ears (with a microphone inside) can be attached to it to produce different responses at different sound locations.

In this research, the HRTFs were chosen to spatially represent the sensors' geometric location of the experiment participant's head. As mentioned in Chapter 2, the sensors were based on the 10-20 EEG sensor placement standard. For example, the standard placement of the Oz sensor is 180 degrees azimuth and 0 degrees elevation.

5.4.4.1 3D Spatial Modeling

The goal of the auditory display of the interfaces used to produce BCI artworks in this dissertation, was to create a VEP sound spatialization system. This is a system that makes a sound source appear to originate from different points in space when listened to using headphones (Binaural listening). For example, this display can make sounds coming from the stream player sound like it is coming from some point in space to the

[7] https://sound.media.mit.edu/resources/KEMAR.html

listener's right or left, simply through signal processing. It could vary the azimuth position of sound sources from 0 to 360 degrees. The sound source's apparent elevation could also vary between -40 degrees, 0 degrees, and +40 degrees, along with the azimuth positions. Fig. 5.14 shows the definition of azimuth and elevation in the context of the above-mentioned Binaural system.

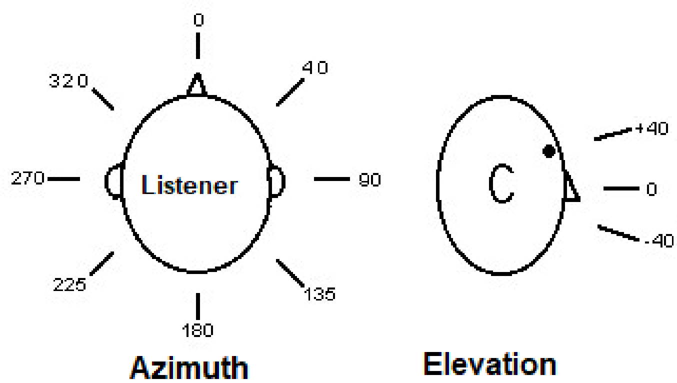


Figure 5.14: Azimuth and Elevation

Sensor	Azimuth	Elevation
Fp1	320 degrees	0 degrees
Fp2	40 deg.	0 deg.
P3	225 deg.	40 deg.
Pz	180 deg.	40 deg.
P4	135 deg.	40 deg.
O1	225 deg.	0 deg.
Oz	180 deg.	0 deg.
O2	135 deg.	0 deg.

Table 5.3: EEG Sensor sound object virtual locations

A pre-user study was conducted to understand the listener's sound experience and perception. An auditory display was designed that uses HRTF theory for binaural listening. In this study, the listeners listened to eight sounds and determined where they perceived the sound to be coming from. The sounds reflect the sensors' location placed on the subject's head during the visual perception experiment. The emanating sounds were also based on Table 1. Sixteen listeners participated in this listening study. Survey questions and quantitative results for this study are indicated in Appendix B. The pre-user study was conducted with Google Forms, and the data was aggregated and exported as a Comma Separated Values (CSV) or comma delimited file.

5.4.5 Discussion

The fundamentals of sonification and sound spatialization have been presented, which is an integral part of designing the BCI artworks in this research. To create the effect of a 3D sound spatialization, the principles of Interaural Time Difference (ITD) and Interaural Level Difference (ILD) were taken into account when designing the auditory display for binaural listening. They were used in the HRTF algorithm to virtually place sounds reflecting the sensors' location placed on the subject's head during the experiment.

5.5 Granular Synthesis Theory

Granular Synthesis, first introduced by Iannis Xenakis (Granular, 2020), takes brief micro-acoustic events, called grains, and combines them to create sound clouds, usually in real time. The grains have a duration from 1 to 100 ms, which is near the threshold of human auditory perception. Grains are considered building blocks of sound, or atomic sound particles (Opie, 1999). The combination of thousands of grains creates a layered sound, with a change in spectrum and timbre. The sonic quality of a granular texture depends on the distribution of grains in real time and of the parameters (e.g., grain size, pitch shifting, delay, etc.) (Fig. 5.15) selected for the synthesis of each grain (Bencina, 2001).

Grain Duration

The grain duration is a critical parameter in granular synthesis. Large grain sizes (hundreds of milliseconds) allow one to distinguish the original sound. With tiny grains (short duration), the sound is broken up, making it difficult to recognize the original sound. The impression of a pitch is achieved by lengthening the grains. Grain durations at 5 ms sound like clicks becoming clearer at 25 ms.

Grain Organization

As grains are the minimal expression of granular synthesis, the configuration of a group of grains shapes the sound. Many different configurations can be used to obtain different effects, synchronous, asynchronous, and algorithmic model-based. With synchronous configurations, the grains are organized in streams, with a specific inter-grain time (delay). This creates a deterministic pattern that indicates how the grains are ordered. With asynchronous configurations, the grains are randomly separated, affecting the amplitude and density of the grains. Model-based is when specific algorithms are applied to the grain distribution.

5.6 Frequency Modulation

Modulation in the audio domain refers to changing the property of sound over time. Frequency Modulation (FM) Synthesis is based on at least two oscillators; a Carrier and a Modulator. The Carrier Frequency is most related to the fundamental frequency pitch and is usually manipulated with a keyboard or other MIDI input. The Modulating Frequency is used to modify the Carrier at a specific Modulation Rate and Modulation Intensity or Index. FM Synthesis was first developed by John Chowning in his paper The Synthesis of Complex Audio Spectra by Means of Frequency Modulation.

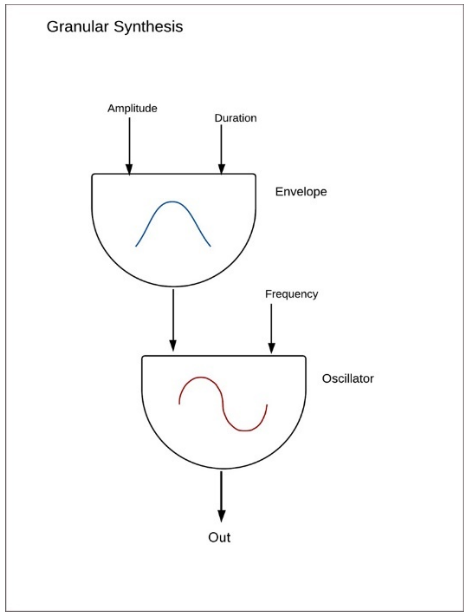


Figure 5.15: Granular Synthesis diagram - Credit: zengrained.wordpress.com

Yamaha acquired the patent from Chowning and began producing digital synthesizer in the late seventies (Russ, 2004); (FreqMod, n.d). The Modulation Index is directly related to the change in the Peak Carrier frequency divided by the modulator's amplitude. "For any given Modulator frequency, it is the Modulation Index thus the amplitude of the Modulator that determines the amplitude of each of the components in the spectrum of the output signal" (Mantione, 2019). Modulating sounds can add a sense of motion, depth, and dimension.

5.7 Visualization Techniques

As previously discussed, sonification is when data sets are represented as sound. With visualization, data information are represented with visual symbols. Visualization techniques allow for discovering data relationships, which are otherwise not readily observable by looking at the raw data. This section reviews various visualization techniques and mapping strategies.

Current research shows several approaches for visualization techniques, which can be broken down into the following categories:

- *Pixel-Oriented Visualization* technique is when the pixel's color is used to reflect the dimension's value. For example, a data set of k dimensions pixel-oriented techniques creates k windows on the screen, one for each dimension. The k dimension values of a record are mapped to k pixels at the windows' corresponding position. A disadvantage of the pixel-oriented visualization technique is that it does not allow for data distribution in a multidimensional space.

- *Geometric Projection Visualization* techniques help users find exciting projections of multidimensional data sets. For example, a scatter plot displays 2-D data points using Cartesian coordinates. Adding a third dimension, such as color, can help distinguish different colors of shapes to represent different data points.

- *Icon-Based Visualization* techniques: A method that uses small icons (e.g., Chernoff faces or stick figures) to represent multidimensional data values, which allows the visual features to change according to the data values.

- *Hierarchical Visualization* techniques: allows subspaces to be visualized hierarchically, that is, visualizing data using subspaces created from the data's attributes. These techniques can be used when specific attributes of the data might be more important than others.

- *Graph-based visualization* techniques: allow for the visualization of large graphs using algorithms and abstraction layers to present a clear overview of the graph.

Even though the aforementioned visualization techniques are very popular, the BCI

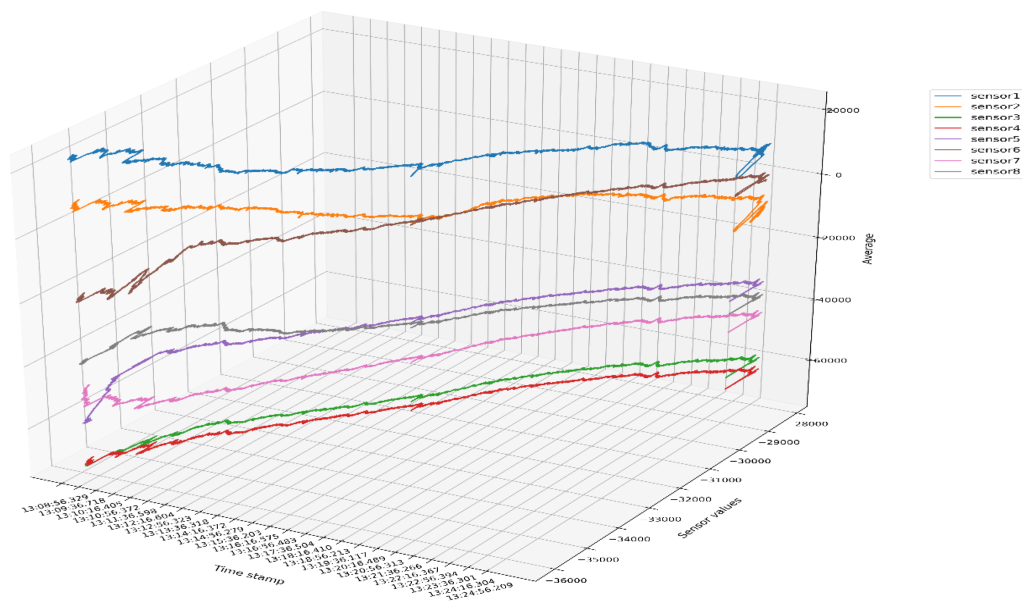


Figure 5.16: 3D 8-channel time series Visualization of EEG data

artworks in this research are not applying them. The BCI artworks' visualization approach takes the data and applies them using algorithms to interactively create visual objects with the data. We tend to be visually oriented and under appreciate the contribution of the other senses. In this research sonification and visualization are used to complement each other to give a better picture of the data. How visualization is used as objects is discussed in further detail later in this chapter.

5.8 VEP as Visual Object

VEP data are segments of physiological data. These types of data are usually visualized as lines (time-series) like in Figure 5.16. Visualization used in the BCI artworks created in this research transforms the data into visual representations by mapping them into visual features such as rotation, 3D, scaling, cutting. Since the visualization is connected to the sonification in these BCI artworks, it is essential to know how the data's sonification occurs. Visual evoked potentials help us understand how the signals travel via the optic nerve, which helps us see. Information contained in VEP data is the latency in response to light. Visualization is used to complement the sonification of the data. The contributions of visualization used here are also for aesthetic exploration of the data and positions audience and participants for greater engagement to evaluate the data features.

5.9 Design of BCI Artworks

The overall conceptual design of the BCI artworks is to integrate data collected measuring visual stimuli within an artistic work. This is done with an EEG device, which acquires and filters the EEG signal collected from a subject looking at the visual stimuli. After that, the data is segmented and trial averaged to remove additional noise and to extract the VEP features (Figure 5.17). The VEP data is subsequently used to control the sonification parameters, which in turn controls the visualization. The point has been to explore the interrelationship between what one hears and sees.

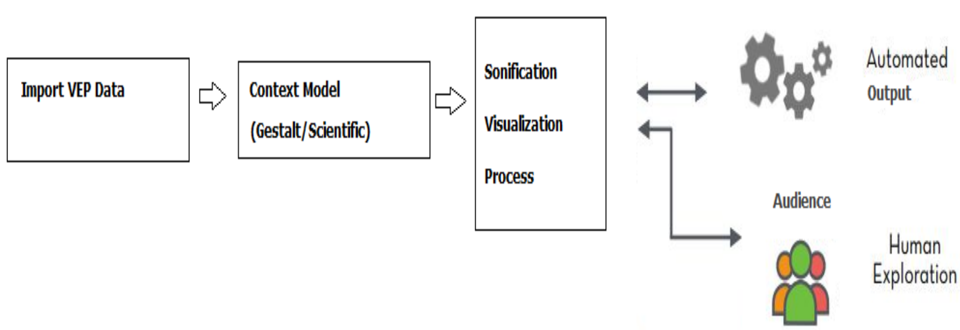


Figure 5.17: BCI Artwork diagram

The following sections explain the two BCI Artworks created in this research in detail.

Both artworks used the data acquired from the same device as described below. In this diagram, the VEP data is imported into the buffer. A scientific model, that is, a model based on the science of Visual Evoked Potential, is applied to the data. VEP science states that there is a spike in brainwave activity around 100 ms post-visual stimulus in the occipital region of the brain. The VEP data is used as a control signal for the sonification and visualization process. There are two ways for the output: 1) automated, which is through the data itself, and 2) output that results from human interaction with the data.

BCI Device The following list the type and features of the EEG device used in this research.
Invasiveness: Non-invasive
Electrode Type: Dry
Sample Rate: 250Hz
Output data: Raw

5.9.1 Affordances

Any action possible with an object based on users' physical capabilities is referred to as "affordance," a term coined by psychologist James J. Gibson in 1977 (Affordances, n.d.). For example, a table affords to place something on it, eating at, standing on. In the Human-Computer Interaction (HCI) field, affordance is described as perceivable action possibilities, meaning actions that users consider possible. So, designers must create objects' affordances to conform to users' needs based on their physical capabilities, goals, and past experiences. Clear affordances are vital to usability. Users will map the possibilities of what an object does according to their conceptual model of what that object should do (e.g., inserting fingers into scissor holes to cut things). Types of affordances considered in the design of the interfaces include:

- Physical - The perceptual characteristics show users what to do - e.g., large text print, indicating what area is designated for "import data", "output/record," etc.
- Cognitive - Design features that help users notice or know about things - e.g., clearly labeled text to announce what will happen if users press a particular key.
- Functional - Design features that help users achieve goals - e.g., data are shown in the buffer after being loaded after a user clicks to import data.

In this research, the BCI artworks both follow these types of affordances to allow "the user as much expressive behavior as possible." Users have the flexibility to map any sonification parameter to any visualization parameter they want via the parameter matrix.

The following sections will cover the BCI Artworks in detail, which includes conceptual framework, interface and installation design.

5.10 BCI Artwork - Visum

In this chapter, *Visum*, is introduced, which is an interface that enables users to interactively create audio/visual compositions with the VEP data sets. Even though the word Visum's current terminology refers to a travel permit or document, the word's true meaning comes from Latin and means 'that which is seen, view, appearance, vision, mental image.' In this research, a novel concept based on brain-computer interface (BCI) technologies is introduced. Visum is an artistic and pedagogical tool that illustrates/interprets scientific methodology applied to visual perception and a new framework for scientific exploration.

Visum focuses on interpretational sonification and visualization design flexibility based on visual perception concepts. It allows for flexibility in composing with the VEP data within an audio/visual design space. This BCI artwork's main contribution is an expressive framework to create sonification and visualization output for this neurophysiological data. It allows the users to interactively arrange sound and visual objects in several ways, creating audio/visual compositions with this data.

The design, implementation, challenges, and limitations for the BCI artwork Visum are presented in the following sections. An overall evaluation for Visum in the form of a user study is presented in Chapter 7.

5.10.1 Conceptual Framework - Visum

Visum is used as a brain metaphor, that is, modeling brain activity. The brain is an organ that processes information from the body in the form of neuronal activity. With Visum, brain simulation is done by projecting multimedia content onto a screen and 3D spatialization of sound objects derived from the pre-recorded EEG data from a subject in real time. Visum is an interactive audio-visual art installation/screen-based artwork based on VEP output. Transforming the visual perception of complex data into a sonic representation allows the audience to interact with indeterminable outcomes. From an artistic perspective, creating compositions with the VEP data creates a creative and learning experience (about brain listening and perception) for the audience. This is done by using the each sensor locations placed on the head and outputting the activity occurring at each location of the head. Visual features of VEPs can be used as an open musical score where performances are executed in unique ways.

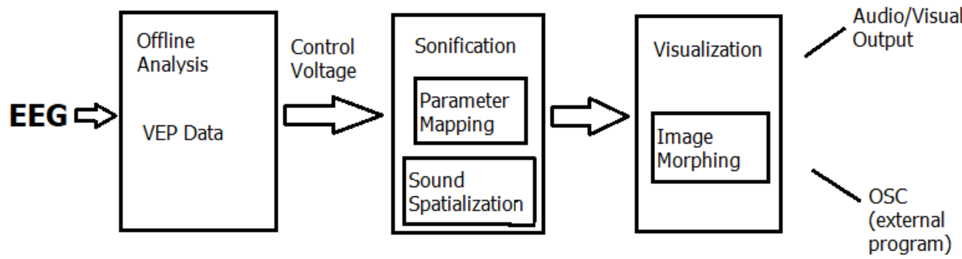


Figure 5.18: Diagram of sonification/visualization framework for Visum

Based on the BCI Artworks taxonomy in section 4.4., Visum can be categorized according to the following:

Input: EEG classification: Short-term coherent waves

Agency: Reactive

Timeliness: Pre-recorded

Modality: Multi-modal (VEP and user interaction)

Mapping: Indirect

Output: Audio-Visual

Format: Installation/Performance/Screen-based (could be all 3)

Audience: Active and or Passive

The framework of Visum is designed to represent audio/visuals that support interactive user manipulation, all within a multimodal interface. The emphasis is placed on allowing users to map sonification elements and optionally link these with the graphical output. By allowing users to define mappings from data to first sound elements, they can directly create and simultaneously manipulate groups of sound elements into interactive visualizations. When dealing with a question about sound design or interface development, one has to think about the process of creating a reality. When one creates reality via measurements (compositional), this can be perceived differently by different minds and used in different ways. The artist/composer is always inside the instrument (interface), bringing about new ways to use it with new possibilities. The audio processing capabilities of an instrument's user interface and engagement have also been considered in the interface design. Most instruments have sweet spots and unexpected side effects when pushed to their limits. Some artists develop instruments or interfaces towards the mainstream potential, such as developing an interface that directly maps real-time data from the device to sound or visuals, without understanding the algorithms involved. In contrast, others go beyond boundaries to see what discoveries exist between sound and or visuals. Experimental music can engage a listener in different ways and interact with the context of their subjective experience of sound and visuals. For artists and performers, this interaction is claimed in the creative choices they make - the sounds they choose to use or discard in the process of composing.

5.10.2 Visum - Sonification Framework

The sonification workflow and design details for Visum are presented in this section. First, an overview is given of the framework designed to render sounds, allowing users to manipulate them interactively. Also presented is the user interface design, explaining how users can create and edit the different parameters. At first, the original thought was to design the data sonfication part of Visum with parameter mapping to the whole tone scale. After getting a better sense of the data, the idea shifted to using granular synthesis. The shift was that granular synthesis would better represent the neurophysiological data, given the fact that the data is highly subjective and very short in duration. Neurons fire at about 100 ms or less, which is about the same size as a typical grain. As presented in Chapter 3, visual evoked potentials take place approximately 100 ms post-stimulus.

Visum's sonification framework includes both granular synthesis and frequency modulation. Frequency modulation can be applied to any sensor data output to make them more salient through sound separation. The Visum interface is shown in Figure 5.19, which consists of 8 audio streams (channels) representing the 8 sensors placed on a subject's head during the experiment. In this interface, the user can apply the Gestalt principles of Grouping and Figure-ground to any streams. Gestalt principles are discussed in section 3.3.5. Figure 5.19 also shows the output of channels 6-8 (representing O sensors), where a resonant filter was applied around 100 ms to modulate the sound, representing VEP activity. Modulation means the changing of the property of sound over time. The modulation of sound requires a source signal called a modulator that controls another signal called a carrier. In this case, the VEP signal would be used as the modulator to a sound file. Modulating sounds adds a sense of motion, dimension, and depth.

Visum uses indirect mapping for the visualization. It takes the sample values to control the granular synthesis parameters, which then control the visualization. Most sonification interfaces are static, whereas with this interface it is dynamic. Dynamic means that it essentially changes (output) according to a scientific model.

In Visum, events trigger a model that changes specific channels' timbre to highlight an event in the data. According to research in visual science, there is an increase in activity around 100 ms in the occipital lobe post-stimulus. After that, around 300 ms, there is an increase in activity in the Parietal lobe (P300) post-stimulus. Visum triggers an event 95-105 ms that affects the sound of channels 6-8, which are the O-sensor data.

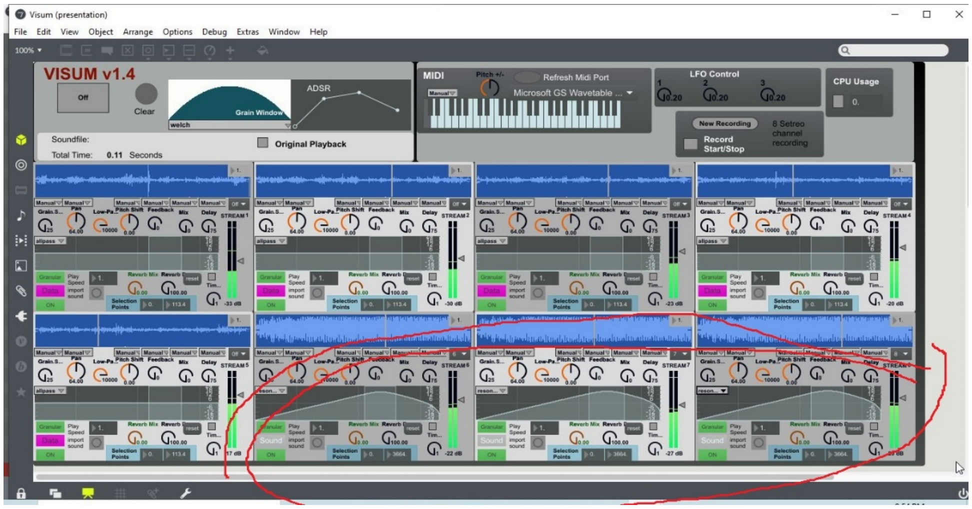


Figure 5.19: Visum interface -Event triggers (P100 model – O-sensor streams)

Between 295-305 ms, an event is triggered that affects channels 3-5, representing the P-sensors. In this case, the model is resonant filters applied to a sound file (chosen by the user). The events trigger a resonant filter set at Quality factor (Q) 1.8 and 19 dB. This extracts a particular sound to draw the attention of the listener. The event triggering also follows the Gestalt principles of grouping and figure-ground and makes an audible difference.

Data Import

There are several parts to Visum, the data importer, data controller, audio control, visual control, and output/recorder. Figure 5.20 shows the data importer. Here the data file(s) are selected and imported into the buffer. Once imported, the data controller and audio control also receive the data information.

The data controller is where the sample data rows (sensor) control the sound parameters. They are linked to the granular synthesis parameters. The objects in Visum are the sound and visual objects. A VEP sound object represents a mapping from the VEP data (CV controlled) items to a set of sound parameters. Each sound object

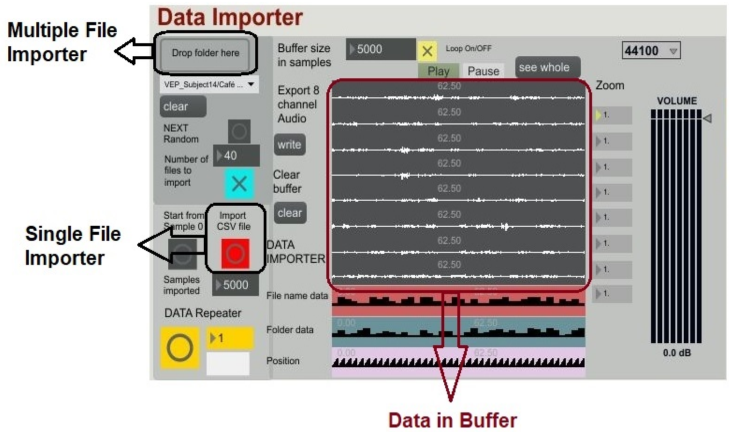


Figure 5.20: Data Importer

has a parameter associated with it that specifies the data it maps to (direct mapping). Each item in this set is rendered as a particular sound. The data controller has default parameters. Users can use the parameters or modify them, allowing more composition flexibility for the user.

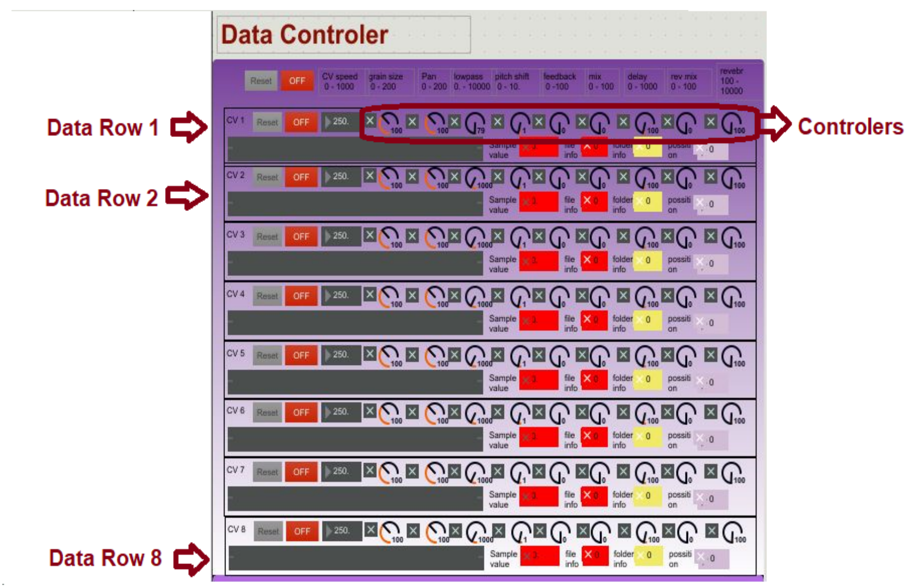


Figure 5.21: Data controler

In the CV panel (purple section), each row of data controls its own set of parameters. Eight rows are representing the data for each sensor. The data can control the CV speed as well as granular synthesis parameters in the stream section. There is a default setting for each parameter. The CV speed indicates how fast the data is read. The default value is set at 250, which is the sample rate of the OpenBCI device. Granular synthesis is a sonification method usually applied to complex data. Since the VEP data is also complex, it seems like it would be good to apply it here. It is also applied here to represent neuronal firings in the brain metaphorically.

Data Controller and Default Settings

As previously mentioned each parameter has a default setting. Users have the flexibility to change these settings or inactivate these parameters by clicking on the 'x' next to that specific parameter. The following presents the parameters and settings.

Grain Size

The default setting for the grain size is set at 100. The algorithm used for the grain size is (x+1)*100+25. The theory behind granular synthesis is that grain sizes less than 25 ms sound like clicks. Based on this theory the range applied here for the grain size is 26 to 200 ms. Here 'x' indicates the user value, which changes as the user increases or decreases the amount. Setting the default value at 100 starts the grain size off at 26 ms.

Pan

The output value for pan is -1 for left and 1 for right. The default setting for this parameter is 0.

Low Pass

The Low Pass parameter cuts off high frequency of a signal at a specific point. The default value is set at 10000, which means that values above 10000 are cut (Fig. 5.22). The default setting is 1000 Hz.

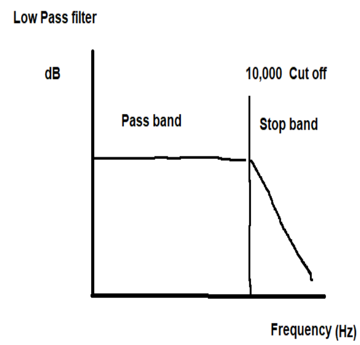


Figure 5.22: Low Pass filter

Pitch Shift

For the pitch shift the values ranges from -2 to 2. This parameter shifts the pitch either up or down up to two times the original signal. The default setting for the Pitch Shift parameter is 0.

Feedback

The feedback parameter controls the amount of the signal that is fedback into it. The default setting for this parameter is 0.

Delay

Delay is an effect that creates an echo. This parameter controls the duration of the echo effect. For example, if the delay is set to 50 ms, then an echo is heard 50 ms after the delay is triggered. The default or minimal setting for this parameter is 75 ms.

Mix

This parameter controls the amount of Feedback and/or delay that is added to the original signal (dry). The default setting for this parameter is 0.

Reverb and Reverb Mix

Reverberation or Reverb is created when a sound is reflected off the surfaces around you, such as walls, furniture etc causing a large amount of reflections to build up and then decay. Reverb can give a sound a richer or warmer feeling. The Reverb Mix is the amount of the reverberated sound that is added to the original (non-reverb effect) signal. The default setting for the Reverb parameter is 100 and for the Reverb Mix the default setting is 0.

5.11 Visum: Interface Design and User Interaction

In this part of the thesis, the design and evaluation of two interactive BCI artworks are presented. The two artworks focus on two important aspects of sonification and visualization authoring for data-driven narratives: data mapping and layout design, respectively. The data collected in this research followed the neuroscientific protocol, such as EEG filtering, segmentation, and trial averaging. First, the EEG data was pre-processed to remove frequencies above 30 Hz and noise. This is necessary giving that the frequencies involved in cognitive brain activity fall below 30 Hz. A notch filter is also applied to the EEG data to remove the frequency at 60 Hz for machine or electrical interference. The time interval to analyze visual evoked potential is about 100-400 ms post-stimulus.

Given this, the data needs to be trial averaged, and the interval chosen in this research is up to 500 ms post-stimulus. This interval covers the P100 deflection occurring in the occipital lobe around 95-105 ms post-stimulus and P300 deflection occurring in the parietal lobe around 295-305 ms post-stimulus. This is the inspiration for the models built to apply to the data. A trial is any image presented to the user; this includes blank or fixation screens. The optical illusion trials are averaged to remove additional noise. In general, VEP data or EEG data is not the most straightforward data to work with, given that it is noisy and subjective. Frequency is the number of cycles per second. The fact that the data is only 500 ms or 0.5 seconds in duration makes it difficult to extract frequency information because it is not a full second in duration. This requires a different approach to interact with the data. One way is to use the VEP data as sound objects. The post-stimulus EEG data has information coming from the eight sensors, which is shown in Appendix C. Seeing that each of the eight sensors provides its information about the visual stimuli lays the interface design's conceptual groundwork.

The interface design for Visum is now presented. The overall user interface is shown in Figure 5.19. It consists of a Data import, Data Controller, Audio channels (with parameters), Visual controls, Matrix, and composition panel. The interface has eight channels or streams, which can be compared to a head with eight sensors. The user is controlling the information of the eight sensors coming out of the head. This research works with a reactive BCI, which means that the data was pre-recorded. The user needs to import this pre-recorded data, which is done in the 'import data' section. The user has two ways to import the data; (1) Drop a folder with data. Here a folder can contain multiple VEP files or (2) Import data one file at a time. Once the data have been imported, it is stored in a buffer. The Data controller panel (Fig. 5.21) of the interface allows the user to use it as a control signal. The buffer contains eight columns representing the eight sensors placed on the subject's head during the experiment. Users can control how the data output is 'processed' by using the controllers. Each controller is connected to the audio stream granular synthesis parameters. Users can select which controllers they want to activate and control. For example, suppose a user wants to control the grain size. In that case, they can check it to activate this controller and manipulate the grain size values.

In the following sections, the typical steps to use this system, including actions to create sonfication and visualization output, and interact with the data. Given the system's flexibility, users could go back and forth among these steps any time they want. The main sonification parameters in Visum are *grain size*, *panning*, *low pass filter*, *pitch shift*, *feedback*, *Reverb*, and *Delay mixing*.

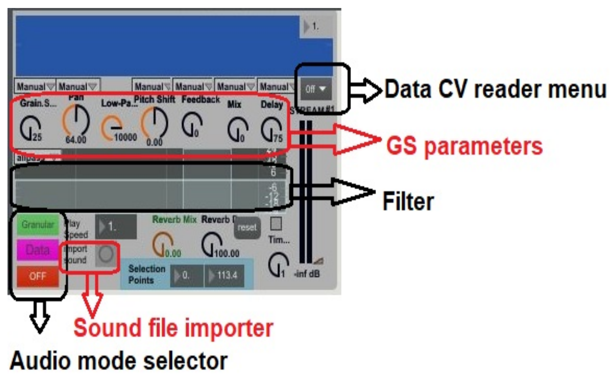


Figure 5.23: Visum Stream components

A stream consists of several granular synthesis parameters that control the time of the sound. Grain size controls the grain length of the sound or data. Grains being the cut-up sound samples. Panning shifts the output from left to right. For audio, this means shifting the output from the left to the right channel. The low pass parameter applies a low pass filter to the grain, filtering out frequencies above a specified amount. Pitch shift is the raising and lowering of a pitch. Feedback sets the amount of the output signal that gets fed back into the loop. The Mix parameter controls how much of the wet and dry signals are mixed. Dry being a signal without any effects. Wet means a signal with effects. Visum users manipulate continuous knobs to explore the data.

Creating Sounds

Data Sonification in Visum is created by:

1. Turning on the CV row in the 'Data Controller' section. For example, to use the data from row one, click on the on/off button in CV1. Adjust any necessary data controllers such as pitch shift.

2. In the audio stream section, choose which audio stream the CV row should control. If the intention is to have the CV 1 data control Stream 1, then select 1 from the drop-down menu in Stream 1. This interface allows the flexibility to have the CV control any audio stream. So, CV 7 can be set to control Stream 4.
3. 'Data' option is selected. This is a toggle between 'Sound' and 'Data' in the audio mode selector.
4. Turning the audio stream on by clicking on the on/off button.
5. Increase the volume level.

Using sound files instead of data for sonification:
1. Click on 'import sound' and select sound file to import.
2. 'Sound' option is selected. This is a toggle between 'Sound' and 'Data' in the audio mode selector.

Using the composition panel (C-panel)

The C-panel (Fig. 5.24) allows the user to compose and save compositions. It has presets that saves the state of the interface (patch). For example, suppose the patch has particular settings in the audio streams, visual controls, or data importer. In that case, the user can save these settings. As indicated in this example, the user can save State 1 as a preset to recall later. The composition can be created by using the presets. Interpolation is also possible between two states, for example, State 1 and State 2, the transition between two states.

State 1	State 2
Grain size 30	Grain size 100
Pitch shift 2	Pitch shift 10

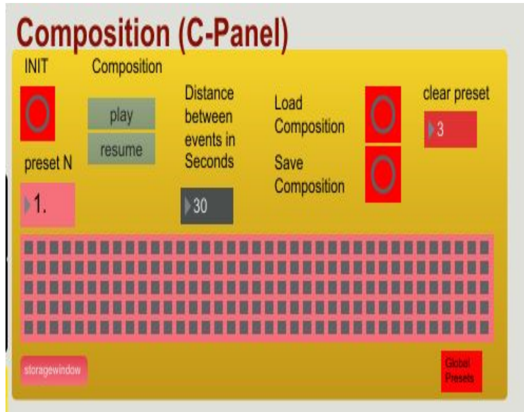


Figure 5.24: C-panel

Compositions can be saved, loaded, paused, and played. The way it works is to save the setting information as Java script (.json) files. All the data information about the state, such as variables, buttons, and parameter settings of the interface, are saved. These files could be seen as scores.

5.11.1 Demo

The C-panel in Visum can be used for demo and composition purposes since it can save the system's various states. A basic setup can be saved in the C-panel to allow users to use the system quickly. For a demo, the data could easily be imported without the users have to go through each step involved in importing the data and setting up the streams. For example, preset 1 can have the buffer data, with an audio stream already setup. The user can create audio/visuals by controlling parameters, most likely important to the users.

5.11.2 Limitations

Even though Visum allows for much expressivity of the data, the biggest limitation is that it is very CPU heavy for audio/visual use. To use all the features of this interface would require a computer with a lot of RAM and CPU power, such as a gamer's computer.

5.11.3 User Interaction

How the user interacts with the interface will now be presented. The general user interface is shown in Figure 5.19. The user needs first to import the data in the interface's buffer. Once imported, the data is ready for transformation into sound and visual objects. The user could then begin to experience the audio/visual output using the sound parameters (manually) or have the data work with the default settings.

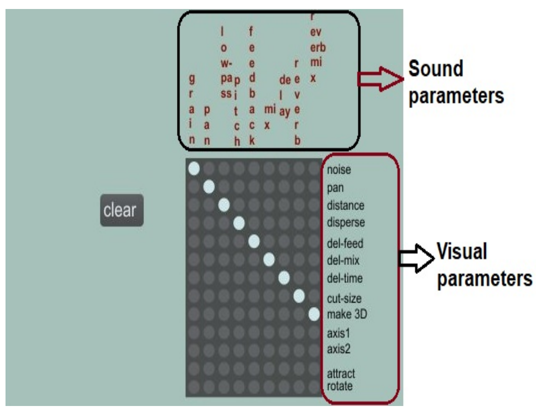


Figure 5.25: Parameter matrix

Suppose the user decides to control the interface manually. In that case, the user can directly manipulate the parameter knobs and create audio/visual compositions. Users have the flexibility to map any sonification parameter with any visualization parameter they choose using the Parameter Matrix (Fig. 5.25). Visum brings an immediate and dynamic output of the interesting data for both the user and audience - especially when projected on a large screen in a darkened room with compelling sounds. Adding flexibility to interaction design, i.e., not only supporting a limited set of interactions, is important. To accomplish this, users can turn off the CV control to allow manual control of the visual data or manual control of the sound output parameters.

The following sections show typical steps needed to use Visum to create visualizations and interact with them.

5.12 Visum - Visualization Framework

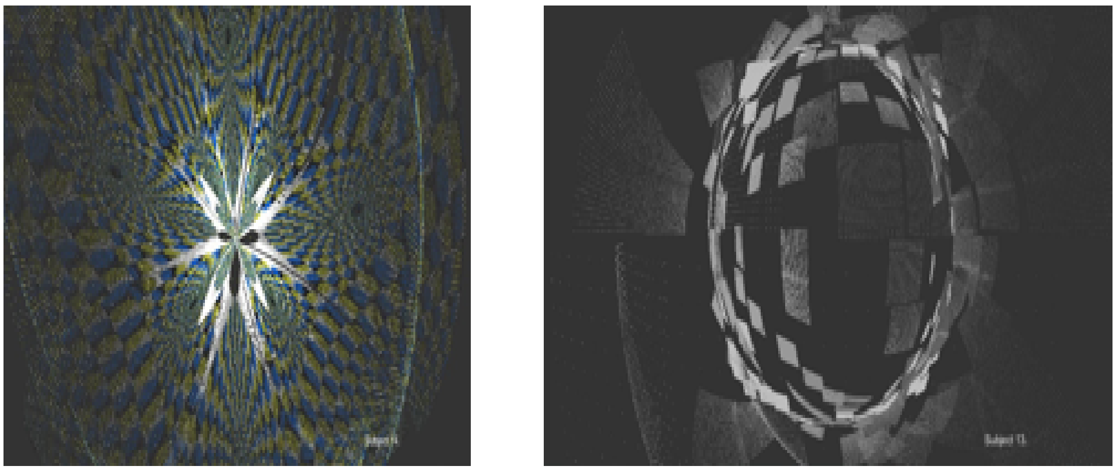


Figure 5.26: Visum - Demo visualization A and B

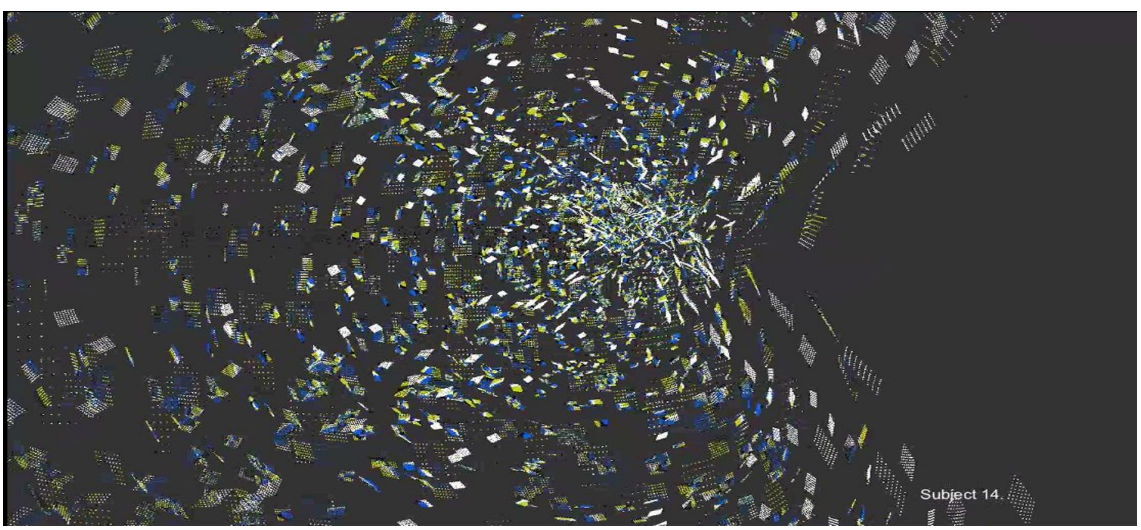


Figure 5.27: Visum - Demo visualization C

Creating Visuals in Visum

The visualization in Visum includes the morphing, distortion of actual illusion images. The interface displays the illusion for each participant, while the VEP data for that specific participant is used as a control signal to morph that specific illusion image. The more brain activity(perception), the more image morphing that took place. The message is: "this is what happened when this subject saw this illusion". Visualization in Visum can be controlled via the sonification parameters via a control voltage (CV) or independently (manually). They are created using the granular synthesis parameters to control visual parameters or manually control the visual controls.

Visualization Parameters

Pan, the swiveling of the image left to right from a fixed position. Distance, the adjustment of the distance of the image (closer or farther). Disperse, the breaking up or scattering of an image. Cut Size cuts the images into pieces. Randomize x, y, randomly changes the x and y coordinates. Rotate, rotates the image in 3D space. Other parameters are *Delay Feedback, Delay Mix, Delay Time, Randomize force, Random time, Destroy, Attract.*

5.12.1 Creating Visualizations

Visualization in Visum is created by:

1. Turning on the Visual Controls section (by checking the on/off box)

2. Select which Data controller (row) will control the image by selecting from the 'CV image' drop-down menu.

3. For syncing audio with visuals, select from the 'Stream' drop-down menu, which stream is used to control the visualization parameters.

4. Select from the parameter matrix which sound parameters are linked to which visualization parameters.

5.12.2 Visum Implementation

The Visum interface is implemented in Max/MSP/jitter [8]. Jitter employs Open Graphics Library or OpenGL objects. "OpenGL is a cross-language, cross-platform application programming interface (API) for rendering 2D and 3D vector graphics. The API is typically used to interact with a graphic processing unit (GPU), to achieve hardware-accelerated rendering" (Segal and Akeley, 1999).

Input: Data are imported into the system as .csv files. The .csv files contain eight columns of data, representing the eight sensors of the EEG device. The data were also separated by subject. There were sixteen subject folders, each containing the VEP data for the four optical illusions. The user can import data for one subject or any amount of subjects into the interface. An MSP data structure (buffer\~) can hold digital audio information within program memory (MaxMsp, n.d). Data is loaded into the buffer and used as control signals. The eight control voltages represent the eight-sensor data, which can control any sound parameter to create sound objects. The sound parameters used in Max/MSP are granular synthesis parameters. These sound elements are then linked to the visualization objects in Jitter for visual output. For visual output, the resulting graphical elements are rendered onto the screen.

Rendering: There are multiple audio streams. There are eight audio streams in the current prototype.

Saving Compositions:

1. In the C-panel, save the configuration into a preset.

[8] Cycling '74 - https://cycling74.com/products/max

2. Click on the Save Composition.

3. In the Save window, enter the file name for the composition.

4. Click save.

5.13 Installation Design - Visum

Installation Event

Entering the space is like entering inside a human brain. In this installation, 3 to 6 viewers mingle in a defined space. Eight audio speakers and a projector produce audio-visual compositions. Visual stimuli are presented on the screen in the front of the room, representing 2D stimuli coming in through the eyes. The eight speakers represent the brain's location where the sensors were placed on acquiring the brainwave activity during the experiment. These sounds are short and granular, representing neuronal brain activity. Projections are displayed unto a projection surface, representing the 3D perception of the visual stimuli. The audience will experience their perceptions while observing those of others.

Installation Layout

The installation requires a darkened (low light) space of about 20x20x10 feet. There are eight speakers (5 standing and 3 elevated/hanging), which are geometrically placed in the space (Figure 5.28). A mounted TV Display is placed in the front of the room. This TV display will be showing optical illusions. Two speakers are standing next to the mounted display at the front of the room. Three speakers are standing at the back of the room, and three speakers are elevated at the near center of the room. These speakers are for the spatialized sounds coming from the data. The exhibition space will be re-purposed as a U-shaped room or use a U-shaped surface display for the projec-

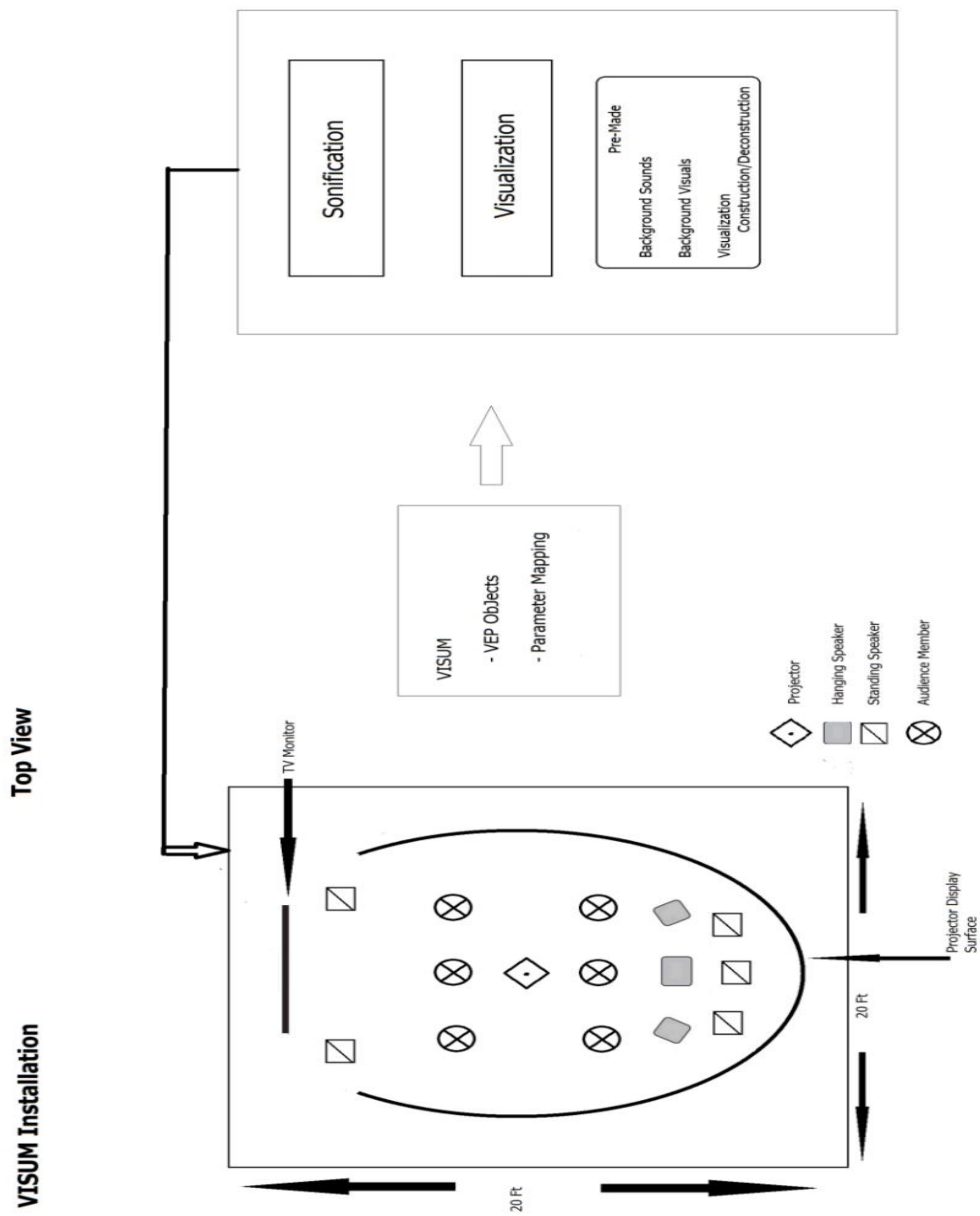


Figure 5.28: Visum Installation Layout

tion. The visuals are projected onto this surface to give the audience an immersive experience. A laptop will be running software that is used for sonification and visualization of the data. Users have the option to interact with the data through the interface.

5.13.1 Streaming OSC Data in Visum

The framework for both Visum can be extended via Open Sound Control (OSC) to external programs that receives OSC values such as Ableton and OpenFrameworks by defining and adding objects. These can be graphical and/or sound elements.

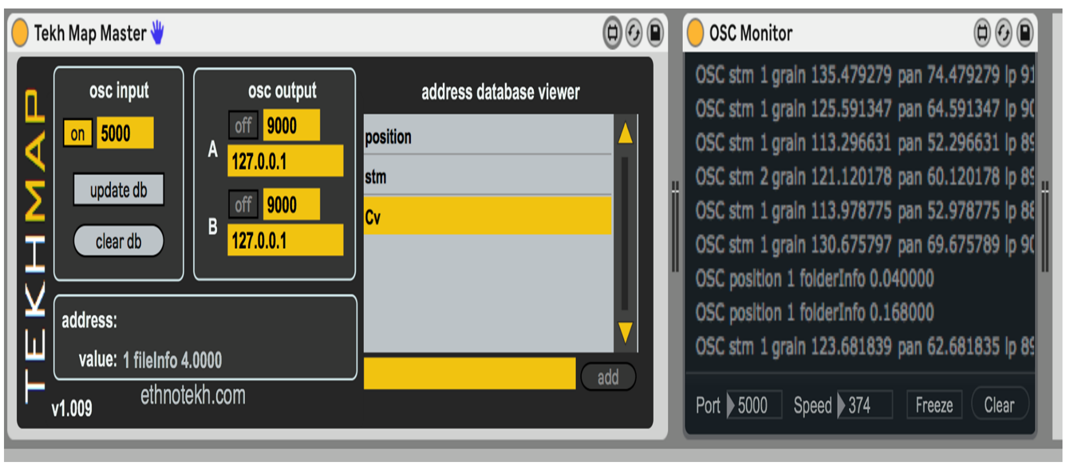


Figure 5.29: OSC Monitor - streaming values - Credit: Susie Green

Every stream's data information can be sent out via OSC, including the subject folder information, which contains information such as the image connected to the data (e.g. Cafe Wall). In Fig. 5.29, an example of an OSC monitor showing all outgoing data, such as the stream and grain size for that stream, is shown. External streaming of the data provides for additional creative possibilities for the users. More details about Visum OSC specifications are in Appendix E.

5.13.2 Challenges in Visum Design

The evaluation and design of creative computing could typically be challenging. It is also highly context dependent for music or audio/visual output, such as expression and performance timing. For the performer to feel engaged with the system, there needs to be a sense of agency, which for artistic BCIs comes down to parameter mappings. The user needs to feel like he/she has active control over the resulting musical interaction. Thus, the mapping between neurophysiological cues and audio and visual parameters must be intuitive for a non-experienced user. The challenge was devising evaluation and design strategies for meaningful mappings, which are most suited to task-specific control of music parameters' aesthetic control. Another challenge was in choosing a location for the sound output that remains distinguishable. If sounds are too close to each other, they will blend, making them hard for the listener to separate.

5.13.3 Exhibitions and Presentations

Visum was presented at SIGGRAPH 2020 as a poster (Mathew and Park, 2020). Visum has been exhibited through several A/V performances involving an interaction between the user controlling the interface at exhibitions. Visum: beyond the physical eye, was selected at the IEEE VISAP 2020 conference[9] and Altered Festival 2020[10] (Fig. 5.30) as an art installation. However, due to the COVID-19 pandemic and the conferences shifting to online formats, it had to be reworked into an online audio/visual performance or video, which included the author's interaction with the interface. This research has also been accepted to Leonardo's Abstract Service (LABS) 2020[11], received a high ranking, and provided the author with a bonus to submit the Leonardo Journal.

[9] https://visap.net/exhibition.html
[10] https://www.alteredfestival.com/festival-2020
[11] https://www.leonardo.info/labs-2020

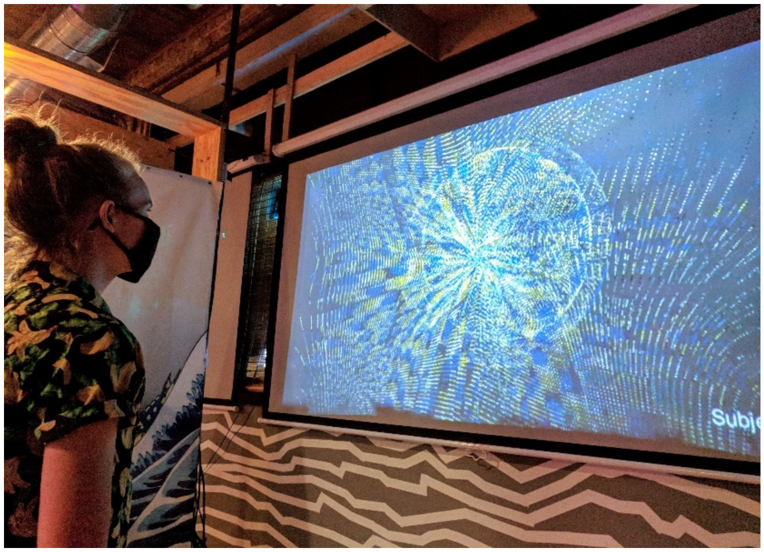


Figure 5.30: Visum A/V exhibition at Altered Festival 2020 - Credit: Altered Festival

There will be more submissions to exhibitions for both Visum and Aspecta artworks in the future. A demo of Visum is located at: https://drive.google.com/file/d/1LJGA56-xQD9SQ8zbjNrR_C1G7HvL66LE/view?usp=sharing.

5.14 Discussion - Visum

Visum, a novel expressive immersive audio/visual application, which uses visual perception through an interface to create sound and visual objects, is presented. Having the most control over the data was influential in the design of the interface. Listening was the primary sense reflected in the Visum interface design by having the sonification output control the visualization output. In this artwork, the brain is analogous to a mixing board, with faders and knobs. The eight audio channels (streams) could be spatialized in 3D space, reflecting how humans hear in 3D space. The VEP data is complex and developing a system to deal with the data complexity is paramount.

This is shown in the data controller feature of the interface. The output streams could be compared to various sections, e.g., brass, strings, woodwinds of an orchestra. Each section has its uniqueness allowing the user to explore a plethora of sonic and visual possibilities. The system user can independently manipulate these data to compose the most basic to the most complex audio/visual works.

Usability issues and possible future improvements are also presented. The mappings and, thus, interactions will become more complex to increase expressiveness, which could also be taxing on the computer's CPU. There is a trade-off between expressiveness and complexity. A simple way to improve user accessibility is to add more templates for existing designs. Users could start with templates or presets and then modify them to whatever they want. During the system design and evaluation process, it became apparent that creating compositions from scratch took more than modifying an existing composition. If the users can focus more on the creative aspects rather than using the interface, they can make better compositions. Working with presets could speed up the learning process. What is also helpful is to include a brief video tutorial on how to use the system. More research needs to be done on reducing CPU usage to address complexity, for example, only to activate specific components when needed.

Chapter 6

BCI Artwork - Aspecta

"The measure of greatness in a scientific idea is the extent to which it stimulates thought and opens up new lines of research."

Paul Dirac

6.1 Introduction

In this section of the thesis, a second BCI Artwork named Aspecta is presented. The organization is as follows: the background and framework are first presented followed by the documentation of the development of this artwork through several versions, including the design, implementation, challenges, and limitations. An overall evaluation for Aspecta is presented in Chapter 7.

6.1.1 Aspecta Background

Like Visum, Aspecta (feminine noun) also comes from Latin and means ‘that which is seen, appearance, vision, mental image’. The BCI Device for Aspecta used to acquire the data is the same as Visum (section 5.3). Humans tend to filter out what is essential in sensory processing. This is evident based on the Gestalt principles. Even though vision is the primary sense when dealing with complex sounds applying Gestalt principles, particularly that of figure-ground, is important. Bringing together combinations of rhythm, texture, and narrative/arrangement to evoke an emotional response within the listener is also essential. Listening to body rhythms is vital in the medical field to detect any rhythmic abnormalities. This is the central concept behind Aspecta. Compared with Visum, which is more expressive or takes a metaphoric approach to visual perception, this artwork is literal in using the actual data to create the images.
The main contribution of this BCI artwork is an immersive framework that generates output from this neurophysiological data. The emphasis placed in this artwork is on listening and observing. Generally, physiological data is visualized, like in Fig. 5.16. Aspecta, however, takes an aesthetic approach to neurophysiological data visualization.

Aspecta BCI Artwork Classification

Following the BCI Artwork taxonomy described in Chapter 4, Aspecta is classified as:
Input: EEG classification: Short-term coherent waves
Agency: Reactive
Timeliness: Pre-recorded
Modality: multi-modal
Mapping: Direct
Output: Audio-Visual

Format: Screen-based

Audience: Passive

In the following sections, the design, implementation, challenges, and limitations are presented. An overall evaluation for Aspecta in the form of an evaluation is presented in Chapter 7.

The following section covers: framework broken down into concept, sonification, and visualization, followed by the implementation, challenges, and limitations.

6.1.2 Design - Aspecta

The purpose of Aspecta is conceptual literal, unlike Visum, which is conceptual (metaphorical). It is based on scientific methods; that is, the data sonification is based on FM literal modification of sound, and visualization is based on data values. The audience should notice that the motion and color output is connected to the sound output, representing the data's output.

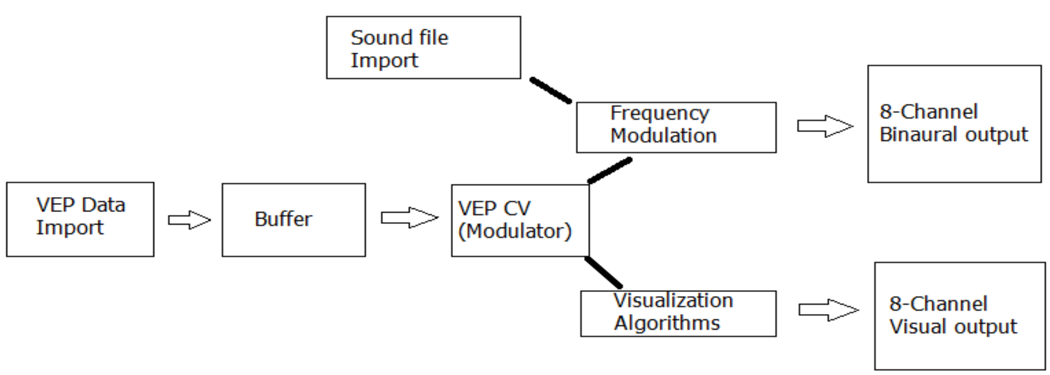


Figure 6.1: Aspecta Framework

6.1.3 Aspecta Interface Design

The interface design for Aspecta is now presented. The overall user interface is shown in Figure 6.2. It consists of a Data import, Data Controller, Audio channels, and Visual controls. The interface has eight channels or streams, which, like in Visum, can be compared to a head with eight sensors. The user controls the information of the eight sensors coming out of the head. Users can drop files in the 'Data Importer' section either through a folder containing multiple files or by selecting one file at a time. The data is stored in the buffer and can be used as control signals. In Aspecta the data controls the sonification and visualization independently, so there is direct mapping of the data values, which is opposite to Visum where the sonification controlled the visualization.

6.2 Aspecta Sonification Framework

Aspecta sonification uses the Frequency Modulation technique, which is discussed in section 5.6. In this BCI artwork, the sound file is the carrier, and the VEP data is the modulator. The sound output is then sent to the channel corresponding to that CV data. Here, the VEP data amplitude modulates the sound file, which is chosen by the user.

6.2.1 Aspecta Sonification

Users can create sonification in Aspecta by:

1. Importing the data. Select a sound file in the audio section by clicking on 'import sound'.

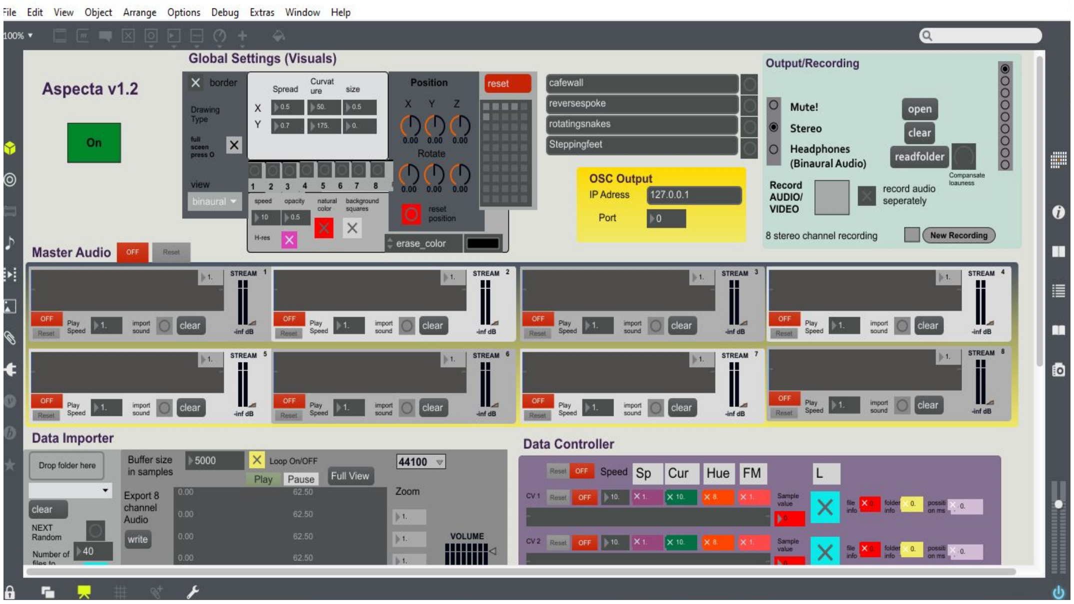


Figure 6.2: Aspecta main interface

2. Turning on the stream by clicking the on/off button.

3. Turning on the corresponding data in the ‘Data Controller’ section will manipulate the sound by turning on the data row (CV) by clicking on the on/off button.

4. Adjusting the Frequency Modulation value (optional).

5. Select the desired output. Users can select Stereo or Binaural for sound output (Fig. 6.3). For Binaural output, the user needs to select the Binaural output folder that contains the IR files, as described in section 5.4.4. A limitation of using the Binaural feature is that it doubles the CPU usage in comparison to Stereo. Using the Binaural feature allows the users to solo a channel if they want to.

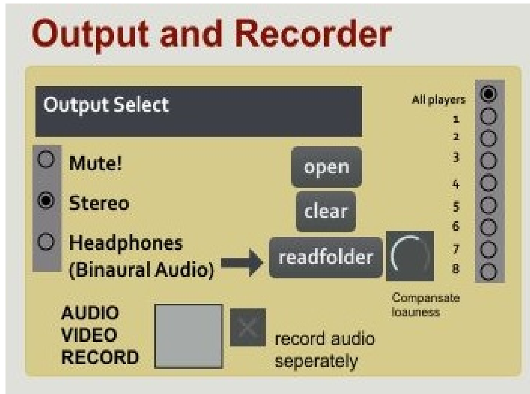


Figure 6.3: Output section

6.3 Aspecta Visualization Framework

This section describes how do the figures react to VEP data amplitude and waveform. Sounds are vibrations represented as waves, and each sound has its unique shape. In Physics, the amplitude is the “maximum displacement or distance moved by a point on a vibrating body or wave” and perceived as the volume in the psychoacoustic field. So, the amplitude determines the renderings’ size, and the louder the sounds get, the more they are graphically magnified. For the wave shapes one sine wave and one cosine wave (sine wave in anti-phase with the other), here can be described as parametric equations on a Cartesian plane where “t” is Time:

x = cos(t)

y= sin(t)

0<=t<=2pi

While thinking about representing VEP data graphically, background research was done on audio waveforms and graphically depicting the motion. This served as an inspiration to apply the same concept in the visual perception field, representing the trend of a visual evoked potential in an XY type oscilloscope.

There are many ways to visualize music or audio. Aspecta explores several approaches of which applying Lissajous formulas was one of them. The meaningful feedback between sound and vision is crucial in delivering an emotionally coherent context for the person engaged in the experience. The following section describes the Lissajous theory in detail.

6.3.1 Lissajous Theory

Lissajous figures or curves are trajectories of points whose coordinates follow sinusoidal movements. They are simple but timeless classic curves with numerous applications and artistic elegance (Roberts, n.d.). To create Lissajous figures, what is needed are two signal generators and an oscilloscope. The oscilloscope needs to have an XY mode in order to control the dots on the screen. The X controls the horizontal(time-based) or X position. The Y controls the vertical or Y position (voltage inputs) on the oscilloscope. When the XY mode is activated, the control signals control both the x position and the y position. Jules Antoine Lissajous came up with an idea to graphically represent two oscillators differently, showing the displacement(phase) that corresponds to one oscillator along the x-axis, while the other displacement is shown along y-axis on a Cartesian plane (something like x=sig1(horizontal), y=sig2(vertical)).

Lissajous curves are the family of curves described by the parametric equations:

$$x(t) = A * \cos(\omega(t) - \delta) \tag{6.1}$$

$$y(t) = B * \cos(\omega(t) - \delta) \tag{6.2}$$

sometimes written in the form

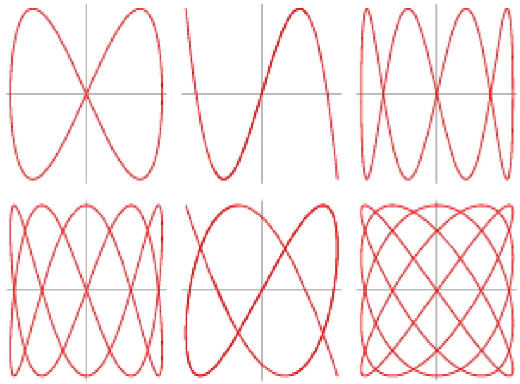


Figure 6.4: Lissajous curves are the family of curves described by the parametric equations - Credit: mathworld.wolfram.com

$$x(t) = a * \sin(\omega(t) + \delta) \tag{6.3}$$

$$y(t) = b * \sin(t) \tag{6.4}$$

These curves are sometimes known as Bowditch curves after Nathaniel Bowditch, who studied them in 1815. They were studied in more detail (independently) by Jules-Antoine Lissajous in 1857. Lissajous curves have applications in physics, astronomy, and other sciences (Wolfram, n.d). Lissajous figures or curves were once used to determine the frequencies of radio signals or sounds. A signal of known frequency was applied to the horizontal axis of an oscilloscope. The signal to be measured was applied to the vertical axis. The resulting pattern was a function of the ratio of the two frequencies. Some science fiction movies made during the 1950's used Lissajous figures as props. A good example can be found in the opening credits of Alfred Hitchcock's movie Vertigo (1958) (Lissajous, n.d.).

Brainwaves are oscillations, though not steady oscillations. In Aspecta, VEP data, which are averaged brainwave data segments, are used to create Lissajous figures and control both the X and the Y, which creates the Lissajous figures. Using an oscilloscope allows for plotting a sinusoidal signal along the x-axis versus another sinusoidal signal along the y-axis. This creates Lissajous figures (as shown in Figure 6.4). Lissajous figures tell us about the phase difference between the two signals and the ratio of their frequencies.

6.3.2 Oscillography

Oscillography was used to create multifarious curvilinear light forms through electronic means (Franke, 1986) in the 1950's. Oscillography uses waveforms generated from several digital (audio) signal generators to control a laser or oscilloscope electron beam's two-dimensional path. It was also used as an expressive artistic medium in the 1950-60s by artists like Ben Laposky (1914-2000) and Nam June Paik (1932-2006).
Ben Laposky explored the theoretical and artistic potential of oscillography. He exhibited thousands of oscillographic images of his work (Laposky, 1958). He became known as the first significant person in creating this type of artwork. The works known as Oscillons, were waveforms composed of colorful images in light appearing on the screen of a cathode ray oscilloscope (Fig 6.5 and 6.6). Laposky also observed two things about the relationship between the sound waveforms and light images: 1) sheets and forms were created during high frequencies (Laposky, 1969). He concluded that the reason for this is that higher-frequency components in a waveform will create more vibratory motion in the same interval of time. 2) Some of the forms tend to have mathematical precision, while others are more free-flowing in their curvatures and symmetries.

Aspecta also uses the concept of oscillography to create artwork with the VEP data. Instead of an oscilloscope for display, *OpenGL* was used for the figure drawing in 3D

Figure 6.5: Oscillon 520 (first colored)

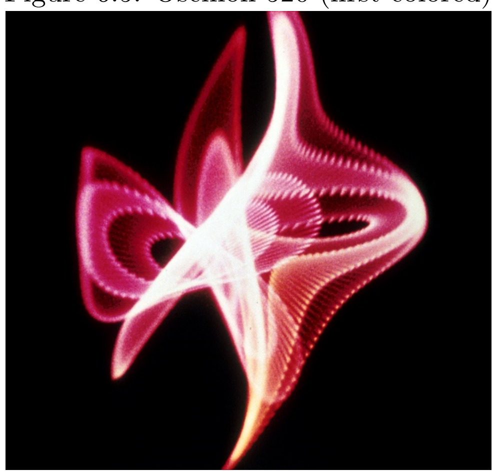


Figure 6.6: Oscillon 1049 Credit: timetoast.com - Credit: ACMSIGGRAPH - Art show archive

space. Throughout this research, several versions of Aspecta were created to explore drawing styles that would produce an excellent visual output of the data. VEP data, unlike audio signals, are not consistent and sparse. Some additional drawing styles represent the audio function in Aspecta that is not found on traditional oscilloscopes. These are *Points*, *Lines*, *Line Stripes*, or *Triangles* that add more options to create figures that are visually different.

The following sections track how Aspecta evolved over several versions by exploring different Lissajous drawing types such as one-point and two-point drawing and figure drawing with motifs.

6.4 Interface Design - Aspecta

The following sections will describe the design of Aspecta in detail.

6.4.1 Aspecta Version 1

In the first version of this BCI Artwork, colors were pre-assigned to each figure for the visualization as shown in figure 6.7. This image shows 500 ms VEP data, with the brainwave of 8 sensors.Like in science where a color could represent a group, sensor, or characteristic, here in this Aspecta, each of the eight sensor waves has its own color.

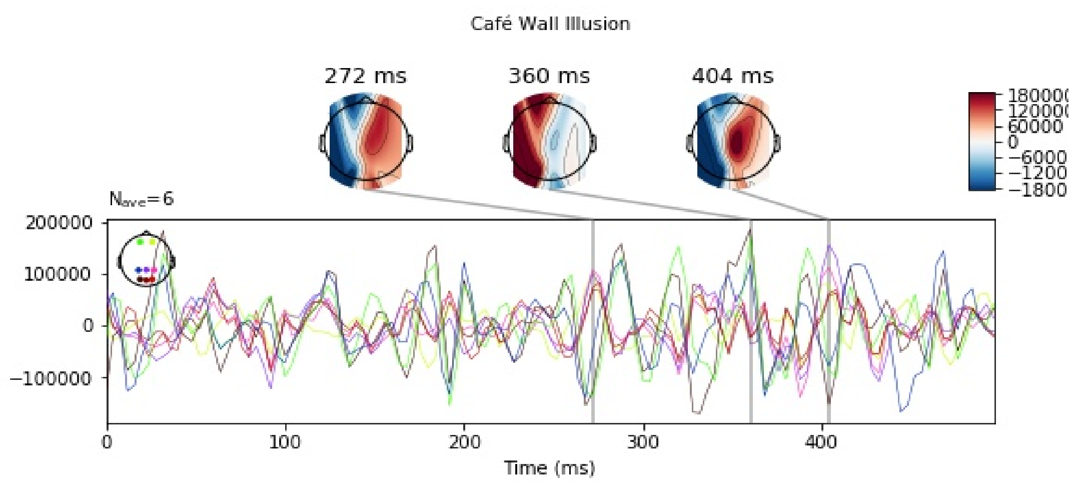


Figure 6.7: 8-channel time-series plot (Raw)

The following shows the formula that was used for the X, Y and Z coordinates used in Aspecta Version 1 (V1).

$$z = a * \sin(k * t + \omega) \tag{6.5}$$

$$x = b * \sin(n * t + \phi) \tag{6.6}$$

$$y = c * \sin(m * t + \gamma) \tag{6.7}$$

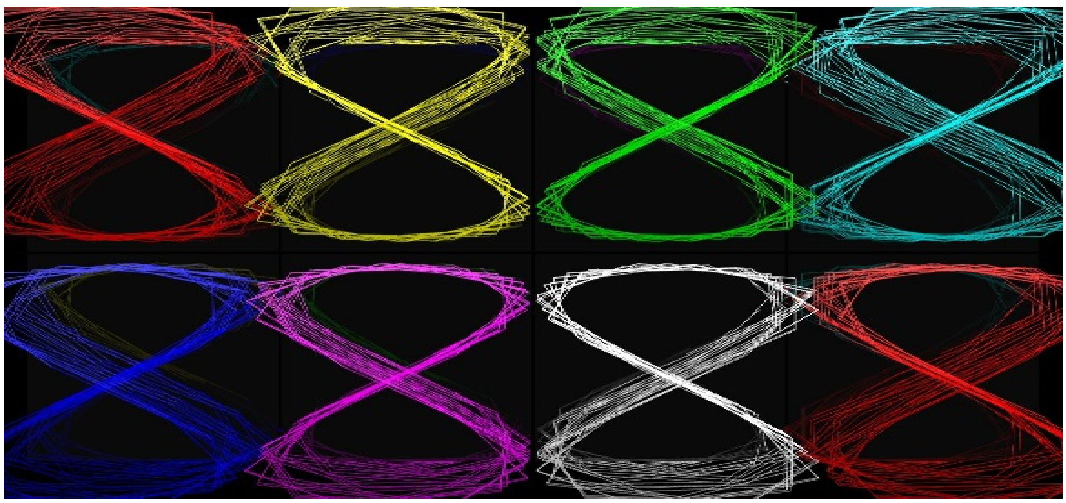


Figure 6.8: Aspecta V1 - no data (rest state)

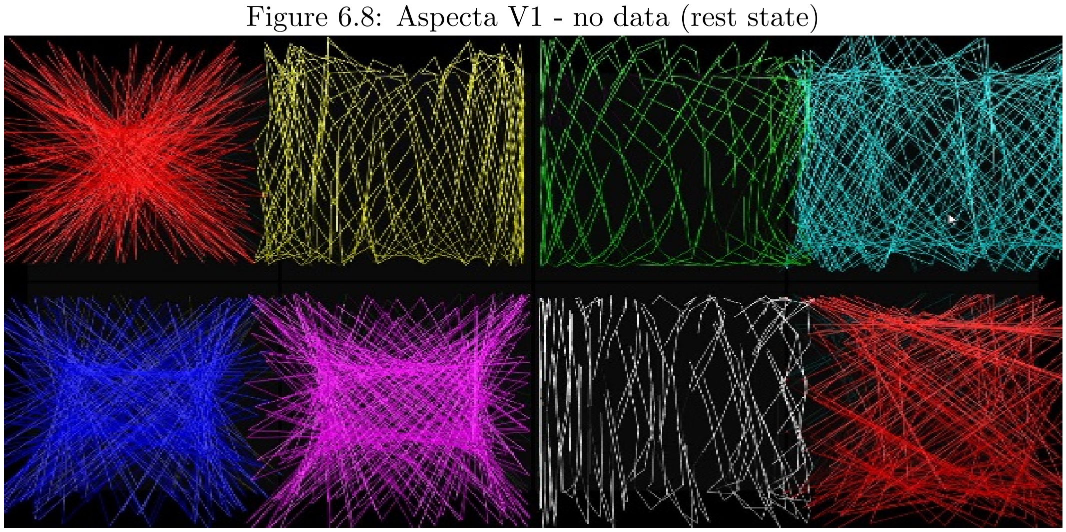


Figure 6.9: Aspecta V1 - with data

In this version of Aspecta, the movement activity is determined by Lissajous formulas (section 6.3.1). The layout of the figures is determined by the layout of the sonification output streams. So, the top four figures represent channels 1-4. The bottom four figures represent channels 5-8.

6.4.2 Aspecta Version 2

Aspecta Version 2 (V2) is inspired by the work of John Whitney often considered the father of computer graphics. Whitney's work explored the relationship between visual art and music. In this artwork I use his method of 2-point drawing/motion drawing to display the VEP data in V2.

According to Whitney, Sr. himself, his works are "asymmetrical, non-centered oriented, a fluid kind of motion that is not stuck in one place, this motion is multiplex, no static elements except when it comes to rest. It has a path and space which is approximately a trajectory, which he called a "linear figure". The central problem with this type of motion is that it must resemble the creative problem of melody writing. It is perhaps in its purest form the most highly concentrated case study of the essence of art itself involving as it does balance, contrast, tension and resolution all brought into play with minimum expenditure."

Aspecta V2 uses 2-point drawing and uses the following formulas:

Point 1

$$x1 = a11 * \sin(k11 * t) + a12 * \sin(k12 * t) \tag{6.8}$$

$$y1 = a13 * \sin(k13 * t) + a14 * \sin(k14 * t) \tag{6.9}$$

$$z1 = a15 * \sin(k15 * t) + a16 * \sin(k16 * t) \tag{6.10}$$

Point 2

$$x2 = a21 * \sin(k21 * t) + a22 * \sin(k22 * t) \tag{6.11}$$

$$y2 = a23 * \sin(k23 * t) + a24 * \sin(k24 * t) \tag{6.12}$$

$$z2 = a25 * \sin(k25 * t) + a26 * \sin(k26 * t) \tag{6.13}$$

a = scaling factor; k = multipliers. Scales affect the size of the figures. The multipliers affect the timing (speed) of the figure drawing.

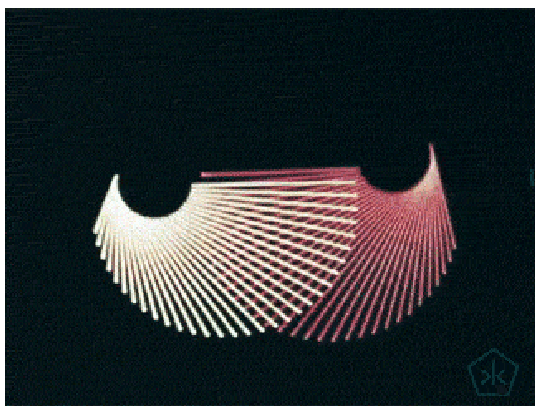


Figure 6.10: Whitney - motion graphics - credit: OKKULT Motion pictures

The difference between the two versions is that V1 uses one point drawing following the Lissajous formula indicated in section 6.4.1. V2 uses the two-point drawing to indicate non-centered motion. In the Figure 6.10, shows a Whitney motion graphic image, which is a still shot of two figures (white and pink), each drawn by two points moving at different speeds to give a sense of motion.

The two-point drawing technique is based on 2 points with a line connecting them. Each point moves at a different speed, which creates a sense of non-centered motion.

Figure 6.11 shows V2, where in the first image, there is constant motion, and no data is applied. The second image shows the data applied. The color change represents the data value. One of the most basic features in scientific visualization is mapping scalar values to colors (Moreland, 2009) which allows the viewing of scalar fields by coloring surfaces and volumes.

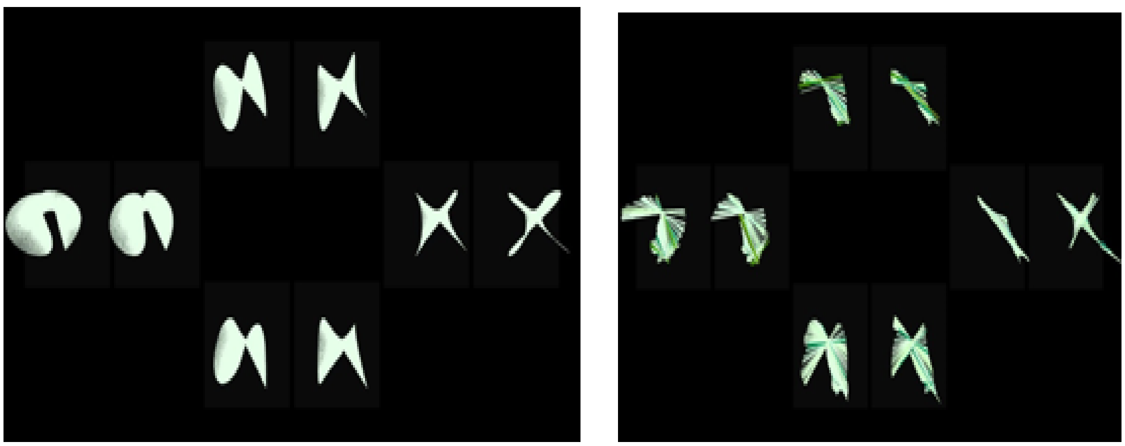


Figure 6.11: Aspecta V2 - no data (left) and with data (right)

Scalar fields give the magnitude of scalar quantities to a point in space. For example, in a thermal image, the temperature is the scalar field located at a certain point in space i.e. position x,y,z (coordinates) at time (t). Where there is a color legend representing data value ranges, the same concept is applied in this artwork. Here, the scalar field is the VEP, and the color is determined by the amplitude (magnitude) of the VEP.

6.4.3 Color Mapping

The color mapping for V2 and V3 uses the Hue-Saturation-Lightness (HSL) color wheel (Fig. 6.13). Hue is the specific color (e.g., red, green, yellow etc.), Saturation is how

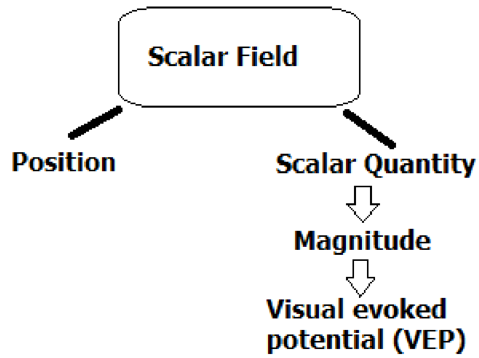


Figure 6.12: Scalar Field diagram

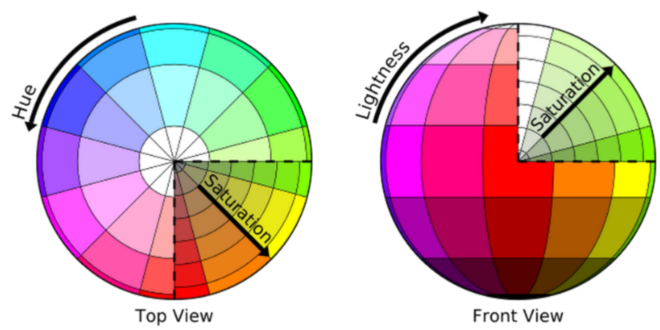


Figure 6.13: HSL Color Wheel

pale or deep the hue is (e.g., light green vs dark green) and Lightness is the scale of black (no lightness) to white (full brightness/lightness). The colors representing VEP amplitude are mapped to the HSL color wheel.

Aspecta Color Map Design

The color mapping used in Aspecta follows similar one to the science mapping. The color corresponding to the data value ranges from blue to red are -1. to 1. The data values ranging from 0.8 to 1 are mapped to red. The ranges of 0 to 0.5 are mapped to white and the values ranging from -0.8 to -1 are mapped to blue/dark purple.

6.4.4 Aspecta Version 3

In version 3 of Aspecta, the approach chosen is to draw a motif at each iteration point creating a Lissajous curve. The motif could be a straight line at an angle, which itself could rotate. Combining these types of lines based on the shape tends to create caustic curves. Some of these simulate the decay effect of harmonograph pendulums (mechanical apparatus that uses a pendulum to create a geometric image) pendulums.

Algorithm used in Aspecta V3

Oscillating variations define the color components. The oscillating part - e.g. (1+sin(time/100) will vary between a lower value and 2, allowing the color component value to take a value less than 255. The multiplying value outside the bracket defines the amplitude of the color variation. The speed of variation is defined by the value that divides time (large values==>slow variation). The color variation follows the algorithms below:

r = int(125.0*(1.0+1.00*sin(time/100.))); oscillating R color value

b = int(125.0*(1.5+0.50*cos(time/120.))); oscillating G color value

g = int(255.0*(0.5+0.50*sin(0.5+time/260.))); oscillating B color value

The coloring of the figures is based on the sample values. V3 again uses the HSL color wheel. The hue is determined by the VEP data's amplitude, ranging from red (positive) to blue/purple (negative). Values hovering around zero produce a yellowish color. Natural colors in the context of Aspecta V3 refer to the figure producing its color based on an algorithm (oscillating r, b, g color value). The following algorithm defines the current coordinate origin, following a simple decaying Lissajous curve. The time (t) is increasing, but the rate is controlled from outside with the global parameter 'speed'.

t = t+1

rotation occurs at the rate of:

angle = angle+ 0.02

the center of the figure moves according to these equations:

xt=-0.5*sin(time/50)*exp(-time/4000.)

yt=0.7*cos(time/175)*exp(-time/4000.)

The figure shape length and width change according to these formulas:

eheight = 0.5*exp(-time/4000);

ewidth = 0.0022*sin(time/500)*exp(-time/4000)

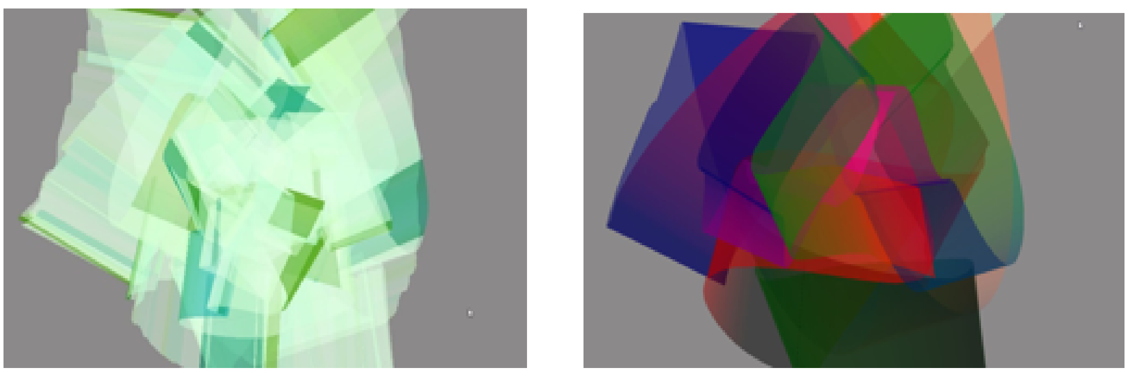


Figure 6.14: Aspecta V3 - one sensor's output of VEP data without natural colors(left) and VEP data with natural colors (right)

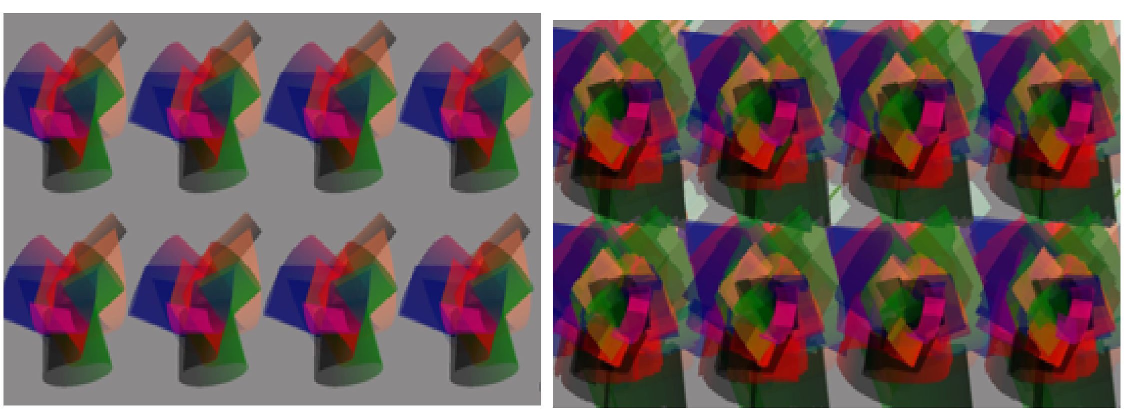


Figure 6.15: Aspecta V3 without Data (left) and with Data (right)

In V3 when the data are applied to the figures, they look smudged, as indicated in figure 6.15. So, the next iteration for this artwork was to improve resolution.

6.4.5 Aspecta Version 4

In this version, the figure resolution was improved so that the figures do not look smudged. The algorithm is the same as used in V3. Also added in this version is the display of data information, such as the sensor, the subject number, and timing of the data as it is being read.

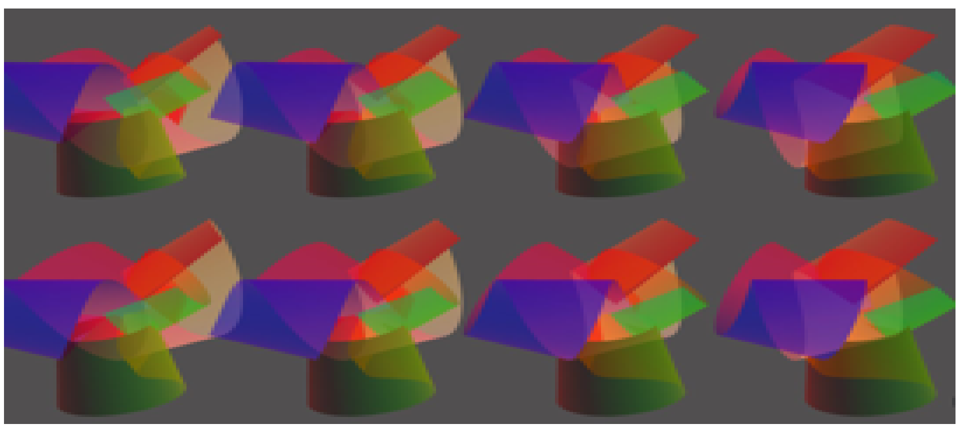


Figure 6.16: Aspecta with improved resolution (natural colors)- 8 sensors

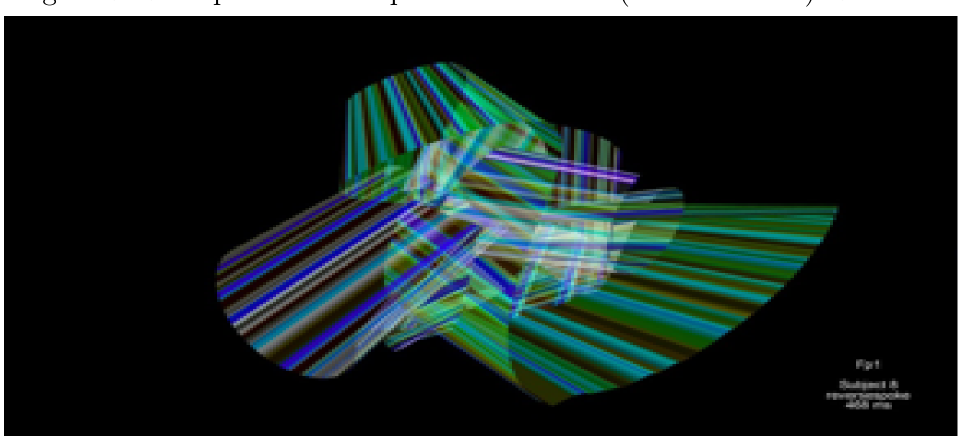


Figure 6.17: Aspecta improved reolution 1-sensor with data

6.5 Aspecta User Interaction

Creating Aspecta Visualizations:

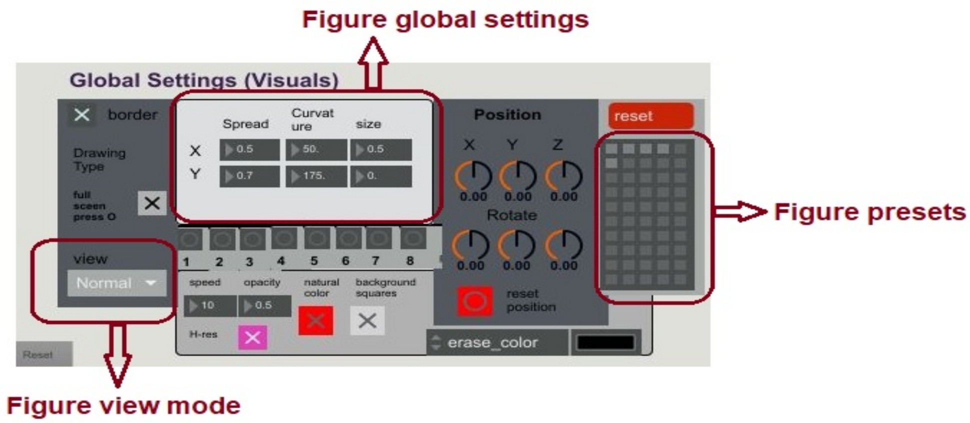


Figure 6.18: Aspecta Visualization settings

A popup screen appears whenever the Aspecta interface is opened. This screen is where the Lissajous are displayed. Users can select a Normal view, which shows all eight figures in the two-row, four-column configuration (Fig. 6.16). Selecting Binaural changes the figures' layout (Fig. 6.19) to two channels in the front, back, left, and right. This is for immersive listening and viewing experience. Users can also select a single figure display. Once selected users can choose how they want the figures to display.

In Aspecta, the Lissajous are drawn with a motif at each iteration point. In this case, a motif is a slowly rotating ellipse at each time point. The users can change the Lissajous figures' parameters in the 'Data Controller' section of the interface (Fig 6.2). The parameters are 'SP' for Spread, and this variable determines how far the figures extends before it curves. The 'Curv' parameter determines how deep the curve is. The larger the number the deeper the curve of the ellipse. The 'Hue' parameter determines the colors of the figures. The 'Speed' parameter, determines how fast the data is read from the sample buffer. The 'FM' parameter controls the speed of the audio players.

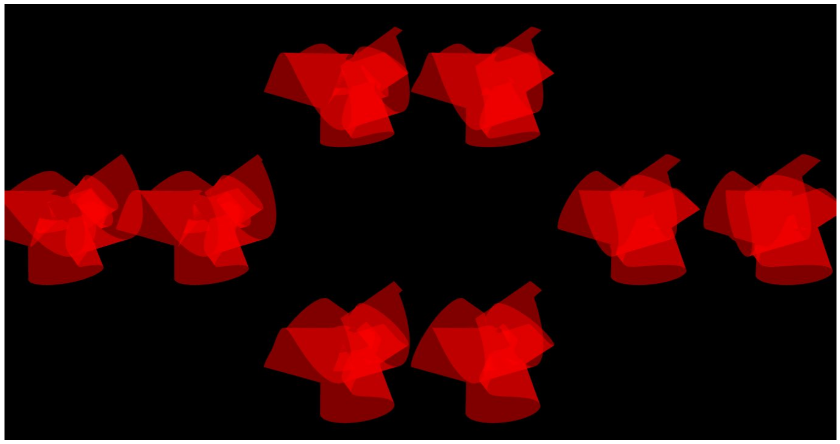


Figure 6.19: Aspecta Binaural Layout

Aspecta allows the users to save the figure drawing type into pre-sets for easy recall.

6.6 Aspecta Implementation

Similar to the Visum interface, Aspecta is also implemented in Max/MSP/jitter. Input: Data is imported into the system as .csv files. The .csv files contain eight columns representing the eight sensors of the EEG device. The data are also separated by subject. There are sixteen subject folders, each containing the VEP data for the four optical illusions. The user can import data for one, or any number of subjects into the interface. An MSP buffer (data structure) can hold digital audio information within program memory (MaxMsp, n.d). Data is loaded into the buffer and used as control signals. The eight control voltages represent the eight-sensor data which can control any sound parameter to create sound objects. The sound parameters used in Max/MSP are granular synthesis parameters. These sound elements are then linked to the visualization objects in Jitter for visual output. For visual output, the resulting graphic elements are rendered on the screen.

There are eight audio streams in the current prototype. There is also a choice of all

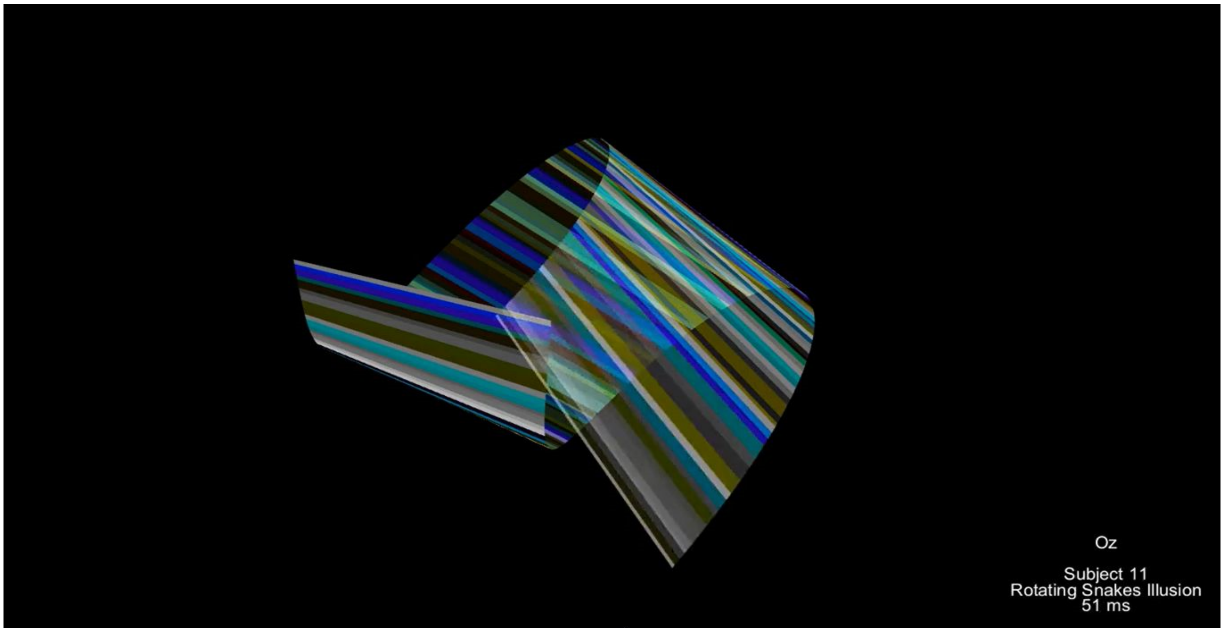


Figure 6.20: Aspecta Demo Visualization A

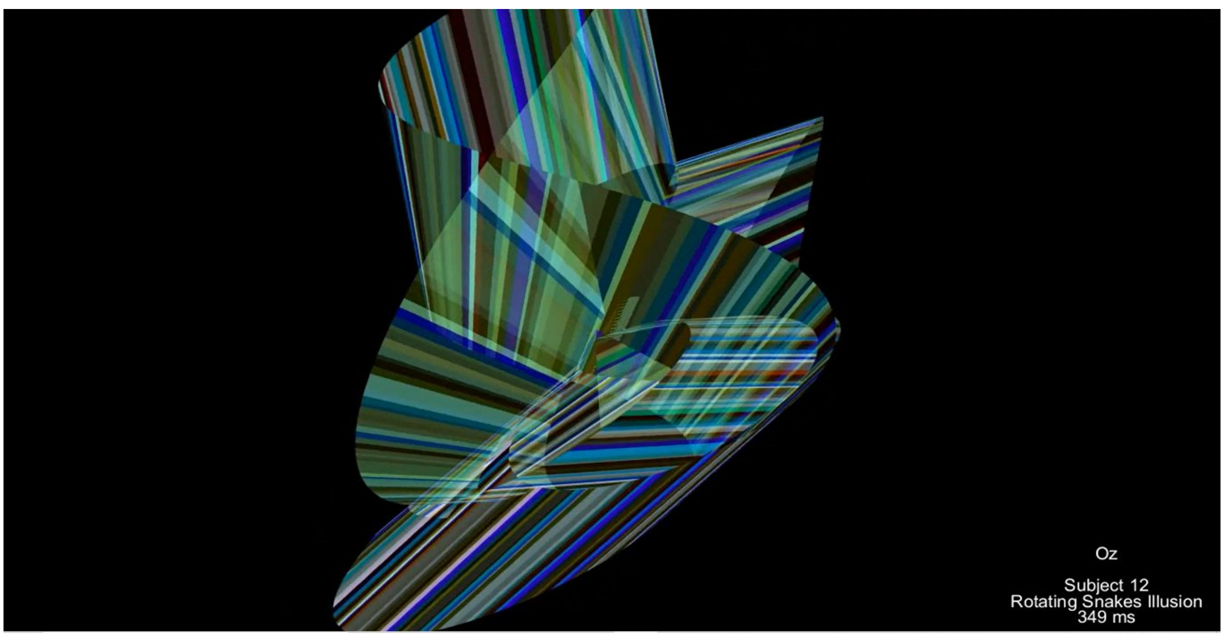


Figure 6.21: Aspecta Demo Visualization B

eight, or single figure rendering. The latter allows for a closer inspection of the A/V output.

6.7 Installation design

This section presents the design and layout of the Aspecta installation.

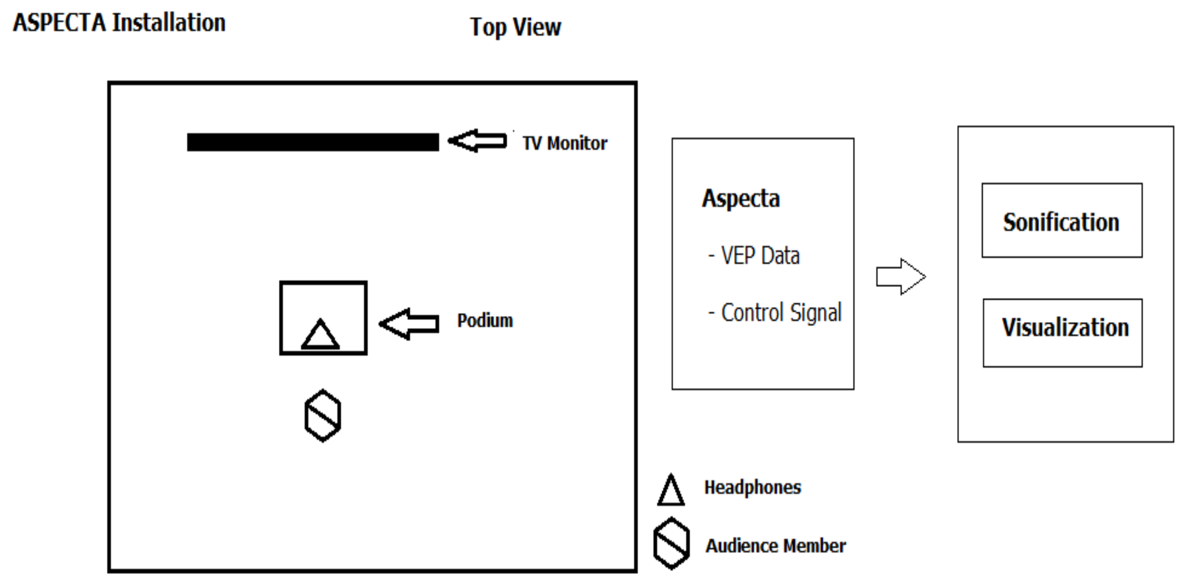


Figure 6.22: Aspecta Installation Layout

Installation Layout - Aspecta

The installation requires a space of about 8x8x10 feet with dim light and a large monitor at the front of the room to display the figure drawings. This TV display will be showing the figure drawings. There is a podium with headphones on it. A laptop is needed to run the software that is used for sonification and visualization of the data. A podium with headphones will be necessary for the spatialized Binaural listening.

A demo A/V output for Aspecta is hosted at: https://drive.google.com/file/d/1QfXVOzh3g3J0k0ssbn8kshFALcEJU8Cr/view?usp=sharing.

6.8 Challenges in Aspecta

Aspecta is a unique piece of software that functions in a space combining Frequency Modulation and visuals. A lot of work went into ensuring it was able to fulfill core characteristics such as literal representing the data value and visuals. The user will have active control over the output, such as Zoom in/out and 360 rotation in order to explore the connection between audio and visual. The challenge was to devise design strategies for the control of aesthetic output, particularly the figure drawings.

6.9 Discussion - Aspecta

This section presented the BCI artwork Aspecta, a novel immersive audio/visual application based on visual perception. Aspecta is intended to serve as a contrasting approach to Visum for exploring narratives of the data. It uses Lissajous drawings as its principal aesthetic focus. Lissajous drawings were chosen because they are time-based and are known to create aesthetically pleasing output, as shown in section 6.4.2. Given that VEP data are also time-based and complex, using Lissajous theory is an excellent way to extract information and explore it. Colors within a figure osscillate and also be linked to the amplitude of the data. Another critical reason for using oscillography is that it is independent of the length of a signal or data and allows for information extraction and creative output from the data. The VEP data is less than a second (500 ms) in duration, making it hard to retrieve frequency information. Frequency is the number of cycles per second. The Aspecta interface is designed to explore and represent the VEP data extracted from an experiment where eight sensors place on the subject's head are used. Each channel in Aspecta represents a sensor. The user of the interface can explore the data for each channel individually or as a group. The interface allows for the speeding up or slowdown of the data ‘playback’ for more in-depth inspection of the data.

Gestalt principles of grouping are applied in Aspecta, by allowing the grouping of channels for their separation from other channels in terms of sound output, enhancing how we perceive and process information. For example, separating the channels representing the P sensors from those representing the O sensors. The figure-ground principle is also tied into the design of Aspecta in order to extract salient information from data by changing the FM parameter, which changes the speed of that channel. The Aspecta interface has pre-sets for easy recall of specific figure configuration, which speeds up the visualization. When sonification and visualization are presented together, it provides a better representation of the observer’s data. Sonification of biological data is important because subtle changes in the data allows the listener to detect them much faster than with visualization.

6.10 Conclusion - Aspecta

Aspecta was designed to be a data listening and observing system inspired by visual perception principles. The design, implementation, limitations, and future improvement possibilities are presented. In Aspecta, the theory of Frequency Modulation for sonification and tracing Lissajous figures for the visualization are presented. The data is directly mapped to both the sonification and visualization parameters. It is also based on scientific modeling, in this case, the color mapping for the scalar quantities. The evaluation is presented in Chapter 7.

6.11 Analysis of Visum and Aspecta

Combined Audiovisual Model

Visum and Aspecta were both developed crossmodally (from the sonification standpoint), meaning that the sonification modality was first considered to affect visualization. The biofeedback artworks presented in Chapter 4, rely heavily on the active BCI paradigm and alpha waves' control. The BCI artworks presented in this thesis follow the reactive BCI paradigm. Also, brain artworks like Sobell's Brainwave drawing use an oscilloscope to present the brainwaves, even for Lissajous output. The BCI artwork Aspecta, also uses Lissajous principles as the output, however, it is graphical. As documented in (Miranda, 2014), Eduardo Miranda's research uses SSVEP retrieved in real-time for the real-time control of a computer or composed music. The BCI artworks created in this thesis use VEP, which are retrieved off-line and used to compose in real-time. The Biomuse developed by Knapp and Lusted uses multimodal physiological signals (EEG and EMG) to generate music. The concept of the Brainarium by (Grandchamp and Delorme, 2016) is like that of Visum. It serves as an artistic and pedagogical tool and works as a brain metaphor. In this research, the BCI artworks also serve as a pedagogical and artistic tool. Aspecta differs from Brainarium in the approach and methodology.

Chapter 7

Evaluation

"Research is formalized curiosity. It is poking and prying with a purpose."

Zora Neale Hurston

7.1 Evaluation

In this chapter, methods of data analysis for the experiment and evaluations for the artworks are presented.

7.1.1 Data Analysis

Data analysis is crucial to extracting VEP data. A raw EEG tends to be noisy and mask ERP signals. To extract the ERP data, the raw EEG needs to go through a filtering process. A total of 40 trials (illusion images) was retrieved from each subject. The raw EEG data were then filtered (band passed 0.5 - 30 Hz) and segmented. A notch filter of 60 Hz was also applied. Data epochs were 500 ms each, that is, segmented at 500 ms post-stimulus. Based on the scientific theory that a VEP is usually detected at around 100 ms and perception at around 300 ms post-stimulus, segments of 500 ms were chosen. Data epochs were subsequently trial averaged (epochs for each specific trial e.g. the Café Wall illusion, were averaged) to remove noise and extract the VEP signal. See Appendix C for more on VEP data visualization.

The few databases that contain VEP data are not readily accessible, including the Steady-State Visual Evoked Potential (SSVEP) and VEP following the P300 oddball paradigm databases. Open databases containing simple VEP data derived from looking at images are hard to come by, not well documented, or file type compatible. It was therefor necessary to design or conduct an experiment following scientific methods to extract VEP data information for this research.

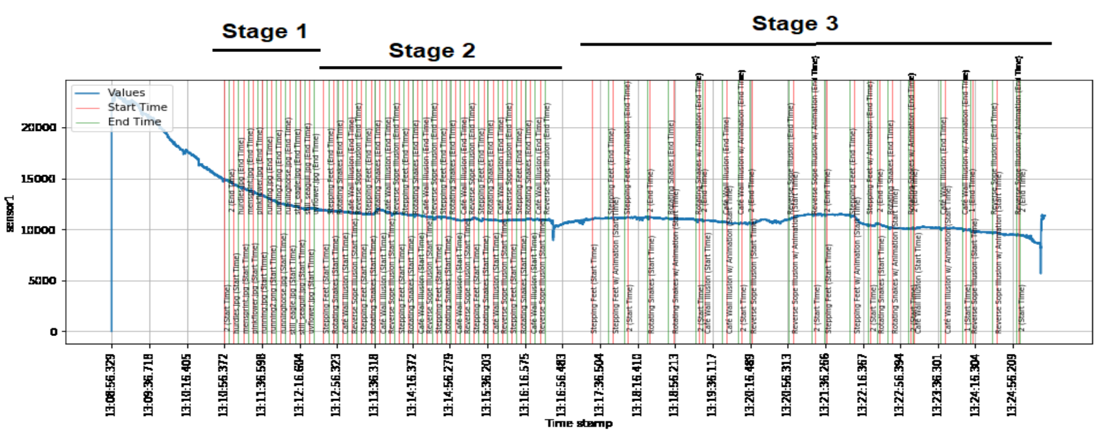


Figure 7.1: EEG Segmentation for each experiment stage

The figure above shows an experiment session for a subject containing the segment begin and endpoints for each stimulus presented in the three stages. These segments are then filtered, and trial averaged to extract the VEP information.

7.1.1.1 Digital Signal Processing

An infinite impulse response (IIR) filter was first applied to the raw EEG signal to extract frequencies between 0.5 and 30Hz. A notch filter of 60Hz was also applied to remove the frequency at 60Hz, a machine-based electrical interference.

7.1.1.2 Plots

Topographic plots are generally a good way to visualize a subject's brain electrical activity. Topographic plots for the Oz sensors for all of the subjects who participated in this research experiment are shown in Appendix C. The trial averaged EEG post-stimulus segments are also included, which are the data used in this research's BCI artworks.

7.1.1.3 Qualitative Analysis

In the experiment, the participants were shown two images: an optical illusion and an altered version of that optical illusion. They were asked questions to see if they could distinguish between the two images. The questions were as follows and were asked twice: Cafe Wall: For which image did you notice that the size of the squares is changing? Select 1 or 2.

Stepping Feet: For which image did you notice that the boxes are moving at different speeds? Select 1 or 2.

Rotating Snakes: "For which image did you notice that the circles are physically rotating? Select 1 or 2.

Reverse Spoke Wheel: For which image did you notice that the spokes are physically rotating? Select 1 or 2.

The correct answer for all the questions is choice 2; in other words, the first image was

the illusion, and the second image was the altered version of the optical illusion.
A qualitative statistical analysis was performed on the experiment data, and the following trend was determined. The general frequency distribution of the optical illusions shows that the Café Wall was the most challenging for the participants in determining changes in the squares' size. For Café Wall, when first asked, only 40 percent choose answer 2, while the second time 30 percent choose answer 2. However, for the remaining optical illusions, i.e., Rotating Snakes, Reverse Spoke, and Stepping Feet, the trend was towards answer 2. For both questions for Rotating snakes, question 2 was chosen at least 80 percent of the time. For Reverse Spoke Wheel and Stepping Feet, at least 70 percent chose to answer 2.

A descriptive statistical analysis was done on the data. The data was also broken down by gender to see if there are any major difference in how the two genders visually perceive the images. For question 1 for the Stepping Feet illusion, most of the females chose to answer 2. For the Rotating Snakes illusion, most of the males chose to answer 2. For the Café Wall illusion, the majority that chose answer 2 were males. However, there is a tie in answering 2 for the Reverse Spoke Wheel for the two genders. For question 2, which is the second time that the illusions were presented to the participants, there is a slight difference in the answer selection. For the Stepping Feet, there was an increase in females choosing answer 2 and a decrease in males choosing answer 2. For the Rotating Snakes, there was an increase of the females choosing answer 2, and for the males, there was no change. For the Café Wall illusion, the second time around, there was a decrease in answer 2 for both genders. For the Reverse Spoke, there was an increase for the males and a decrease for the females for answer 2. The graphical representation of all the answers is shown in Appendix B.

The experiment results suggest that the participants were typically consistent in what they claim to perceive. With a few exceptions, they tend to answer the question consistently. The gender breakdown suggests that the males did better with the Rotating Snakes question than females. They also did better on the Cafe Wall, and the response difference between males and females was more pronounced. For the Reverse Spoke Wheel question, the males, after first tying with the females, adjusted and did better on the second question than the females. For the Stepping Feet questions, the females did better than the males both times. A comparison between the non-illusion image plots with illusion plots is shown in Appendix D. The criteria show the non-illusion plots with the illusion plots of the subjects who got most or all of the questions correct.

7.1.1.4 Data Comparison

In neuroscience, visual evoked potentials occur around 100 ms post visual stimulus. Activity should be taking place in the occipital area of the brain, which means that there should be positive values, suggesting neuronal activity. Looking at the plots in Appendix C, which shows brain activity after the subjects looked at optical illusion images, this appears to be the case in some of the topographic plots. For example, for subject 9 for the Reverse Spoke Wheel illusion, at about 100 ms, there seems to be an increase in neuronal activity indicated by the Oz sensor, which is the middle sensor at the back of the head. In this particular subject, it shifts from blue at 0 ms to red at 100 ms. It also needs to be noted that the timing of neuronal activity may vary depending on the subject. Some may be before 100 ms, and some may be after 100 ms for this activity type.

Brain activity for non-illusion images, indicated in Appendix D, seems more discernible than for illusion images. The following subjects (8, 4, 3, and 13) received the highest scores (15-16) overall for the experiment. The scores were determined by adding up the answers to the experiments' questions in stage 3. For example, if a subject chose 2 (choice 2) for an answer and 1 (choice 1) for another answer, the total score is 3. In this experiment, the most amount of points a subject could get is 16 for eight questions (four illusions presented twice). Subject 8 answered all the questions right (score 16), indicating that he could distinguish between an optical illusion image and an altered version of the optical illusion image.

7.1.1.5 Illusion vs. Non-illusion

A comparison is made between a non-illusion image, showing a still image (no illusion) and an optical illusion image. Table 7.1 shows the choices of the four highest-scoring subjects by optical illusions. An X indicates that they chose the correct answer twice. A 2/1 indicates that the subject first chose 2 then the next time around for the same question chose 1. The 2/1 answers were excluded from the comparisons in the Appendix.

	CW	Rev Sp	Rot Sn.	Step. Ft.
Sub 8	X	X	X	X
Sub 4	2/1	X	X	X
Sub 3	2/1	X	X	X
Sub 13	X	X	X	2/1

Table 7.1: Highest scoring subjects' answers

The comparisons were also shown with the scientific topographic output in the artistic (Aspecta) processed version. When comparing the two plots, it seems like the non-illusion one is darker, suggesting that the segment seems noisier than the optical illusion one, which is trial averaged. In general, there appears to be more discernible activity in the occipital part of the brain for the observation of non-illusion images compared to the observation of optical illusions post-stimulus.

7.2 Visum Evaluation

To examine how each participant experiences unique interaction with VEP data, user evaluations were conducted. The purpose of the user study was to evaluate how each participant has a unique experience with “Visum”. Due to the COVID-19 pandemic in the year 2020, it was challenging to have in-person evaluations. The workaround was to create an executable file of the interface and send it along with the data to users for them to use it locally on their computers. The artwork included a custom-made interface implemented in Max/MSP/Jitter and the VEP data. Participants could evaluate the program from the comfort of their home or office. After experiencing the interface, they complete a questionnaire following a Likert scale, created a sample composition, and uploaded both into a Google Form. Seven participants were included in the user study, which consisted of five males and two females with normal to corrected vision. Their ages range from 26-44, with a mean age of 33. Five participants indicated that they have experience with music interfaces. The other two indicated that they are artists but not familiar with music interfaces. The results for the post-trial questionnaire are presented in section 7.1.1.3.

Visum Study Results

After providing a brief explanation of the study and video tutorial, the participants were asked to complete a pre-study background questionnaire followed by composition and evaluation of the interface. They were asked to upload a composition. The evaluation of the interface was based on a Likert scale. 70 percent thought the auditory display was easy to navigate. Just over 50 percent thought the visualization section was easy to navigate, and 70 percent thought the interface design was good. There was feedback that there were many features to process in a short amount of time. After following up with some of the participants and asking them if had they looked at the tutorial, some said no, they did not. Only one of the participants tested out the OSC feature.

The feedback provided by the participants will be used to make necessary adjustments to the interface. Potential enhancements for Visum would involve giving the user an option to activate features when necessary. This would allow some users not to feel overwhelmed when using the system. Currently, the tutorial video only shows how to import data and control data with audio and video streams. A future version might include how to use the C-panel.

Questions for Visum User Interaction Study:

-Do you wish to participate?

-Sex?

-Age?

-Do you have 20/20 vision (corrected or uncorrected)?

-Any hearing loss?

-What is your dominant hand?

-Do you have any experience with music interfaces?

-Please compose a piece and upload:

-Any other comments or feedback?

Post-Trial Questionnaire: -Auditory display (sonification section) easy to navigate?

-Visualization (Jitter) section easy to navigate?

-Interface Design is good?

-Were you able to export data to any external programs (via OSC)?

-Please provide feedback about the OSC export?

-It was easy to compose/interact with the interface?

-Please elaborate on your answer to previous question.

-Should any features be added to this interface?

-If you answered Yes to the previous question, please elaborate.

-Any other comments or feedback?

7.3 Aspecta Evaluation

Aspecta was evaluated using documentation based on performance measures. These measures were the drawing of the Lissajous figures and the audio output and included the following factors:

- Aesthetic quality (mapping) In the visualization, the main parameters that affect the aesthetics of the figure drawn are the 'Curv' and 'Sp' parameters (Fig. 6.18). The Lissajous figures draw a motif (ellipse) at every iteration, with iteration being every data value change. Here evaluation was done to manipulate these parameters to find what would be aesthetically pleasing. Setting the *Curv* for curvature and *Sp* for spread to 0 allows for a smooth tracing of the figures. Increasing these values changes the output qualities of the figure. For example, increasing Sp to 1 causes it to extend or spread out 1 unit before curving at every iteration, making the figure look like it was drawn with lines.

- Critical listening for accuracy. Listeing evaluations were conducted to determine the accuracy of the sonic representation of data values. For example, for positive values, there should be a higher pitch versus negative values for a lower pitch. FM allows for the audible enhancement of the data values. This is very important to those who listen for any abnormalities within the data.

- Comparison of the artistic output with scientific output: Evaluating the audio-visual output with the topographic mapping output to look at how well the BCI artwork processed the data—for example, comparing the color output of the data being read. Suppose the data have many values close to 0, and the color representing 0 is white. In that case, the visual output of Aspecta should also have a lot of white colors in the visual output.

The evaluation for *Aspecta* also showed that there is no latency between the audio and visuals. The CPU usage is also relatively low.

7.4 Final Discussion

In Part I of this dissertation, an overview of BCI technology and visual perception was presented to introduce the terminology used in the field and motivations for the work, and to lay the groundwork and for the design of artistic BCIs. The previous works by the author then followed. Part II discusses the two new artworks that were designed based on BCI technology and visual perception, particularly visual evoked potentials. The conceptual design and implementation of these interfaces aimed to express data as a reflection of the science and how we perceive the world. Making sonification and listening the primary focus was also important because visualization or the visual sense is considered the primary sense. Visualization can only give us a 2D view of an object, so objects that are in front of us. However, we can hear sounds in 3D space; in other words, we can hear sounds coming from all around us.

Visum, a new expressive interactive data sonification, and visualization artwork were presented. The design and control classification for Visum are Short Term Coherent Waves (STCW) for EEG classification, which are the brain's response to sensory stimuli; Reactive Input for Agency, which are brainwave changes created by an external stimulus; Pre-recorded for Timeliness, which refers to data retrieved some time ago

and multimodal for Modality, this being the data and human interaction. The concept applied to Visum is that of a brain metaphor, creating narratives of what happens in the brain when someone looks at an image. Models were applied to represent the visual perception of the P100 component, which is vital for image detection. This is the component that occurs about 100 ms post-stimulus. Given that Visum was based on a brain metaphor, the neurons of the brains were represented using the granular synthesis methods to break the data up into grains and rearrange them. The grains, which are approximately the same size as neuron firings, represented this brain activity.
The data mapping methods applied in the Visum sonification was direct and for the visualization was indirect. It was direct in the sense that the actual data values controlled the sonification parameters. It was indirect for visualization because the sonification parameters (output) were mapped to the visualization. The visualizations are time-based interactive animations. Visum offers the users much flexibility in how they want to map their data; in other words, the sonification to visualization mapping is not hardcoded; rather they can apply any mapping scheme they choose, which is done with the mapping matrix (Fig. 5.25).
There are two limitations for *Visum*: (1) The learning curve is high for those unfamiliar with music interfaces. This was also apparent with the user studies. Most participants familiar with music interfaces found that it was not difficult to use. In contrast, some of those with no experience found it challenging. This has been addressed by having users review a brief tutorial on how to get started in Visum. (2) *Visum* is very CPU heavy when using the audio and visuals, which would require computers that can handle this processing capacity. These drawbacks have been addressed in *Visum* by (1) clearly conveying the design concepts in the user interface and providing much more versatile interactions by having pre-sets in the control panel. Here a pre-set can contain already loaded data with sound and visuals working in a primary setting.

The user can then add or explore with the pre-sets in the composition panel (C-panel) and create compositions. The evaluations of and adaptations to *Visum* will empower a broader community to create richer audio/visuals for data-driven storytelling or just for simple creative/composition purposes.

In *Aspecta*, the emphasis is mainly on listening and a different conceptual approach in design and implementation was taken. Here the data are not used to create a metaphorical narrative. *Aspecta* is designed for critical listening like a doctor listening to a heart rate listening for any abnormalities. It loops through the data for each chosen subject while applying a similar method to brain mapping. Optional interaction uses a video controller for zooming in/out of the figure, equivalent to fractal zooming. Here the audience member can rotate to look at the figure from different angles and zoom into the figure for a close-up. Speed can also be changed like in *Visum*, for slow motion and fast motion effects. *Aspecta* was self-evaluated; that is, the author explored how the system performed and documented output and accuracy. Future *Aspecta* evaluation and user studies will be conducted after the COVID-19 pandemic is under control.

Chapter 8

Conclusion and Future Works

> "But that the reasoning from these facts, the drawing from them correct conclusions, is a matter of great difficulty, may be inferred from the imperfect state in which the Science is now found after it has been so long and so intensely studied"
>
> — Nassau William Senior

This thesis explored the use of Brain-computer interfaces with visual perception, particularly the retrieval and use of visual evoked potentials (VEP) from optical illusions. Part I summarized the background and theoretical understanding of the field. Part II applied the concepts of Part I into the creation of BCI artworks. In this chapter, contributions and potential future works are summarized and discussed. Ultimately, the author argues that exploring optical illusions through BCI technology gives us insight into our cognitive processes. It could also provoke meaningful conversations between the sciences and the humanities (and fine arts). In this dissertation, two BCI artworks were designed for audio/visual authoring, emphasizing the creation of sonifications/visualizations for immersive data-driven narratives applying scientific principles. The bespoke interfaces were evaluated based on data mapping, layout, and performance in user studies for interface evaluations. Visum and Aspecta are ongoing research projects, both addressing the many challenges that need solutions regarding both the scientific methodology and artistic and technical development.

Future work includes:

- Conducting more experiments to increase the data set to improve VEP signal accuracy. Having data that contains at least 30 subjects would be ideal for a statistically normal distribution of the VEP signal. Increasing VEP or neurophysiological data and making them more accessible will also open up more diverse approaches and methods to convert these data into artistic output.

- Applying machine learning for feature extraction and real-time processing of the VEP data for future applications. With more experiments and reliable optical illusion based VEP signals, there is potential to use these machine-learned signals for feature extraction. Real-time feature extraction could allow for real-time (active) control of artworks instead of offline (reactive) control. Offline processing of sensory information can take a long time to process due to preprocessing. "Deep Learning has often been exploited to automatically discover the representation of features at different levels, even producing representations across modalities (Fried Fiebrink 2013)". *Visum* and *Aspecta* can send Open Sound Control (OSC) values to external machine learning programs such as the *Wekinator* [12].

- Working with Head Mounted Displays (HMD). Using HMD would involve the

[12] http://www.wekinator.org/

application of an interactive, 3D audio, immersive virtual world constructed from VEP data.

8.1 Summary of Contributions

In this dissertation, two different works have focused on two different artistic BCI design and implementation approaches using scientific methods. First, it explored the interaction with the VEP data by developing bespoke interfaces, allowing users to interact with the data through composition and exploration. Second, the VEP data is used for critical observation.

This thesis presented the following contributions:

1. Potential contribution to the visual perception field (optical illusions give insight into brain function). A qualitative study on determining if there were any differences between optical illusions versus non-illusions. This to essentially determine if subjects could determine when they observed an optical illusion and compared that with brain activity output to non-optical illusions. This could be a potential contribution to the visual perception field, particularly for showing insights into the visual perception process for optical illusions.

2. EEG-based Interfaces enable immersive interaction between the users and neurophysiological data. This is the first system enabling users to visualize and interact with VEP signals in an artistic way. The interfaces manipulate VEP data by applying mappings and other features to investigate specific brain activity (through channels/streams) during visual perception.

3. Contribution to the Neuro-aesthetics field. This emerging field investigates experimental science that aims to combine (neuro-)psychological research with aesthetics by

investigating the perception of art. Though optical illusions themselves are not considered art, they have been used in many artworks. Many artists have developed creative ways for tricking the eye, such as using specific colors and lighting to create a three-dimensional effect on a 2D surface. Neuro-aesthetics attempts to explain the biology behind these visual tricks. EEG and fMRI methods are used to detect areas in the brain affected by visual art perception. As previously stated in Chapter 4, not much research has been done on optical illusions and their effect on brainwaves. This work contributes because it presents optical illusions and EEGs and takes the work further into the media arts field rather than 'remain in the science' domain.

4. Models built on existing science were applied for the interface design. Most artistic interfaces are not built modeling scientific principles. Models are built-in to the system that triggers events representing, for example, the P100 component principle. In Chapter 2, the VEP components were presented, and these principles are used as models that are built-in to the interfaces. The main contribution is how the artworks interpret neurophysiological data and creates models and expressive systems based on existing science.

Visum is an interactive multi-modal artwork generating distinct audio/visual results based on the VEPs of a subject. Aspecta is a generative artwork that uses a subject's VEP data and algorithms to create audio/visual works. *Visum* took the metaphorical approach and Aspecta the more literal approach. This dissertation has investigated visual perception through a novel approach for computationally generating audio/visual output. The objective of developing this type of perception has been to explore its ability to produce new meanings through audio/visual content and explore the conceptual meaning-making process within our perceptual system. Gestalt psychology, which describes how we perceive our environment, was applied towards the sonification and visualization process. In order to make the VEP data more meaningful, the analysis of neurophysiological data was connected to historical, cultural, and interactive models. This scientific data was explored within the context of these models.

This thesis is concluded by presenting future enhancements for the two artworks discussed in the previous chapters. *Visum* enables users to interact with VEP data by applying individual mappings for creative audio/visual outputs. The exploratory study conducted indicated that the metaphor appears to work well. Most participants seem to understand and interact with the system. However, given the system's capability for demo and the challenges faced by people with no experience in music interfaces, it would be better to have the users access features on a need basis. Instead of having all the features displayed in the interface (Visum), it would be more efficient to have features activated depending on what users want to do. Simplifying the interface would be necessary, and as users became more familiar with it, they could activate more features. Adding drop-down menus could be an option. In *Aspecta*, users can become more active than just listening and observing the figures. Future works for Aspecta would include allowing users to directly interact with the figures by zooming in to specific areas, similar to Fractal zooming, using a device such as a video game controller. This brings the user into the actual figure as it is drawing and allows for additional control of the figures through rotation and panning.

8.2 Final Remarks

One of the primary underlying motivation while developing both *Visum* and *Aspecta* was a desire to know more about our brain function. Of course, physiological computing does not mean that there is an open door to the mind. However, it offers an interesting technological and creative way to gain insight into how our brains work. Even though there has been much interest in using BCI technology in the arts for general purposes, there is still a lot to learn about our cognitive processes. As shown in the brain activity output in appendices B and C, EEG is not the most consistent signal. However, while not completely necessary, the belief is that artistic BCIs can serve as essential tools to support and maintain a dialogue between media art practice and the sciences.

Appendix A

This appendix presents the artist's statement and composition strategies of the BCI works developed in this research.

A.0.1 Artist's Statement

Visum narrative
"The Observer becomes the observed"

We can learn a lot through observing, this includes observing other people. The brain is a complicated organ, that controls every aspect of our body. This includes what we process through our senses. Visual perception is making sense of what we take in through our eyes. In *optical illusions,* color, light and patterns can create fig/images that may be deceptive to our brains. They tell us something about the mechanisms involved in visual perception. In science our visual process is measured through visual evoked potentials at the Occipital(fig/image detection) and parietal lobe(fig/image reaction/perception), which are changes in brainwaves after a stimulus is presented to an observer. Visual evoked potential data was retrieved from subjects of an experiment that were observing optical illusions. Can we learn something about how a subject visually perceives?

The VEP data are used to create a narrative about how the subject may be perceiving the optical illusions. In Visum, the data is used to create sound cues in 3D space (using granular synthesis), representing the neuronal firing in the brain. This immersive experience gives the viewer the feel that he/she is in someone's head observing the visual process. The visual projection uses the data to create the story on how the brain processes visual information. The fig/image starts out at a distance and blurry, showing that the brain has not processed the information yet, this is why it is blurry. There are several transformations that take place before the fig/image is close up and clear representing that now the observer is starting to make sense of what he/she saw meaning that now perception has taken place. The fig/images are based on the illusions used in the experiment with the data creating distortions of them.

The experience is for the viewers to observe an observer of optical illusions, while experiencing their own illusions.

Aspecta Narrative
"The imperceptible becomes perceptible"

In this artwork, visual evoked potential data is used to create an immersive audio-visual experience for the user while learning about visual perception. It is to listen to different sounds representing how the brain works that we may not be aware of. Here audience members can listen to the sounds based on the location of the sensors placed on the experiment subjects head. Frequency modulation is applied to enhance certain features of the VEP data. The visualization of the data is based on Lissajous figures, which are parametric drawings. The data controls the coefficients of the Lissajous formulas to draw the figures. Based on the scientific convention on EEG data values (microvolt), the intensity ranges from blue to red. Blue being negative values and red being positive values. The visual projection is based on the physical layout of the sensors placed on the subject's head during the experiment syncing the audio with the visuals. The figures in Binaural mode are displayed spatially based on the sensor location on the participant's head.

A.0.2 Composing With VEP: aesthetic considerations

This research's journey started almost ten years ago as an interest in understanding brain function through sound and emphasizing the listening sense. Humans are primarily visual beings, so the sense of sight (for those who have it) is mainly used to navigate the world. Since the 1920s, we were able to listen to brainwaves. However, it was mainly used in the clinical sense. Data sonification has grown in popularity since the 1990s. More and more people apply sonification to their data sets, such as the ocean, solar, stock market data, to listen to any trends or patterns. Working with visual evoked potential (VEP) data is among the most difficult, especially when working with optical illusions. This is due to the subjectivity and sparseness of the data. This data type is less than a second in duration, so extracting frequency from it is challenging. As a composer, a question that needs to be answered when working with data is how to decide what type of sound to use for a specific data set? This was certainly the case for deciding this for the VEP data.

The first thing to do was get familiar with this data and truly get its sense, which is the challenging part. The second thing was to figure out which sound fits this data. At first, the thought was to map peaks and valleys in this data to a whole tone scale. This scale was chosen for its simplicity and to fit the Western thought and music style. After getting a sense of the data, I decided that this scale would not fit VEP data. I started to explore Granular Synthesis and found that it best fits the data because of the grainy sounds, which best reflect neuronal data. I started working with pitch shifting and time manipulation. From working with pitch-shifting, the interest also brought in Frequency Modulation. The main reason is the have the data manipulate the frequency of a sound file. Since the data is so short in duration, there was a need to slow the data down to allow the listener to listen to the data's details. Sound spatialization was also an essential factor to represent the human head and the various sounds coming from different locations.

When designing the interfaces, these important features had to be included. There are ways to control the playback timing and spatialize and audio/visual output of the two artworks' data. In Visum, the interface design was to put sonification (listening) ahead of the visualization (looking), which led to having the sound parameters control the visual parameters. For Aspecta, the emphasis was equally placed on both listening and observing the data. In Aspecta, timing control and spatialization allow the users to place themselves into the data. Given the data's subjectivity, questions arose about narratives, and can this data give us some idea as to what is going on, and as a composer, can I use this data to create compositions? This set me out on this current journey of learning about visual evoked potential data and composing with the data.

When composing with Visum, the most important thing for me was placing myself in the data by metaphorically getting inside someone's head. This was done through the detail to spatialization (panning) and enhancing the sensor(s) sound output by changing their pitches to hear what the sensors are 'saying.' On the science side, after working with the data collected during the experiment conducted and observing the EEG visualization, it shows that activity occurs in the visual processing part of the brain; however, it slightly varies by subject. Statistically, the data pool should be much more extensive for a normal distribution. In other words, conducting many more experiments (including using different equipment for comparison purposes) is necessary to find a strong trend.

A.0.3 Curator's Statement

In this section, a curator's statement of Visum is presented.

Lena Mathew
"Visum: Beyond the Physical Eye" (2020)
An audio, visual, data driven installation

It is a well-established practice that many contemporary artists today work with data. The traditional artistic practice of creating artwork relied on the human response to what they could see and hear, feel and sense: physical data. This activity is a reflection on the world around the artist, and is s a response that ranges from the intricacies of minute detail, the complexities of emotional connections, and the reaction to the vastness of history, nature and even the universe. These artistic responses are often realized as a 'realistic' processing of data, and also as interpretation; the interaction with the data is the artistic element. Artists who work with technology have long realized that digital data is a quantity of information that can be used to inform content, and this artistic practice can also take many forms, as many as artists who can imagine it's use.
It is also common practice for curators to explore artistic precedents and cite groundbreaking artistic works when assessing the value of new works (and/or) new artists. This is a longstanding procedure of the observational and critical response to new work. Since the development of digital technology, this observational practice has become more complex and requires expertise and familiarity with the terminology, experimental practices, and artistic output, often with artists who also use traditional techniques for their output. Digital technology has enhanced our ability to look deeper into data, manipulate it, and employ it as art in ways that are not always easily observable (especially in the traditional sense). Artists engage in the analytical process, and interpret data freely, as accepted artistic practice. The process is sometimes considered to be the 'art', and in other instances the process is invisible, and also unnecessary to consider by the average viewer of the work.
Intrinsically tied to the development of the technical means, artists, often the earliest adopters of technology, have pushed boundaries of acceptability and have probed the depths that the possibilities that digital technology (and within this genre data sets) reveal previously unimagined levels of responses: to inquiry, observation, exploration, quantification, and emotion.
There is hardly a type of data that has not been exploited and investigated as art, by artists in many fields of practice (dance, music, film/video, photography, 2D/3D, etc.). The outcomes are as varied as the artists themselves, and include visual, aural, performative, moving fig/image, experiential, and as telematic, electronic and data transmissions. Artists have used weather patterns, the stock market trends, the moon cycles, wind, traffic, border crossing statistics (as a few examples) to feed their output. Looking at the work of Lena Mathew, "Visum: Beyond the Physical Eye" (2020), an

interactive data driven sound/visual installation, I needed to reach into my experience with artists who use data, and ultimately regard it critically within this media history as a new and original way to work with data. Several of these works are given cursory citation below.

"Visum" is the outcome of encounters that volunteers have had, observing optical illusions, whilst having their brain waves recorded. What they see is interpreted, not subjectively by their conscious thoughts, but from brain responses from deep within their physical body. These responses then become the visualizations of data, which is transformed into various shapes and sounds, to be presented to viewers in a public space with sound and moving fig/image displays. The data output is probably most interesting to scientists, but we can also interpret it as artistic practice. I look forward to investigating the very new publication from Routledge by David Gruber, *Brain Art and Neuroscience: Neurosensuality and Affective Realism* (2020). Gruber's work focuses on the role of neuroscience in society and the reasons why brain findings can be so persuasive. The art of brain mapping, a term often applied to neuroscience and art, has been emerging over the past couple of decades, as science institutions have begun to offer many research opportunities to artists.

Mathew's interest in neuroscience, and how the brain reacts to what it sees, is taken a step further in "Visum". The audience viewer is an additional layer, the final stage that witnesses the resulting sound mix, visuals, and the combination of the two which creates the interactive installation. These viewers can manipulate and manage how they receive the sound and visuals and can additionally manipulate how they receive this presentation.

Mathew states, 'entering the space is like entering the human brain,' which as a curator, I realize demands a leap of faith. The artist actually requires that the viewer exercises some effort, and allows one's self to ramble among the speakers and the projected fig/image, perhaps even alter the presentation. One's ability to transcend the physical elements of the installation is required. It will be necessary to be amenable to unprejudiced speculation, and become curious, to receive unfamiliar sounds, strange fig/images and just respond openly to the mix (we will respond based on our subjective experiences, I see butterflies, for example). This is by necessity, a theoretical exercise, due to the current circumstances beyond our control.

But then, if our consensual agreement is to interact, and to respect the tradition of presenting personal data as art as an expression of a personal response to a controlled set of fig/images, as Mathew notes, the response will be a subjective one. Although the algorithms created will control the forms presented, the collaboration is between the subjects and the viewers, and the way the resulting fig/imagery and soundscape is interpreted is going to be subjectively different, depending on who is receiving it. A scientist will receive the information one way, based on the quantitative results which can be measured. Scientists are more likely to seek ways to navigate the raw data, to determine what is meaningful and useful. An artist (and I will include a curator in this category) will interpret data driven work another way! How does it make you feel, what fig/images, memories, and experiences does it evoke? An artistically trained observer will also evaluate the output by its form, structure, and any patterns that might evolve. A musician or performer might have yet another layer of response to the personal data as it is presented, what is the rhythm, the tempo, and the tone of the sound mix?

If we are to understand a data driven artwork, especially if that data is derived from a human, biological source, it is important to acknowledge that humans probably create very noisy data patterns. When it is turned into art, as the artist Laurie Frick explains, "art makes data sticky – it gets you to look longer and carries emotion…" So, when scientists work with the data as numerical quantifiers, they observe these differences. The resulting conversation between the artistic and the scientific is a valuable one that can result in a new way to resolve the art/science dilemma. Each brings their perception to the viewing experience, each is valuable, each is informed by experience. To bring this discussion about how to interpret data to the table, so to speak, is to rely on the power of each side's commitment to collaborate. Each perspective is correct within the definition of the field of research and practice. And, it is the resulting outcome of the process (complex or simple) that is the determination of its success. Is what we as a viewer experience, backed-up by an understanding of the process? We walk away with the visceral, physical encounter of the installation. "Visum: Beyond the Physical Eye" will leave an imprint of the encounter and we trust that 'the imperceptible becomes perceptible."

My personal experience as a curator working with media artists began in the mid-1970s. I have a 45-year history of working with and observing artists, listening to their concepts and rationale for working with technology. I have commissioned, exhibited, and partnered with artists on the development and presentation of media works that involve fig/image production, interactivity, performance, film and video, and data. What has been most challenging, and highly variable, is the personal, human data which artists probe. This is the most personal, and therefore the most highly subjective use of what we consider objective data. For this evaluation, I find myself scanning my memory to site several significant projects that have also influenced my curatorial practice, that bring together developing technology, data, and human interaction in performance. There are dozens of additional examples, this is just a small sample that gives various methods of using data derived from the human body, as performance, connectivity, and observation, to create the art.

The first early example is "Brainwave Drawings," (1974 -ongoing) a work by Nina Sobell that relied on what was the early physiological practice known as bio-feedback. It was an experimental performance work that relies on the brainwave data from participating subjects who by using EEG electrodes attached to their temples attempt to communicate while they watch their brainwaves displayed, overlapping on a single screen. They attempt to manage their brainwaves and collaborate on bringing the output under their control. This performance was presented while the audience watched. "Brainwave Drawings" was included as a live performance work in the exhibition I cu-

rated in 1983, called 'The Artist and The Computer' at the Long Beach Museum of Art. The complete unknown output of this work and the excitement it created among the audience participants, influenced my practice considerably, especially my willingness to push boundaries and even give artists the chance to fail. The ongoing practice of bio-feedback that Sobell used has been implemented in contemporary artistic works and is a known practice that include gaming and experimental interactive filmmaking. But, bio-feedback (which was relatively new and quite suspect in 1974) as a genre has become more respected and valued as a physical therapy treatment ranging from sleep disorder treatment, pain management, and as a method to control high blood pressure (all outside the expertise of this writer). It is a powerful, very personal procedure.
Another notable work took place in 1977, as the opening event of documenta VI, expressing the critical attitude focused on the growing power of the media and its tendency to distort reality. "The Last Nine Minutes," by Douglas Davis was a telematic event performed for international audiences via satellite telecast. In this work, the artist puts his hands up to a clear glass panel placed in front of the camera (which then appears to the TV viewer that he is on the other side of their TV screen). Douglas asks that the viewer place his hands on their home screen to 'connect' with him. Although there is no actual physical contact, the idea of touching thru communication space was a theoretical bomb that had longstanding implications. The documenta opening event also included works by Joseph Beuys and Nam June Paik; it was not an outsider event, but a fully funded Rockefeller Foundation interactive performance that attracted the international attention of critics, curators, and media theoreticians.
The continuation of telematic investigation continued in the 1980s, evidence that technology, interactivity, and data driven art has been an important sub-genre of the media art landscape for decades. Telecommunication work was quite visible on the media scene during the 1970s and 1980s, and connectivity was in part an activist reaction, and critique, of television's lack of content and the isolation it forced on viewers (couch potatoes sitting alone in front of their TV screen). A notable work that has gained widespread recognition over the years for its reliance on a non-art audience, and its public presentation, is the telecommunication sculpture that took place between New York City and Los Angeles by Sherrie Rabinowitz and Kit Galloway, 'Hole in Space' (1980). As curator at the LBMA at the time, I was the fiscal manager of the project, supported the video documentation, and exhibited all the project documentation in the museum's main galleries immediately afterwards. The excitement and effect of real time communication between strangers, individuals who were physically apart, at great distances, opened the hearts and minds of previously skeptical critics to the immense possibilities. As a result, many more artists jumped in and the new genre followed.
The British media pioneer Roy Ascott, well known for his focus on cybernetics, telematics, and consciousness, created the early work "La Plissure du Texte" (1983), a commission for the major exhibition 'Electra,' in Paris (which I attended in 1983). This multi-authored work was one of the first telematic events where participants in different locations and time zones around the world collaborated on a single piece, simulta-

neously. Using the 'new technology' of the time, the remote interactions attracted reactions from artists like the Canadian artist Robert Adrian to comment: "the content is the contact." Ascott updated this work using his noted telematic practice, in the following years. The next generation of artists transcended telecommunication technology and embraced and utilized the new era of digital technology, which had become available during the 1980s. The Canadian artist Char Davies created the immersive work 'Osmose' (1995). It was a ground-breaking work that has had lasting influence on the digital art community. It utilized the human body with a data response to one's own breath and body movement. Unfortunately, it was not widely circulated (and few were able to experience it) because it required a specialized environment and a stereoscopic head mounted device, that interfaced with a motion-tracking special vest. The participant (who is in isolation within a special darkened chamber) is immersed in their own physical and mental space. 'Osmose' was dependent on a high-powered Silicon Graphics computer which was, at the time, state of the art, and not portable. It was a once in a lifetime experience for the participant, but external viewers could follow the participant's visual experience with fig/imagery shown on a monitor. The VR output was derived from the data from the immersed subject's breathing, which could be controlled somewhat by the participant. This intimate experience was given a public presence; the audience observed this process as a second set of responses. A powerful early personal data gathering project, it emphasized multi-dimensional responses to human interaction.

The Austrian conceptual artist Eva Wohlgemuth, in her work "Bodyscan" (1997) utilized the new technology of body scanning, which - at the time - was only available at a special lab in Monterey, CA, and was utilized for making bespoke astronaut suits and the like (Playboy Bunnies were scanned there too, for example). She made contact, scheduled an appointment, paid a fee of $2000, and had her body scanned and reduced to a 35 MB data set (I accompanied her and documented this process). The resulting data set has been re-imagined by Wolgemuth in many formats, from 3D sculptural replicas of the artist (in various sizes and materials), 2D prints and multi-layered transparent works, and also as a VR interpretation created for the Humphry project at the Ars Electronica Center. Humphry is a human shaped physical apparatus that hangs from the ceiling, which individual participants enter (one at a time) and lie vertically within Its structure. It uses a combination of virtual reality and force feedback technologies to impart a feeling of weightlessness that is as realistic as possible and recreates the centrifugal force generated by flying. In the "Bodyscan" experience, participants could fly thru and around the inside of the artists' body, entering and exiting via seven various tatoo points on her body.

Raphael Lozano-Hemmer created "Pulse Index" (2010), an installation work that uses the heartbeat and fingerprints of viewers to activate a visual output, the projection of many fingerprints on a large screen that spans horizontally across a gallery space. The last viewers – up to 10,962-, are saved and replicated in a graphic matrix of fingerprints, with corresponding heart rates graphically shown. Lozano-Hemmer has created

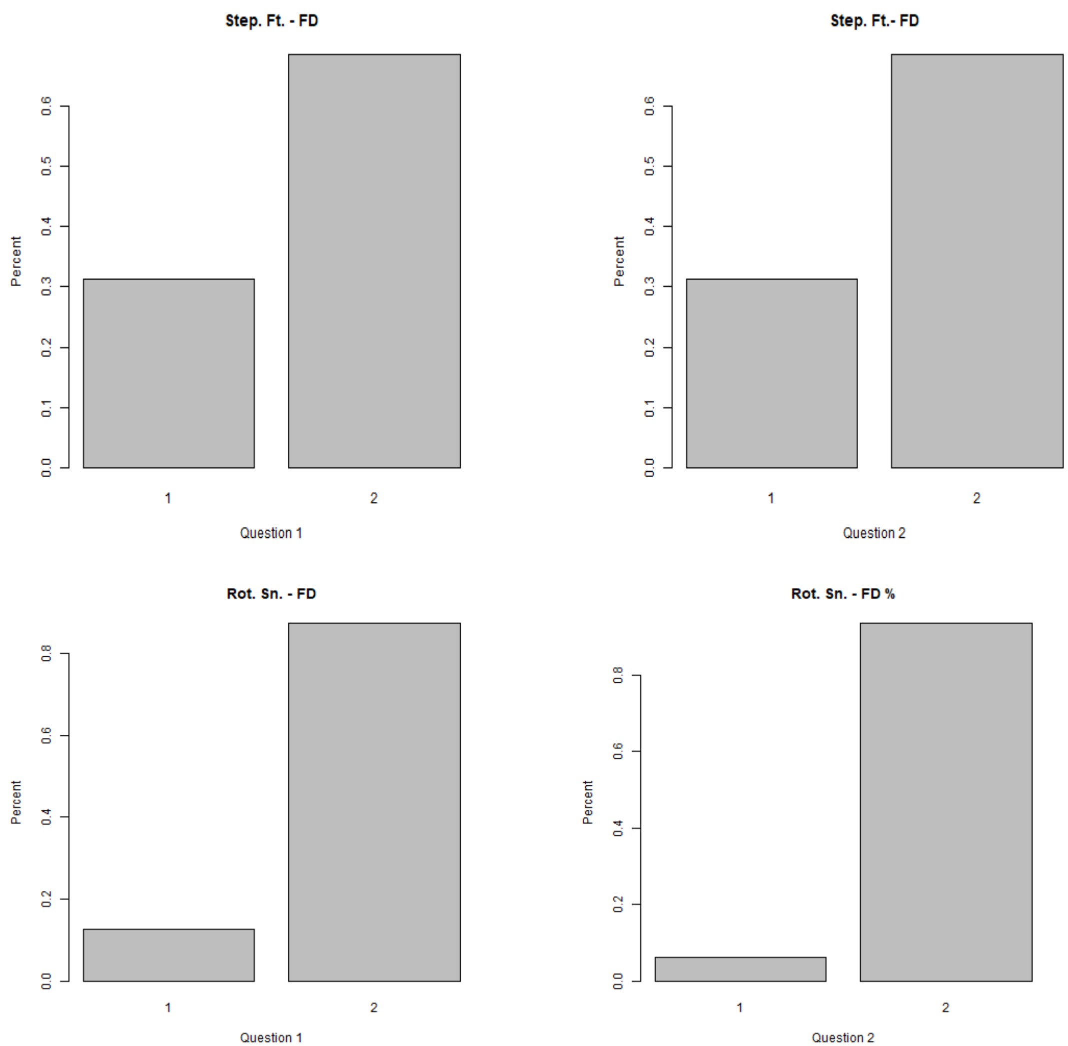
a large body of interactive, data driven work, but “Pulse Index” is of particular interest, as it uses the two common biometrics which are the usual human identification metrics.
Another data driven artist, Laurie Frick, uses data extensively and has a body of work that explores ways to represent it, using various traditional art materials (paper, felt, glass, etc). She controls all the data from her body and has done so for several years. As well, she acknowledges that her personal data is accumulated in many ways…and recognizes how many ways data from our body and our daily routings is gathered and made available. She tracks various data that she can, like from her Fitbit (steps, heart rate, sleep patterns), her social media accounts, dating websites, Google browsing history, credit card use, GPS and cellphone use… and she contemplates how this data is powerful and fluid. Finding ways to represent this data as art. She works between the scientific, the sociologic, and the artistic, to bring a visually powerful representation of her personal information - her raw data - in the hope it will generate critical attention to the way humans are tracked, profiled, and monetized from these activities. Her 2016 solo exhibition at Edward Cella Gallery in Culver City, CA, created a huge response, especially from Silicon Valley corporate giants, who invited her to advise them concerning their response to gathering personal data.
What do these artistic projects have in common, and how do they relate to Lena Mathew and her work "Visum: Beyond the Physical Eye” (2020)? First, we need to recognize the limited manner of presentation that is available to the artist at any time. Flat screens, curved screens, full wall projections, dome projections, surround sound, mixed soundtracks, interactive methods, all installed in various critically acceptable set-ups. These are all dependent upon the technology that is available, and what the artist can tweak to emphasize their message. Innovations in presentation are dependent on the space available, the time available to set up properly, and the ability to control light. In the current situation (in COVID time) no space is available, and we are limited to imagine how this work will be received, based on our common experience in many previous installations (that are by now numerous and span decades). I look forward to the time when Ms. Mathew can professionally install her work. Until then, I will imagine it quite well from the information and illustrations she has provided, this is after all, how curatorial decision are made.

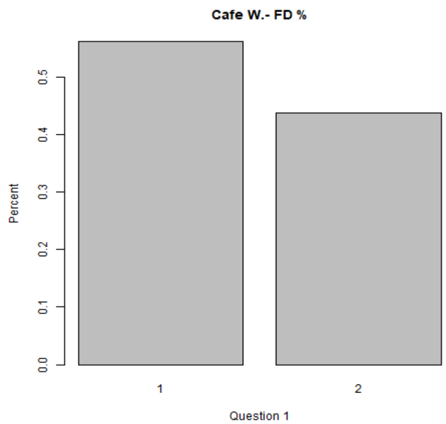
Kathy Rae Huffman
Independent Curator
December 2020

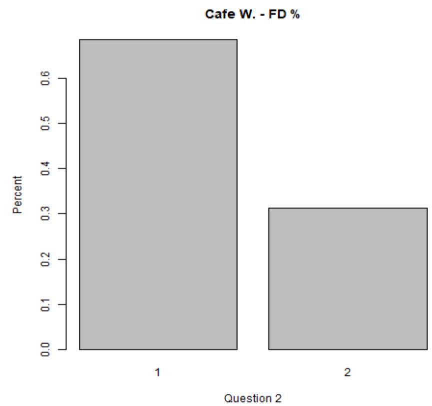
Appendix B

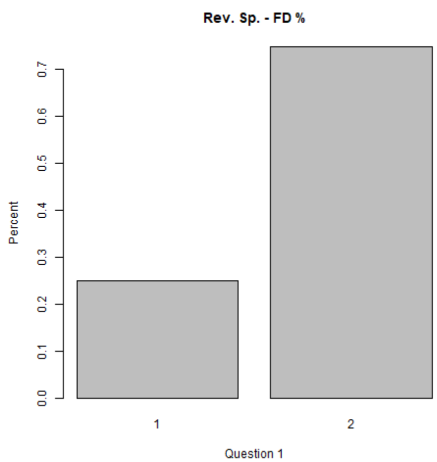
This appendix has several sections. The first one shows the general frequency distribution of the results for the experiments of Stage 3. It is broken down by optical illusions and the responses indicated in percentage (%) for each question presented to the subject. The second section shows the results of the auditory display listening study, broken down by gender.

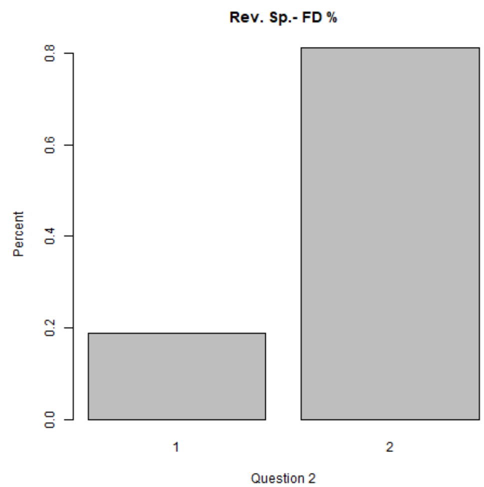
B.0.1 Experiment - General Frequency Distribution (FD - Percentage) of Results





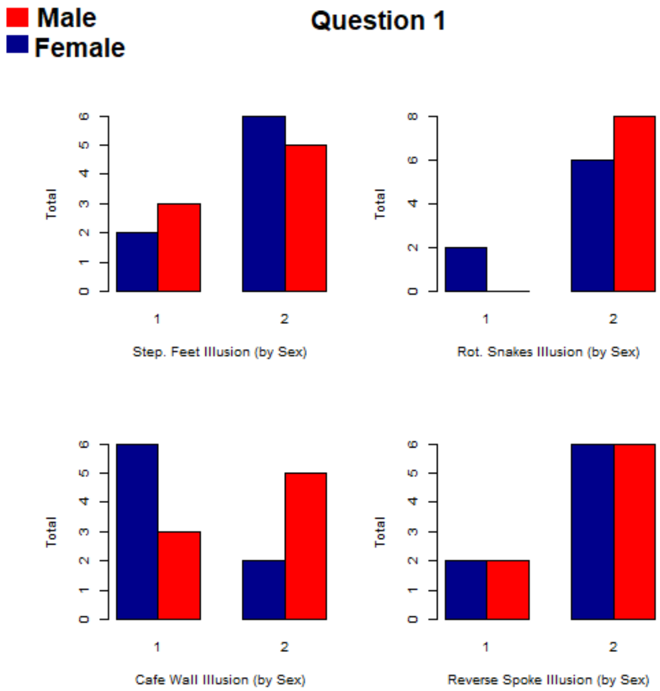


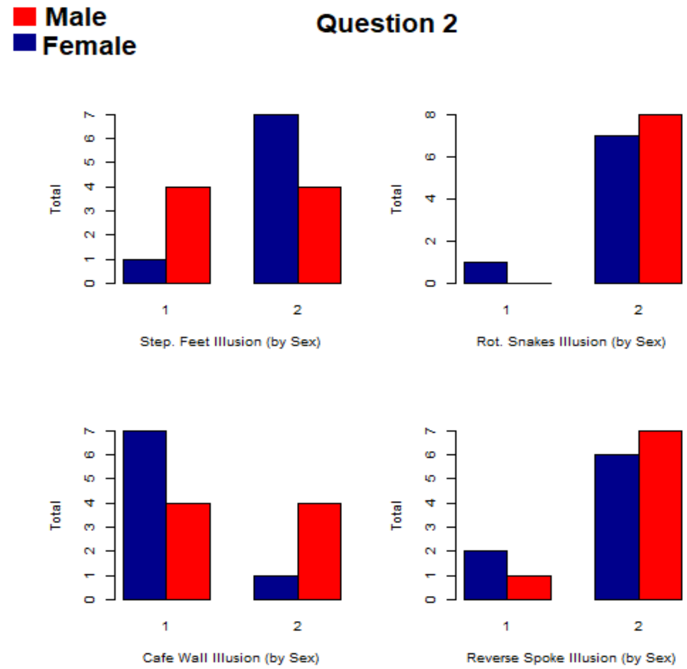




B.0.2 Experiment overview by Gender

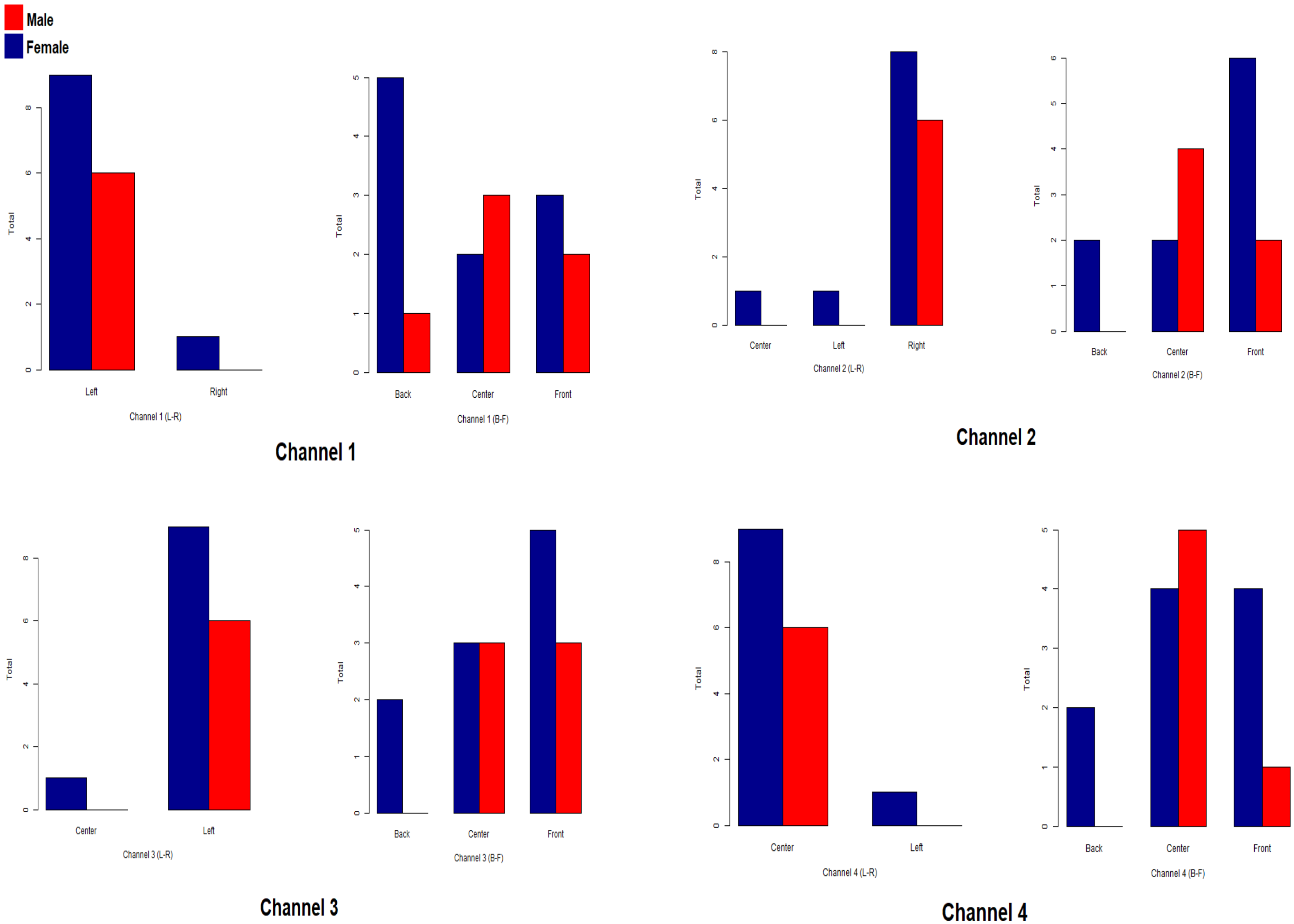
This section of this appendix shows the results of the questions asked to each subject broken down by gender.





B.0.3 Auditory Display Listening Study – By Channels

This section presents the results of an auditory display listening study, broken down by channels and by sex.


Male
Female
Channel 1
Total
Left
Right
Channel 1 (L-R)
Back
Center
Front
Channel 1 (B-F)
Channel 2
Center
Left
Right
Channel 2 (L-R)
Back
Center
Front
Channel 2 (B-F)
Channel 3
Center
Left
Channel 3 (L-R)
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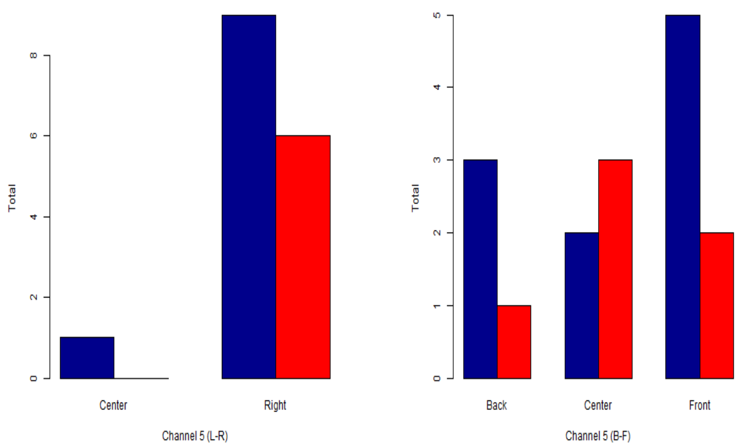
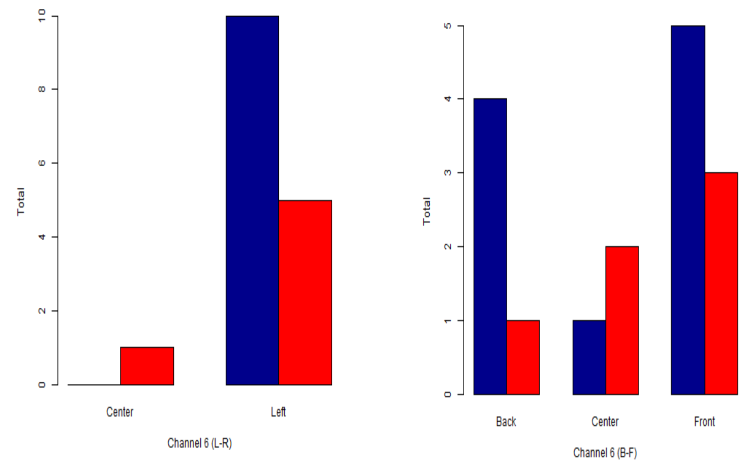
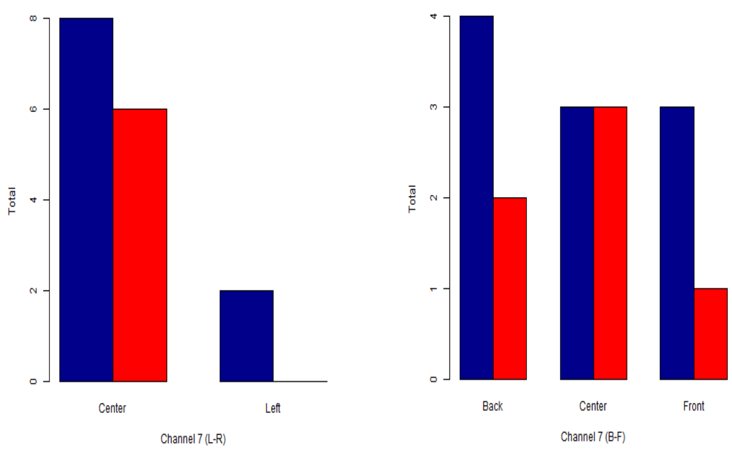
Center
Front
Channel 4 (B-F)



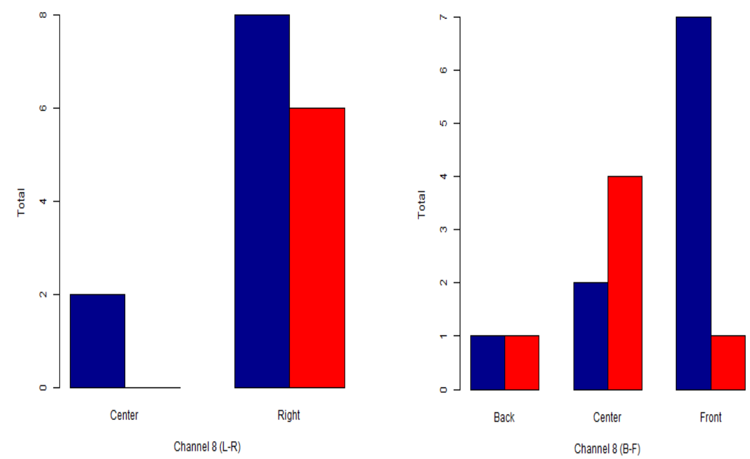
Channel 5



Channel 6



Channel 7



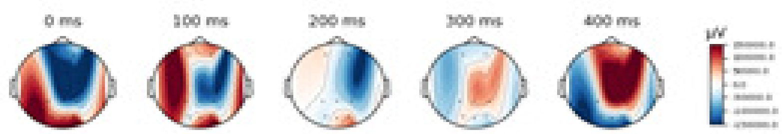
Channel 8

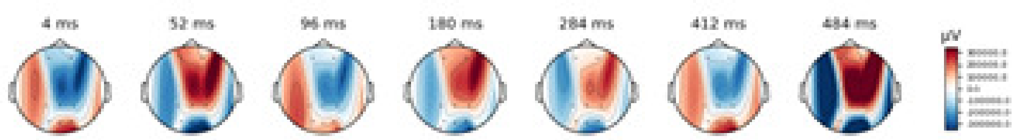
Appendix C

This appendix displays the VEP segments and brain topographic mapping of each optical illusion by subject. The segments (500ms in length) show the activity after an optical illusion was presented to a subject. The brain mapping shows the Oz sensor's brain activity (see figure 5.8 for sensor layout) at specific time intervals in milliseconds, where the scalar quantity is measured in microvolts. The Oz sensor is the primary sensor for the measurement of VEP data. The colors represent the intensity (shown in the legend) of the activity in a particular area of the brain post-stimulus.

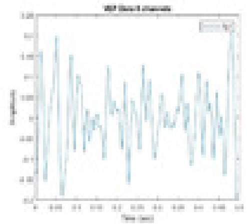
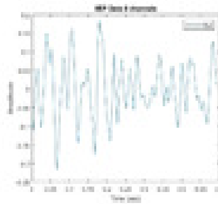
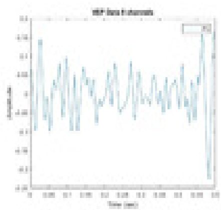
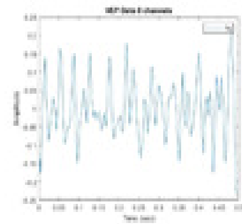
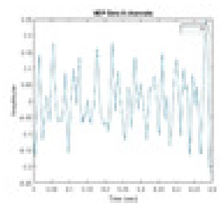
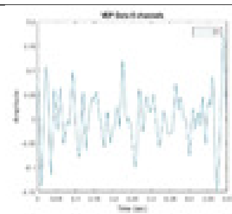
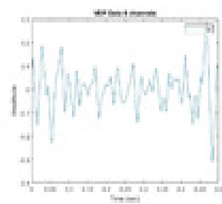
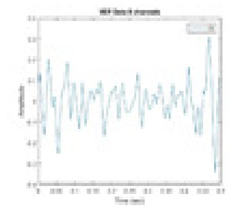
C.0.1 VEP Segments and Plots

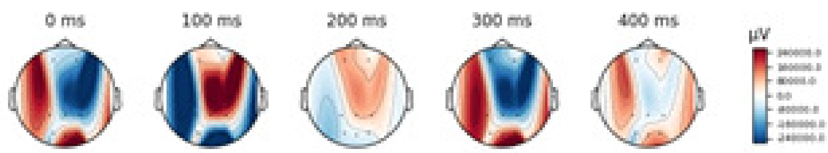
Cafe Wall



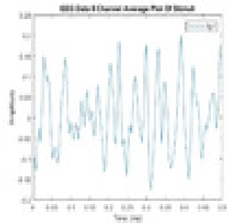
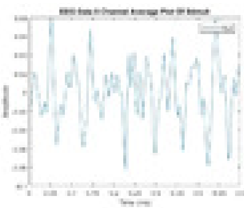
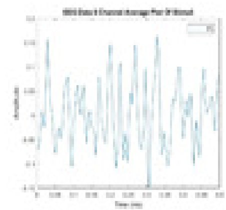
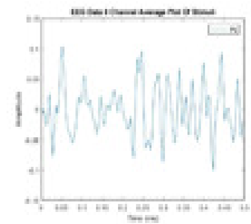
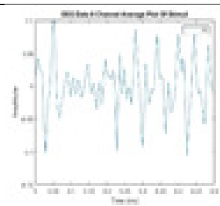
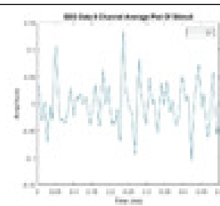
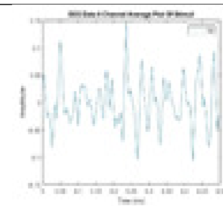
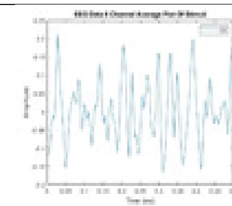


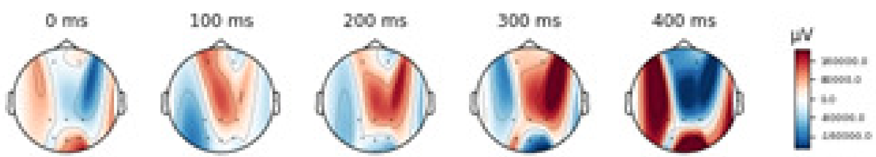
Subject 2 Café Wall Plot – Oz Sensor
VEP Segments

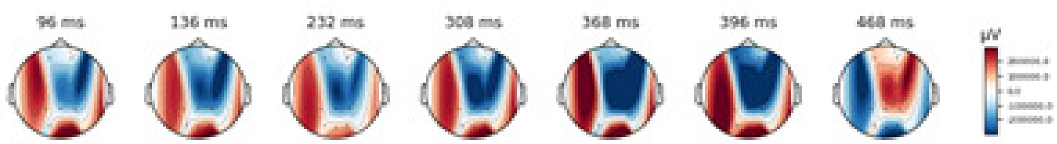
Subject 2	**Fp1**	**Fp2**	**P3**	**Pz**
CafeWall				
	P4	**O1**	**Oz**	**O2**
				



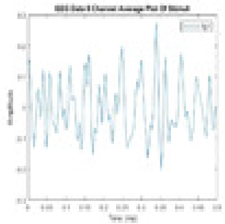
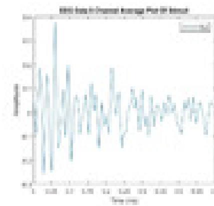
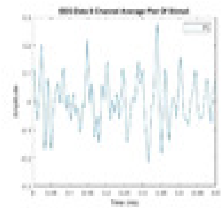
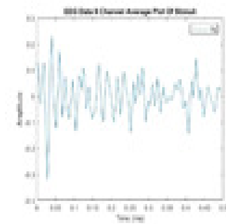
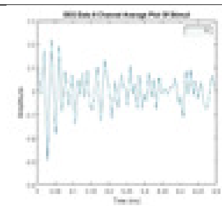
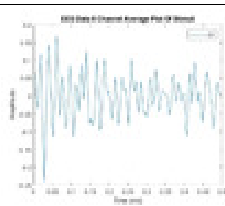
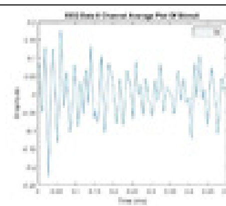
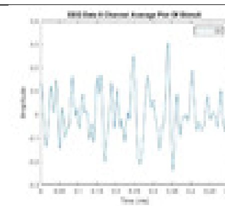
Subject 2: Reverse Spoke Wheel Plot – Oz Sensor

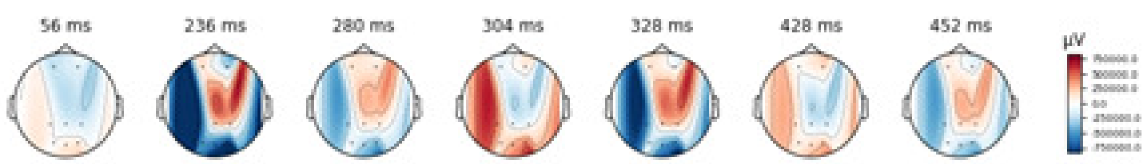
Subject 2	**Fp1**	**Fp2**	**P3**	**Pz**
Reverse Spoke Wheel				
	P4	**O1**	**Oz**	**O2**
				



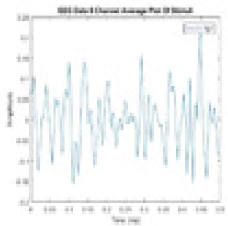
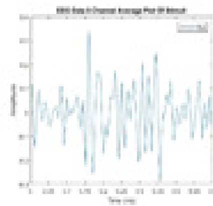
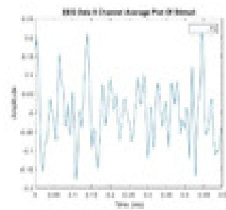
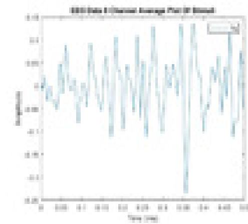
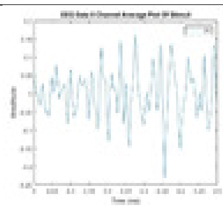
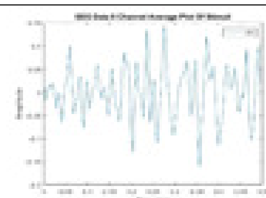
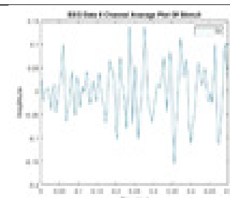
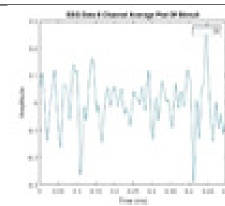


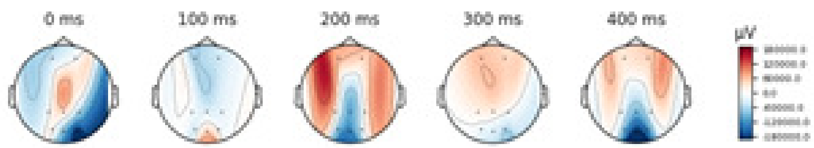
Subject 2: Rotating Snakes Plot – Oz Sensor

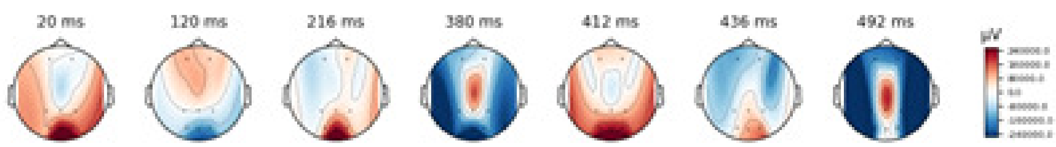
Subject 2	**Fp1**	**Fp2**	**P3**	**Pz**
Rotating Snakes				
	P4	**O1**	**Oz**	**O2**
				



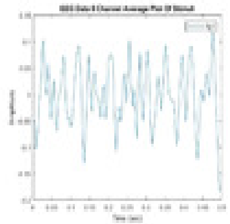
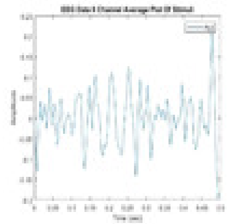
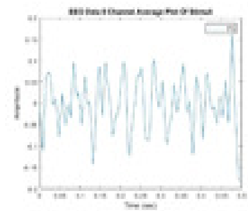
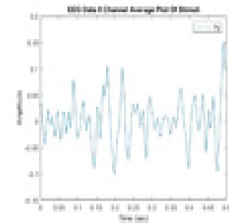
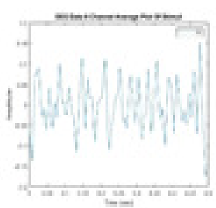
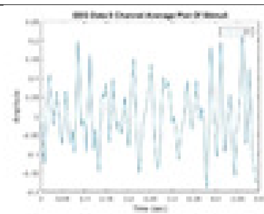
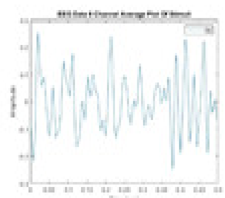
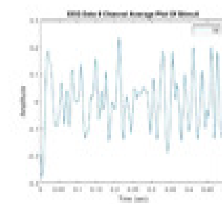
Subject 2: Stepping Feet Plot– Oz Sensor

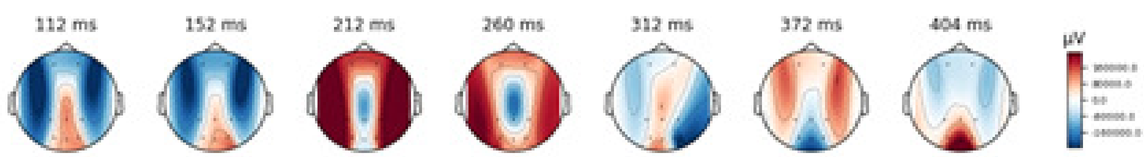
Subject 2	**Fp1**	**Fp2**	**P3**	**Pz**
Stepping Feet				
	P4	**O1**	**Oz**	**O2**
				



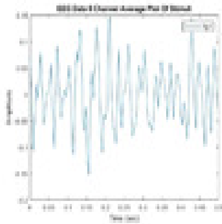
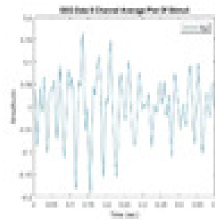
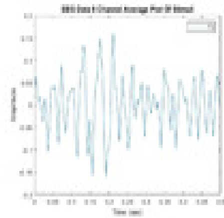
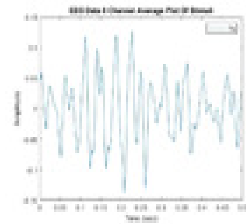
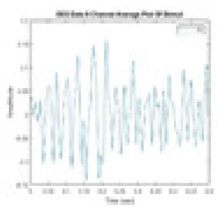
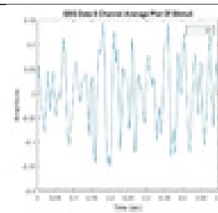
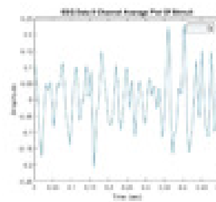
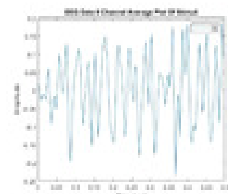


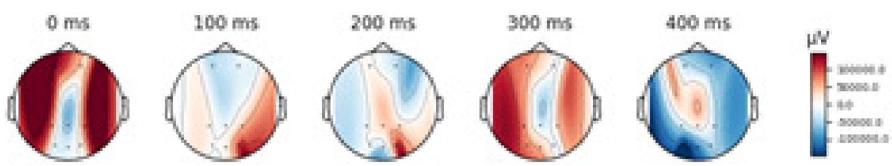
Subject 3: Café Wall Plot – Oz Sensor VEP Segments

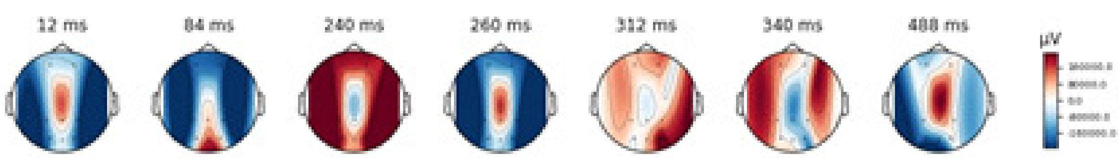
Subject 3	**Fp1**	**Fp2**	**P3**	**Pz**
Café Wall				
	P4	**O1**	**Oz**	**O2**
				



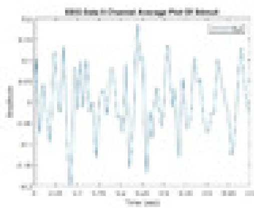
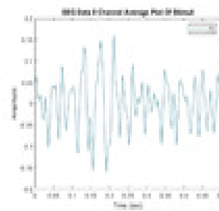
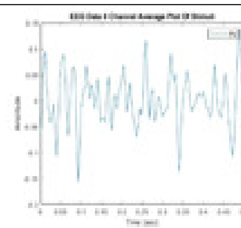
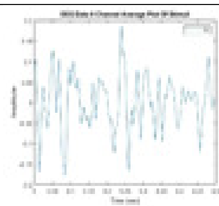
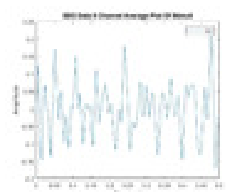
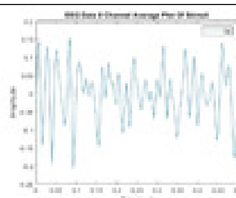
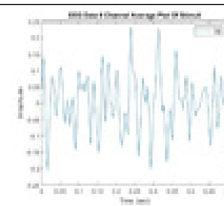
Subject 3: Reverse Spoke Wheel Plot – Oz Sensor

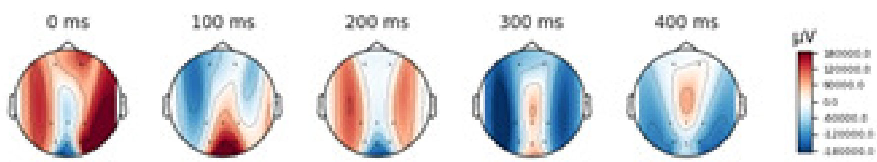
Subject 3	**Fp1**	**Fp2**	**P3**	**Pz**
Reverse Spoke Wheel				
	P4	**O1**	**Oz**	**O2**
				

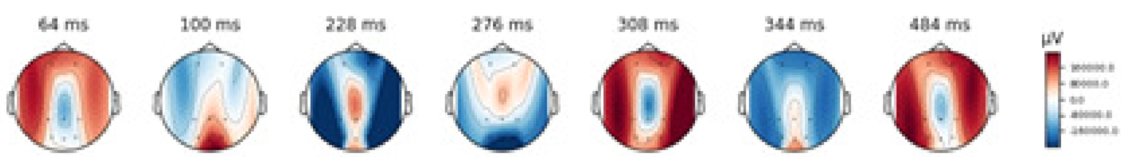




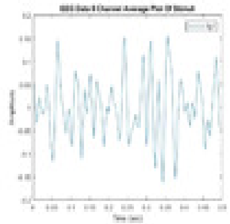
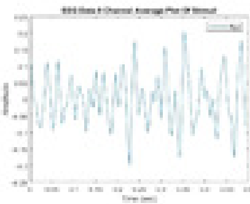
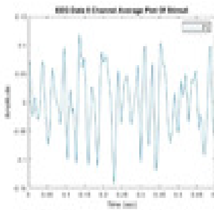
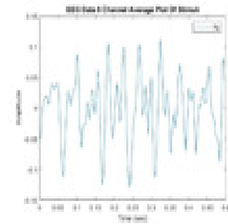
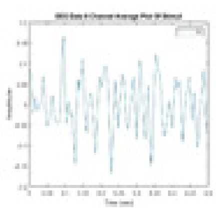
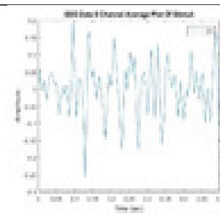
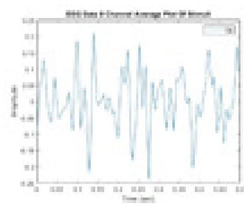
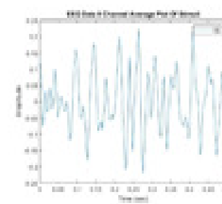
Subject 3: Rotating Snakes Plot– Oz Sensor

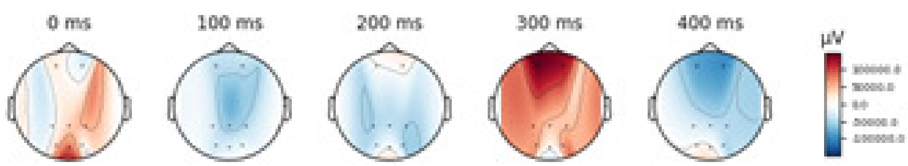
Subject 3	**Fp1**	**Fp2**	**P3**	**Pz**
Rotating Snakes				
	P4	**O1**	**Oz**	**O2**
				

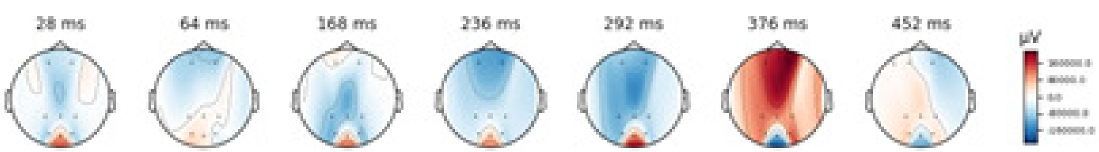




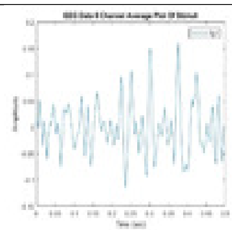
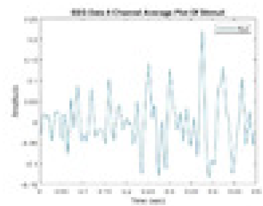
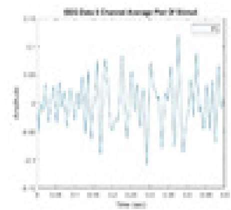
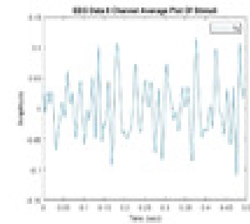
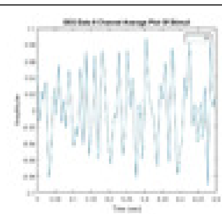
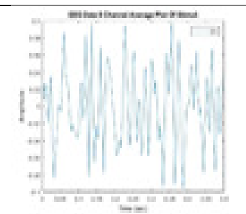
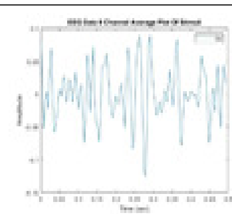
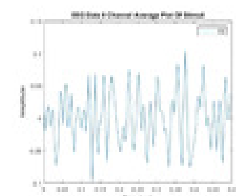
Subject 3: Stepping Feet Plot – Oz Sensor

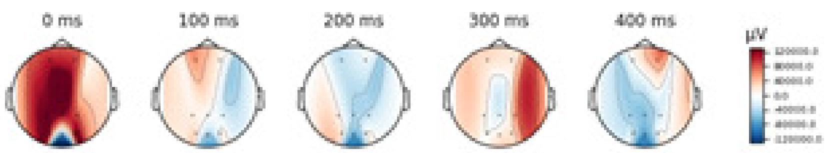
Subject 3	**Fp1**	**Fp2**	**P3**	**Pz**
Stepping Feet				
	P4	**O1**	**Oz**	**O2**
				

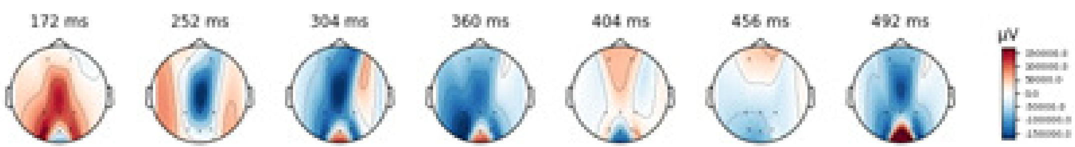




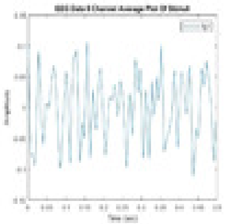
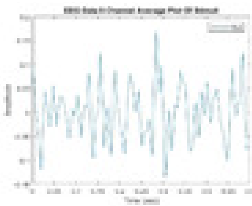
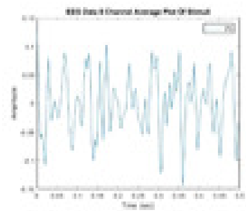
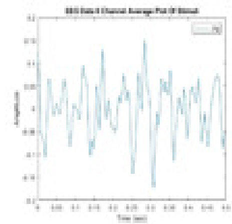
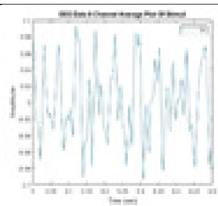
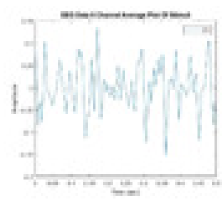
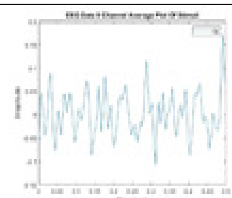
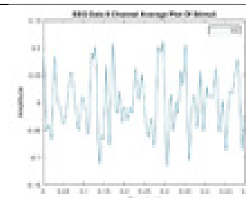
Subject 4: Café Wall Plot – Oz Sensor VEP Segments

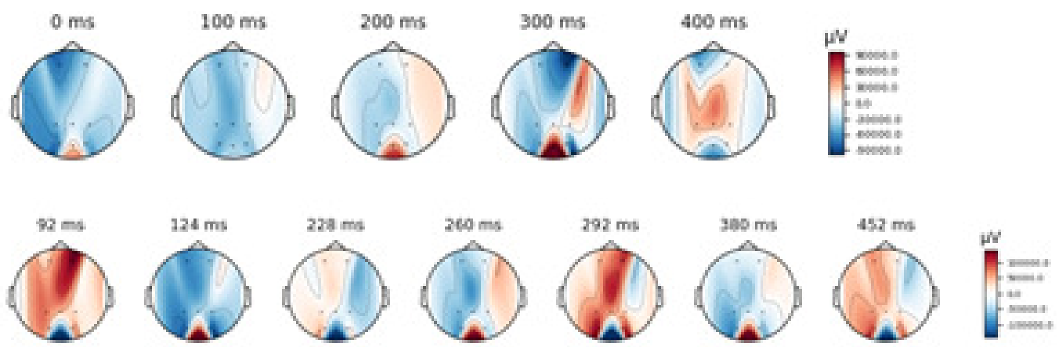
Subject 4	**Fp1**	**Fp2**	**P3**	**Pz**
Café Wall				
	P4	**O1**	**Oz**	**O2**
				



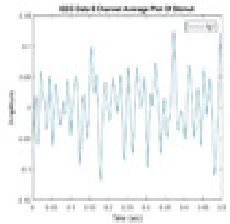
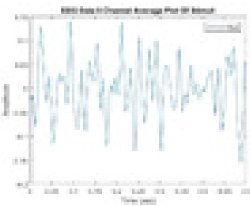
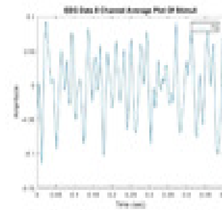
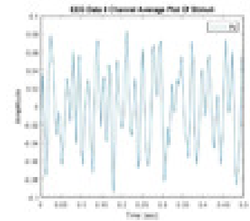
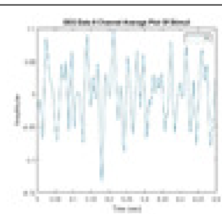
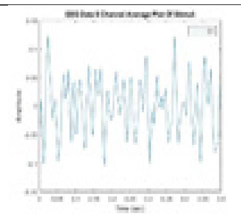
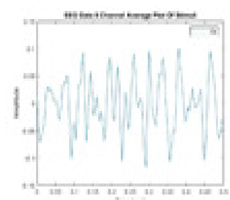
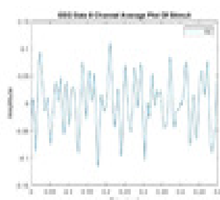


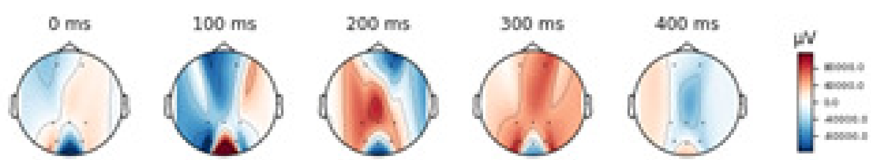
Subject 4: Reverse Spokes Wheel Plot – Oz Sensor

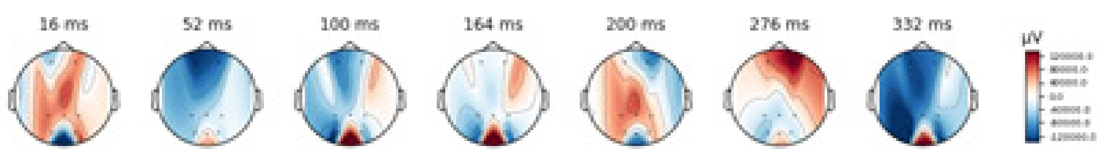
Subject 4	**Fp1**	**Fp2**	**P3**	**Pz**
Reverse Spoke Wheel				
	P4	**O1**	**Oz**	**O2**
				



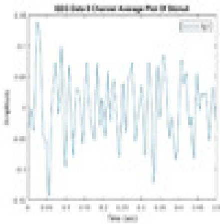
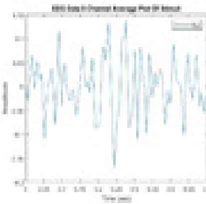
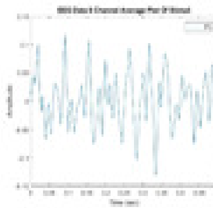
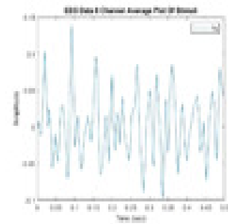
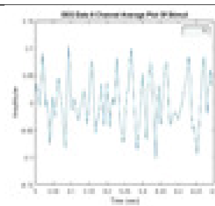
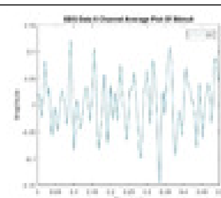
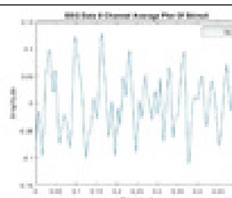
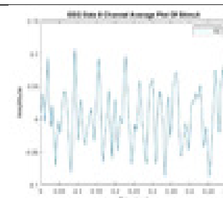
Subject 4: Rotating Snakes Plot – Oz Sensor

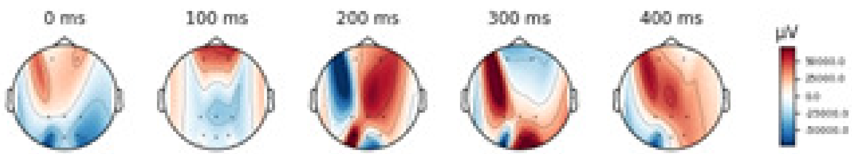
Subject 4	**Fp1**	**Fp2**	**P3**	**Pz**
Rotating Snakes				
	P4	**O1**	**Oz**	**O2**
				

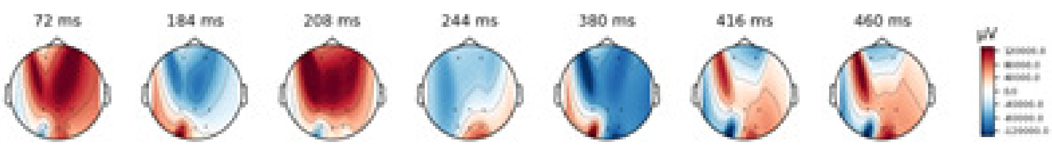




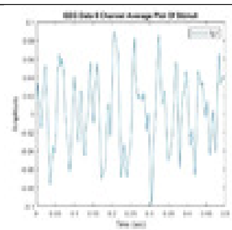
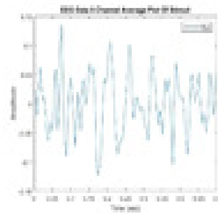
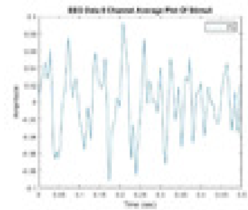
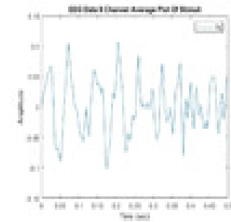
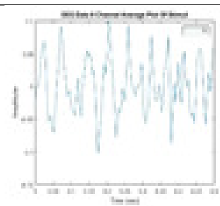
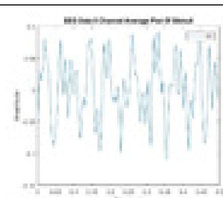
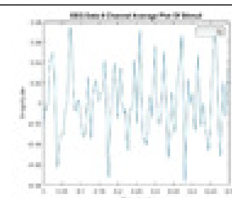
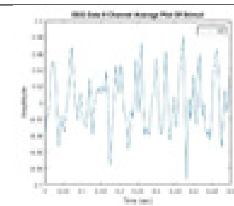
Subject 4: Stepping Feet Plot – Oz Sensor

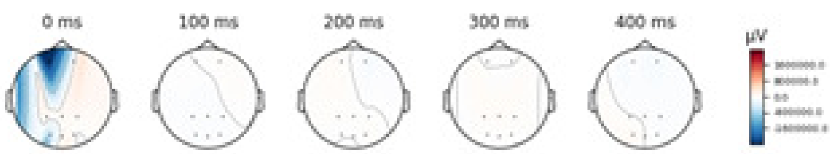
Subject 4	**Fp1**	**Fp2**	**P3**	**Pz**
Stepping Feet				
	P4	**O1**	**Oz**	**O2**
				

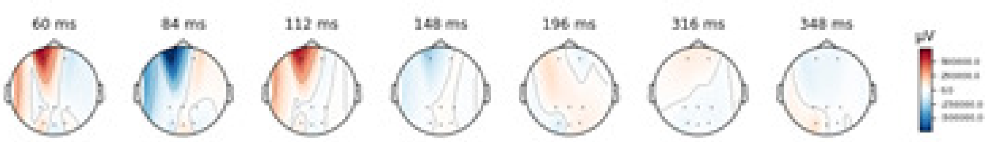




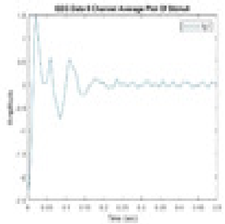
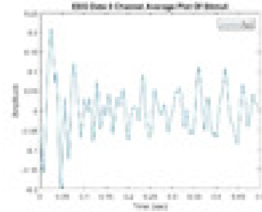
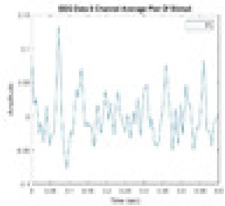
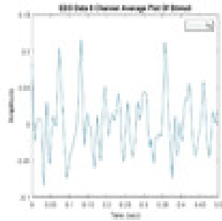
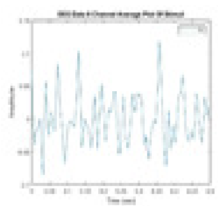
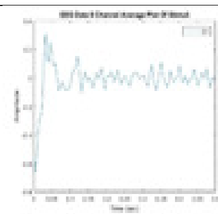
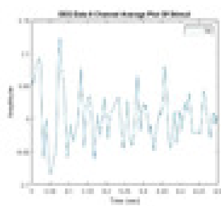
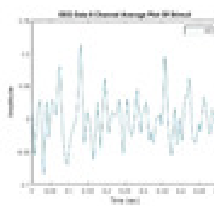
Subject 5: Café Wall Plot – Oz Sensor VEP Segments

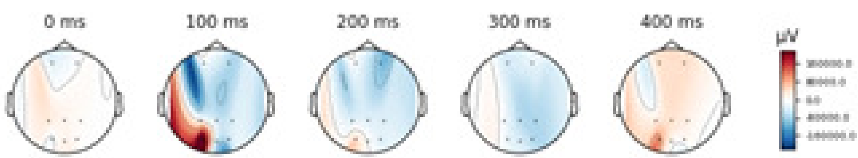
Subject 5	**Fp1**	**Fp2**	**P3**	**Pz**
Café Wall				
	P4	**O1**	**Oz**	**O2**
				

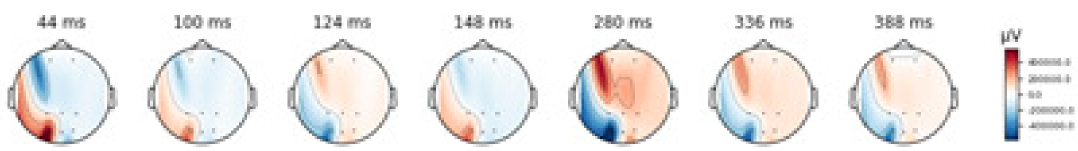




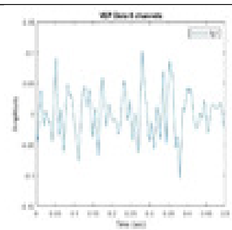
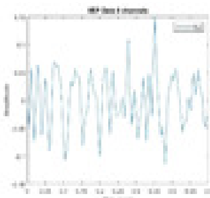
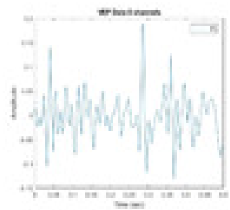
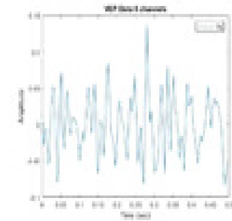
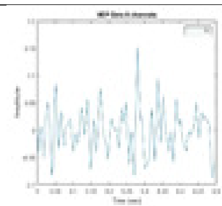
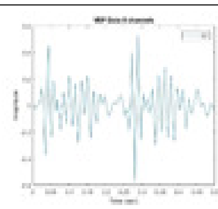
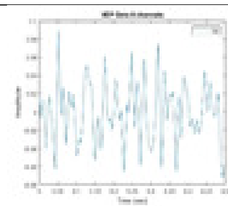
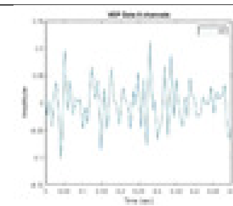
Subject 5: Reverse Spokes Plot – Oz Sensor

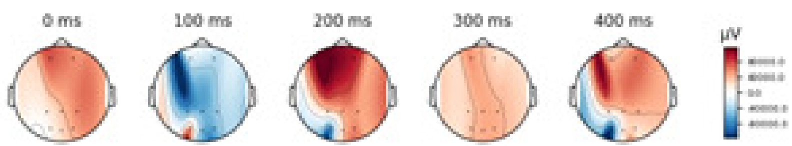
Subject 5	Fp1	Fp2	P3	Pz
Reverse Spokes Wheel				
	P4	O1	Oz	O2
				

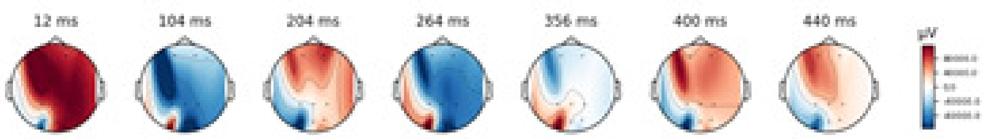




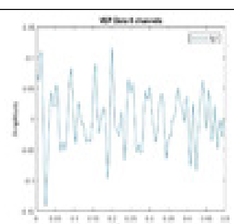
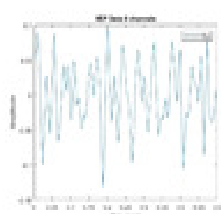
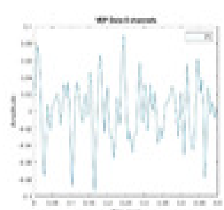
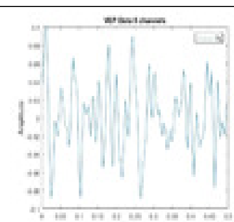
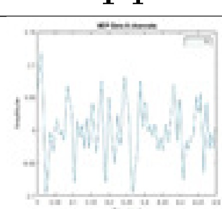
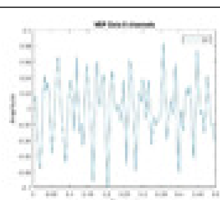
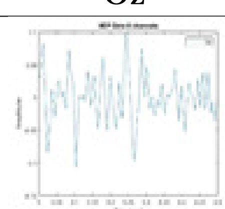
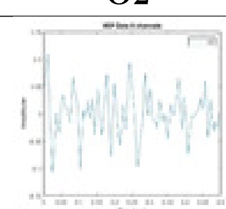
Subject 5: Rotating Snakes Plot – Oz Sensor

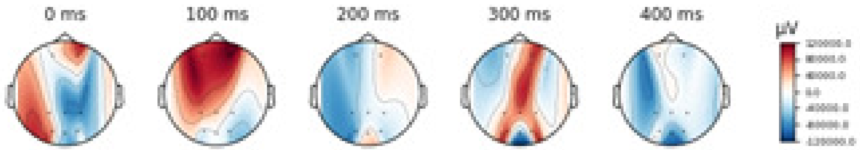
Subject 5	Fp1	Fp2	P3	Pz
Rotating Snakes				
	P4	**O1**	**Oz**	**O2**
				

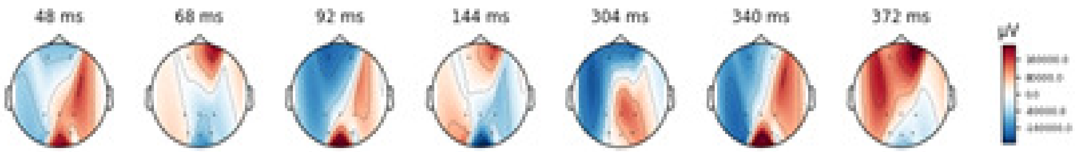




Subject 5: Stepping Feet Plot – Oz Sensor

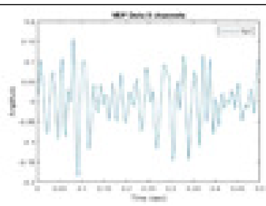
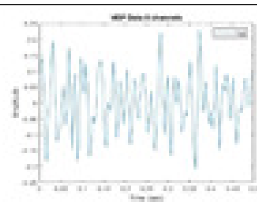
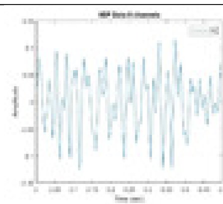
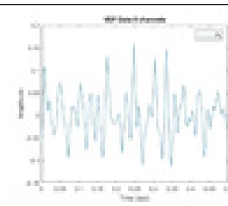
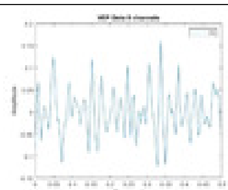
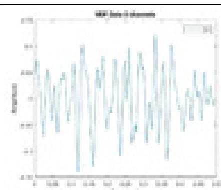
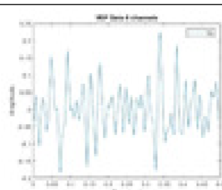
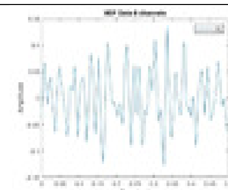
Subject 5	Fp1	Fp2	P3	Pz
Stepping Feet				
	P4	**O1**	**Oz**	**O2**
				

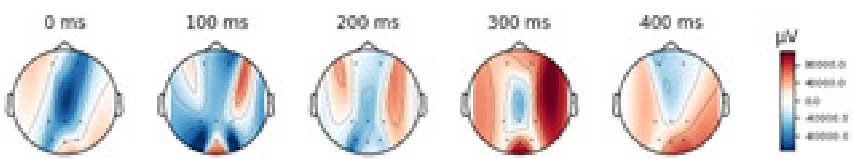


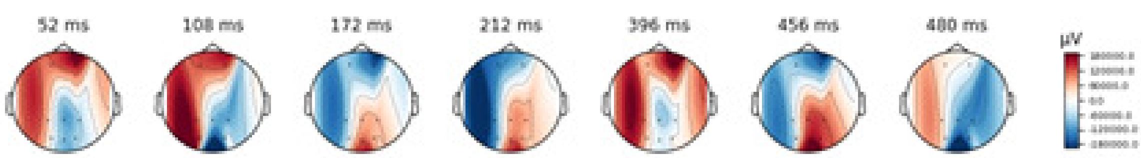


Subject 6: Café Wall Plot – Oz Sensor

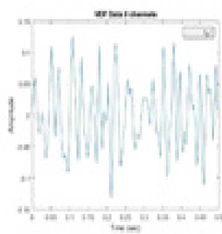
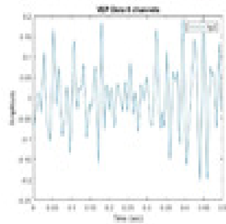
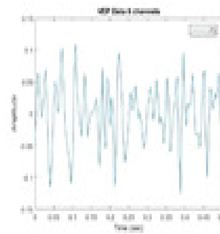
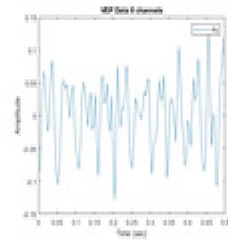
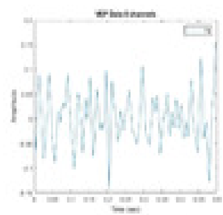
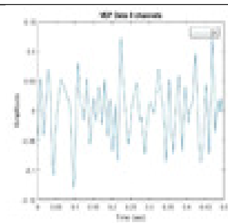
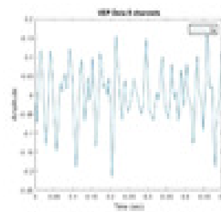
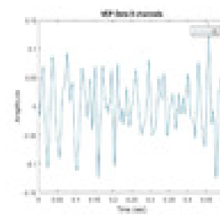
VEP Segments

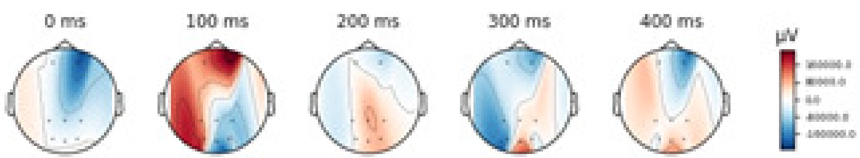
Subject6	**Fp1**	**Fp2**	**P3**	**Pz**
CafeWall				
	P4	**O1**	**Oz**	**O2**
				

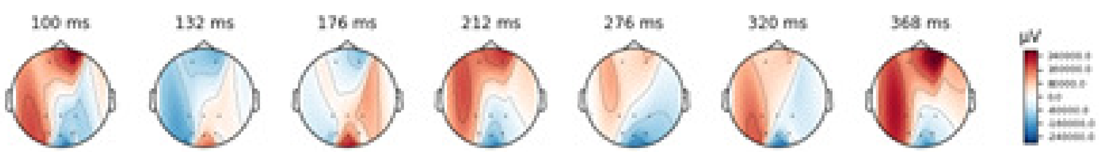




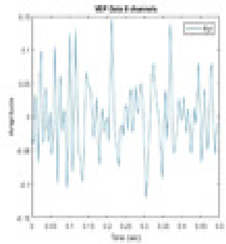
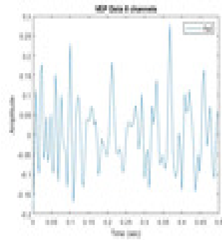
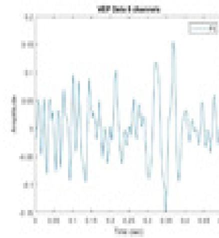
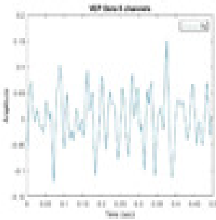
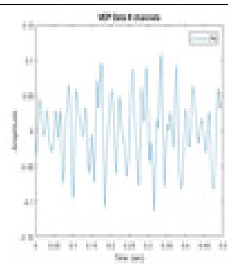
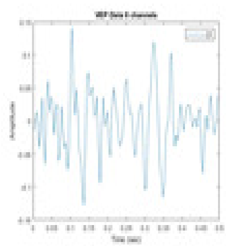
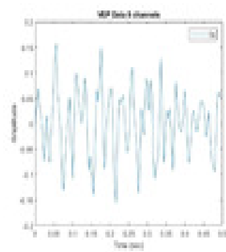
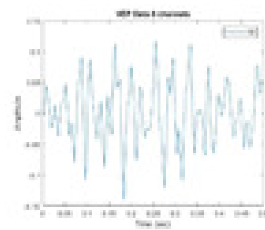
Subject 6: Reverse Spoke Wheel Plot – Oz Sensor

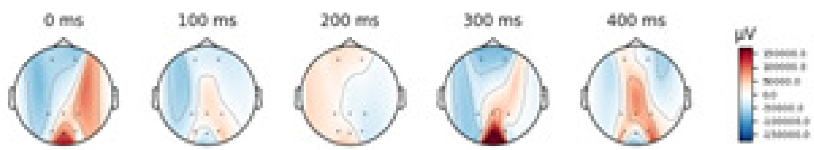
Subject6	Fp1	Fp2	P3	Pz
Reverse Spoke				
	P4	**O1**	**Oz**	**O2**
				

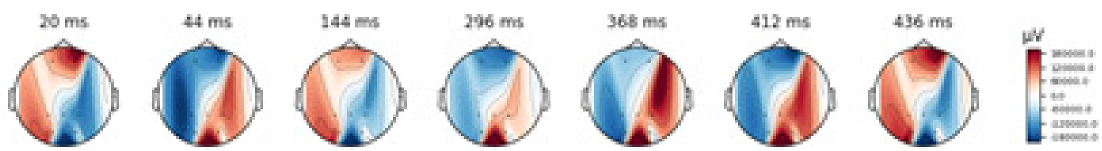




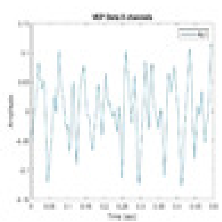
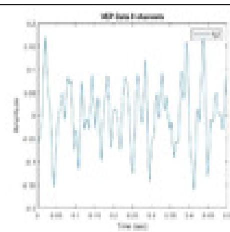
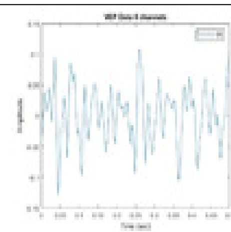
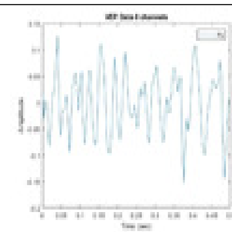
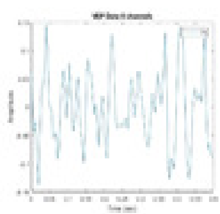
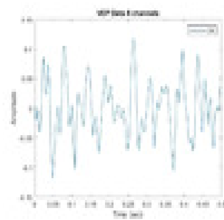
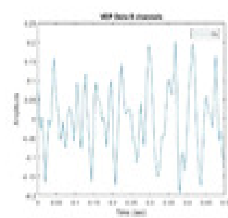
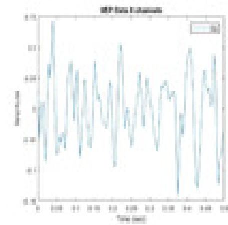
Subject 6: Rotating Snakes Plot – Oz Sensor

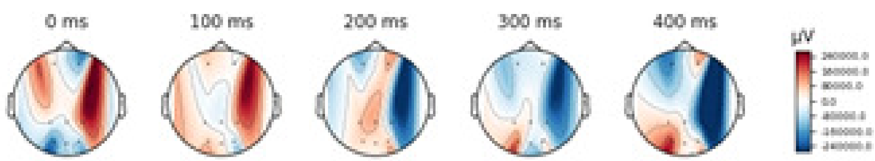
Subject6	Fp1	Fp2	P3	Pz
Rotating Snakes				
	P4	**O1**	**Oz**	**O2**
				

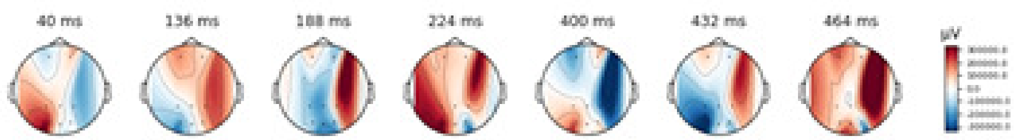




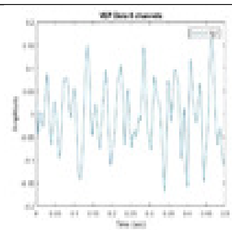
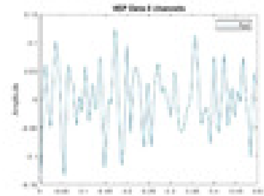
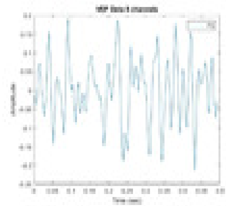
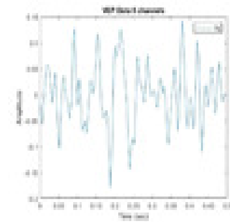
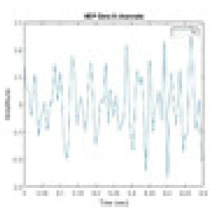
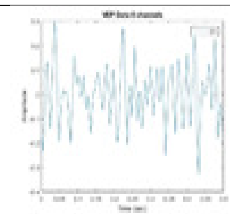
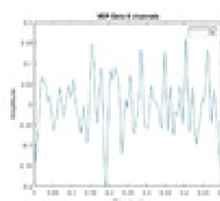
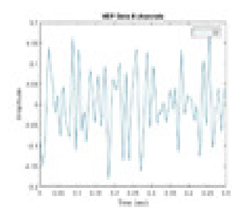
Subject 6: Stepping Feet Plot – Oz Sensor

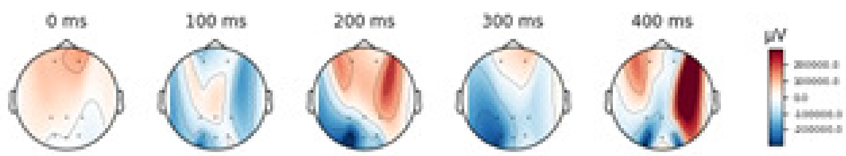
Subject6	Fp1	Fp2	P3	Pz
Stepping Feet				
	P4	**O1**	**Oz**	**O2**
				

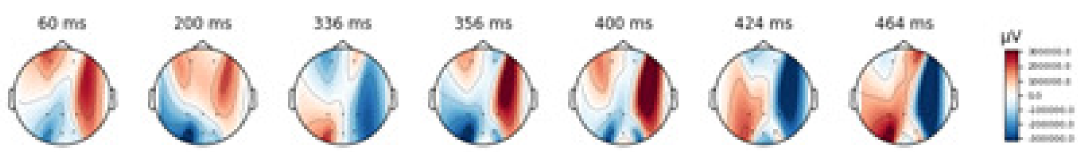




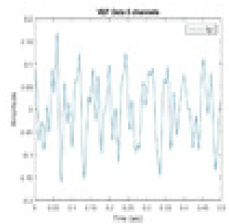
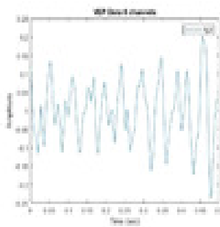
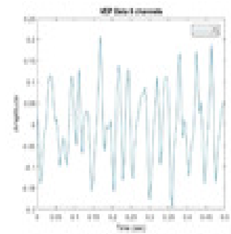
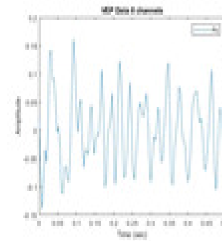
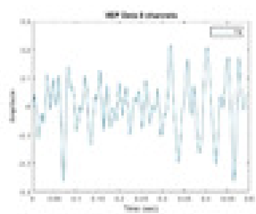
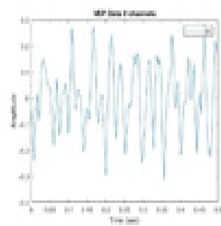
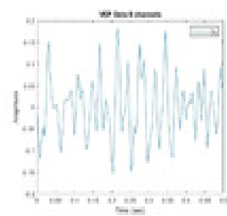
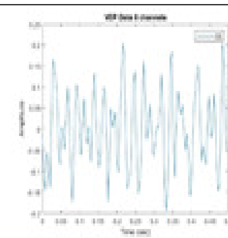
Subject 7: Café Wall Plot – Oz Sensor VEP Segments

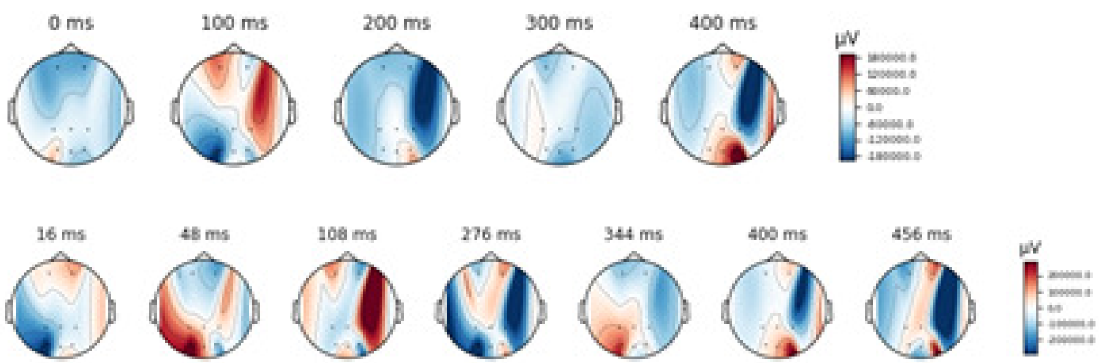
Subject 7	**Fp1**	**Fp2**	**P3**	**Pz**
Café Wall				
	P4	**O1**	**Oz**	**O2**
				



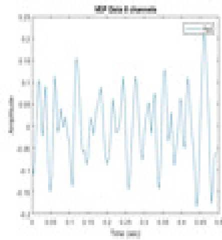
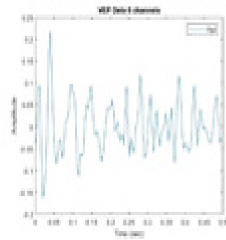
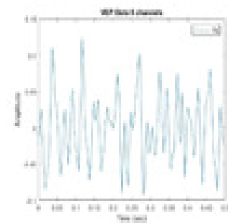
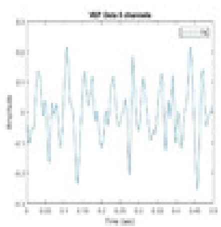
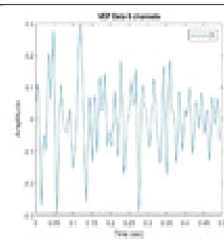
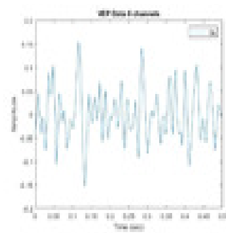
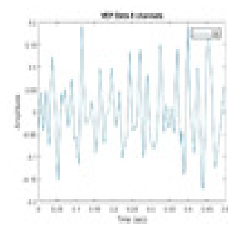


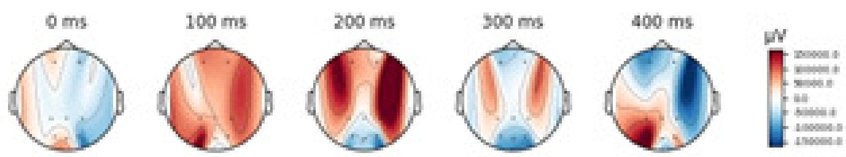
Subject 7: Reverse Spoke Wheel Plot – Oz Sensor

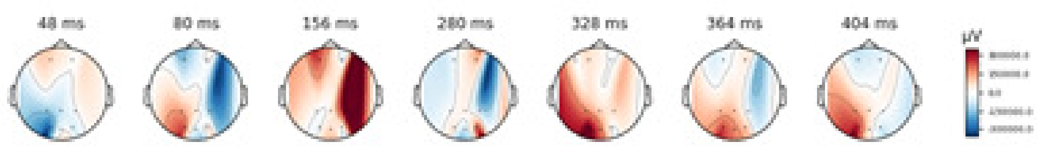
Subject 7	**Fp1**	**Fp2**	**P3**	**Pz**
Reverse Spoke				
	P4	**O1**	**Oz**	**O2**
				



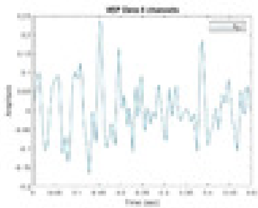
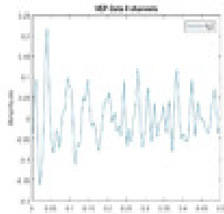
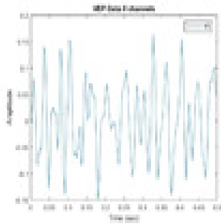
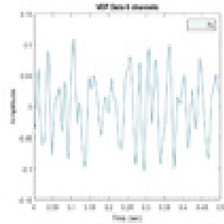
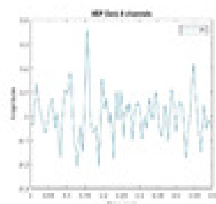
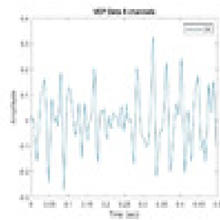
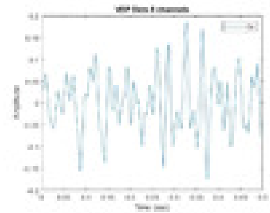
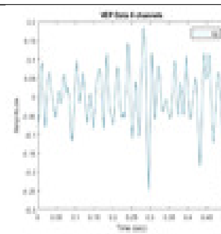
Subject 7: Rotating Snakes Plot – Oz Sensor

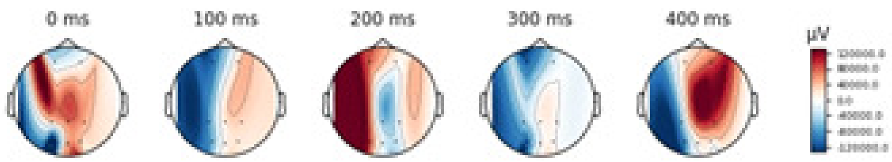
Subject 7	**Fp1**	**Fp2**	**P3**	**Pz**
Rotating Snakes				
	P4	**O1**	**Oz**	**O2**
				

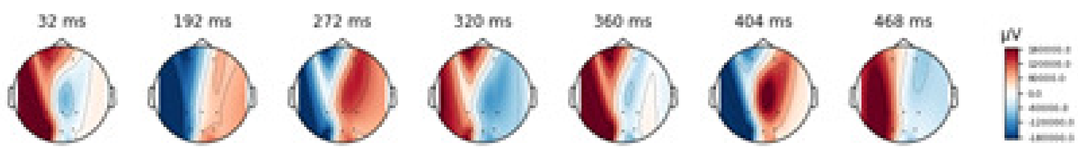




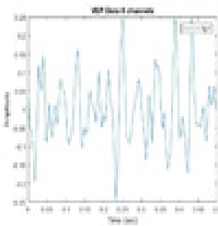
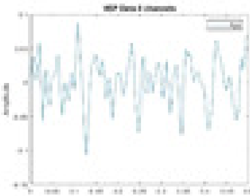
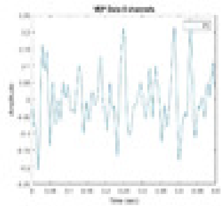
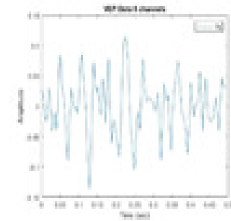
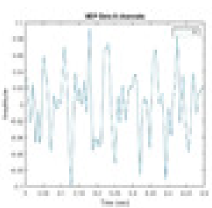
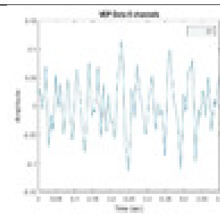
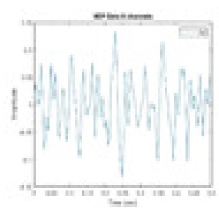
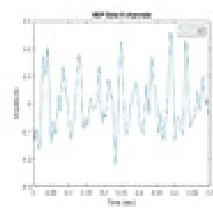
Subject 7: Stepping Feet Plot – Oz Sensor

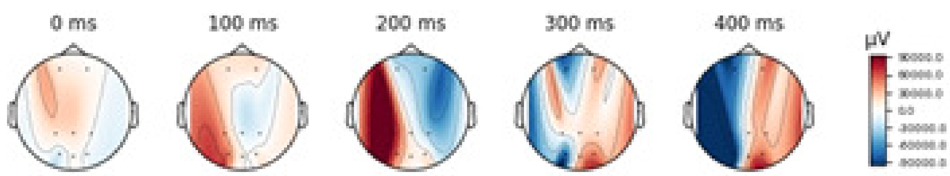
Subject7	Fp1	Fp2	P3	Pz
Stepping Feet				
	P4	**O1**	**Oz**	**O2**
				

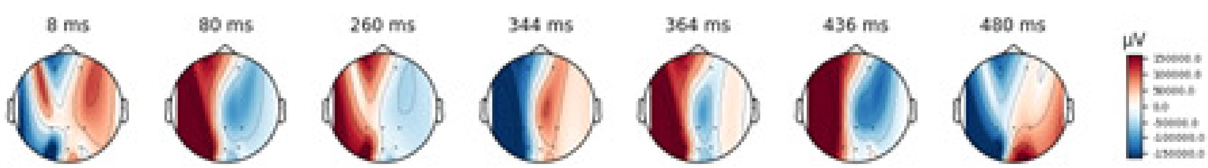




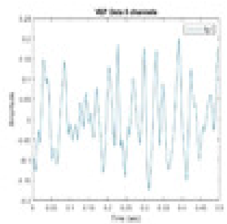
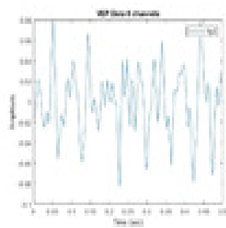
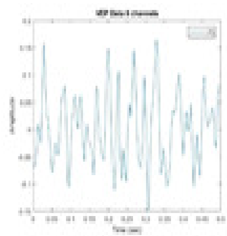
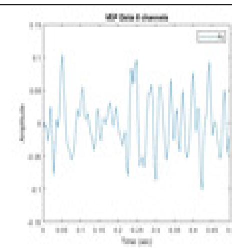
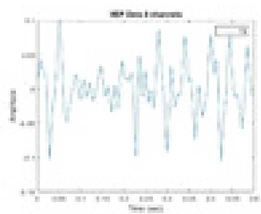
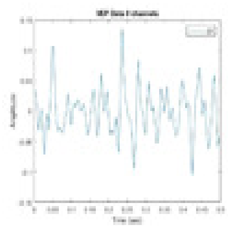
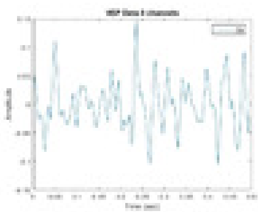
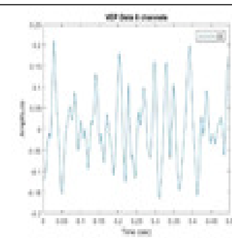
Subject 8: Café Wall Plot – Oz Sensor VEP Segments

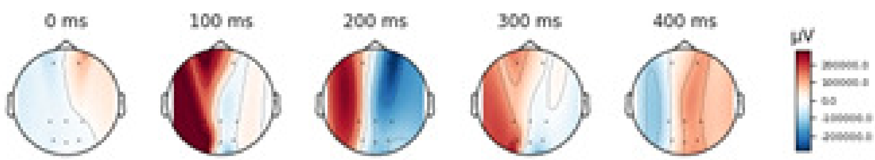
Subject 8	**Fp1**	**Fp2**	**P3**	**Pz**
Café Wall				
	P4	**O1**	**Oz**	**O2**
				

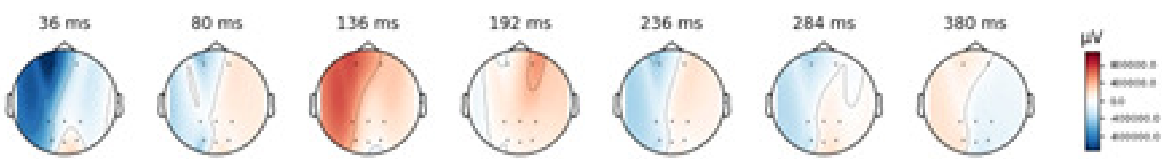




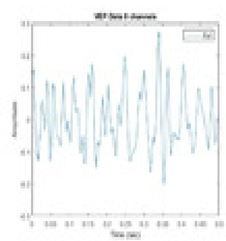
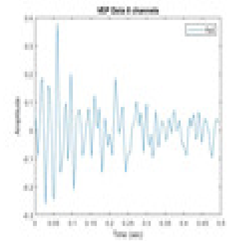
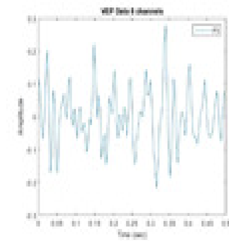
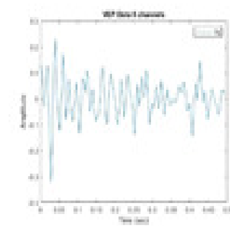
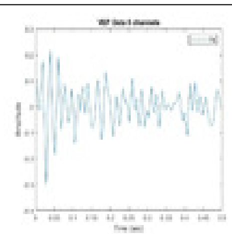
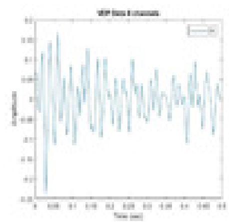
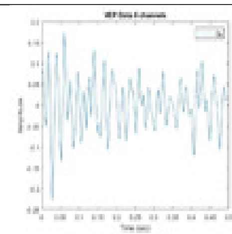
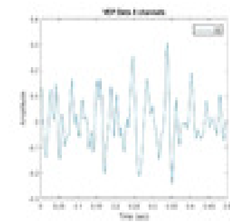
Subject 8: Reverse Spoke Wheel Plot – Oz Sensor

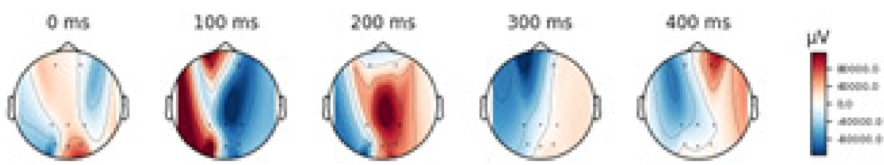
Subject8	**Fp1**	**Fp2**	**P3**	**Pz**
Reverse Spoke Wheel				
	P4	**O1**	**Oz**	**O2**
				

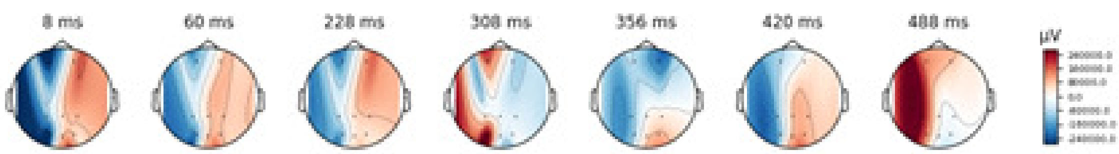




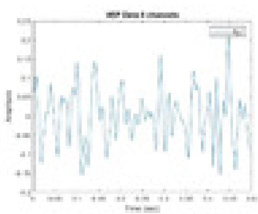
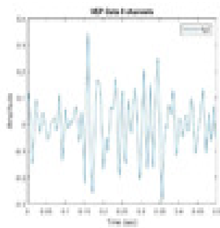
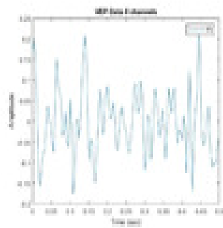
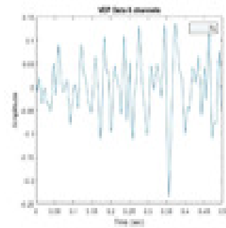
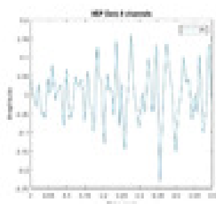
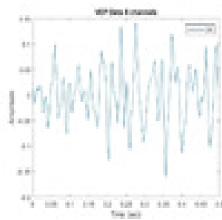
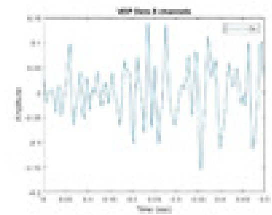
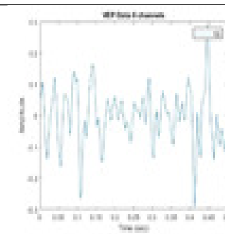
Subject 8: Rotating Snakes Plot – Oz Sensor

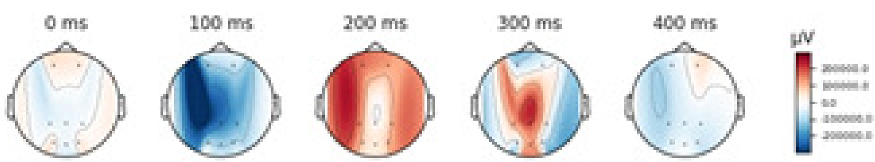
Subject 8	**Fp1**	**Fp2**	**P3**	**Pz**
Rotating Snakes				
	P4	**O1**	**Oz**	**O2**
				

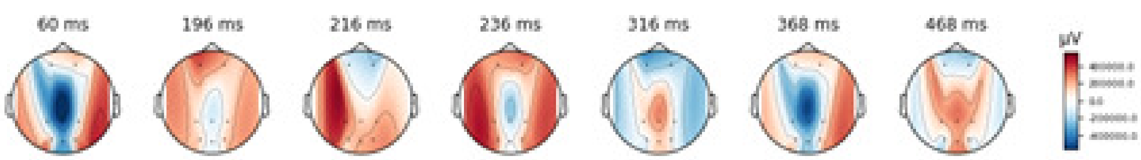




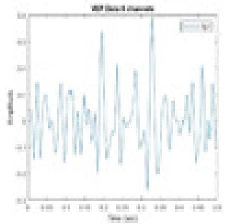
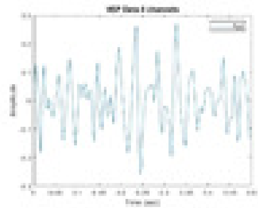
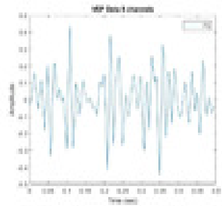
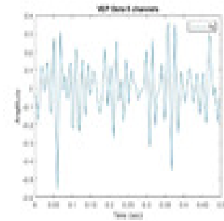
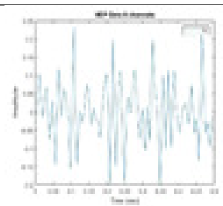
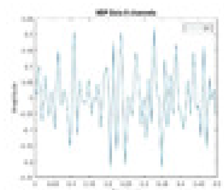
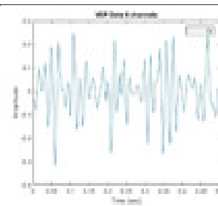
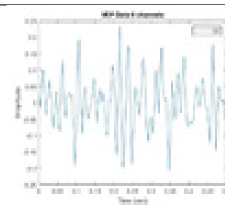
Subject 8: Stepping Feet Plot – Oz Sensor

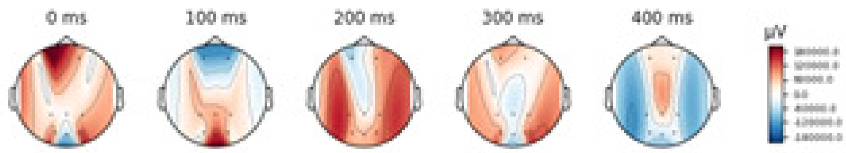
Subject8	Fp1	Fp2	P3	Pz
Stepping Feet				
	P4	**O1**	**Oz**	**O2**
				



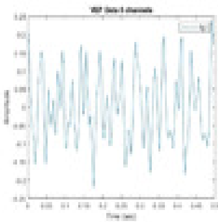
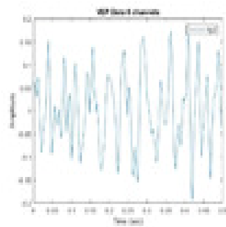
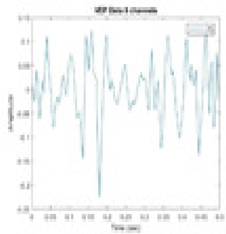
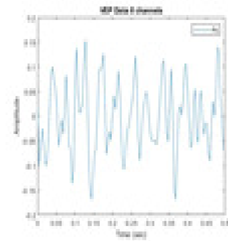
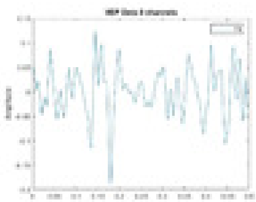
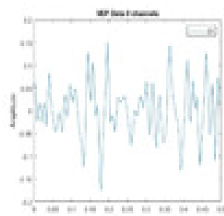
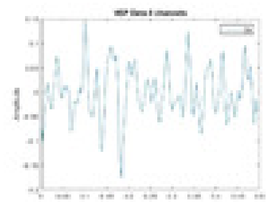
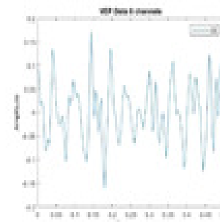


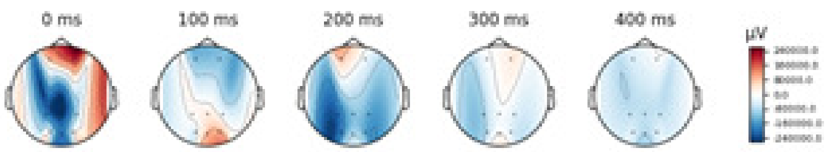
Subject 9: Café Wall Plot – Oz Sensor VEP Segments

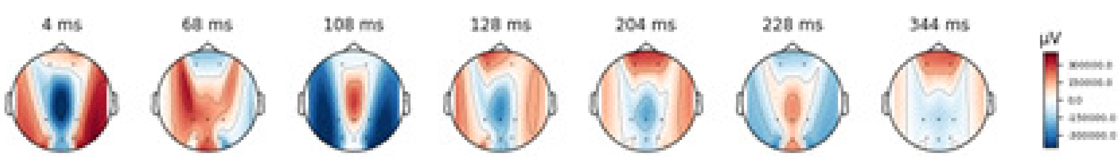
Subject 9	**Fp1**	**Fp2**	**P3**	**Pz**
Café Wall				
	P4	**O1**	**Oz**	**O2**
				



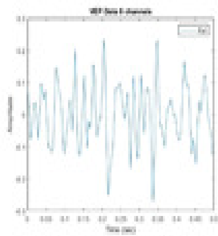
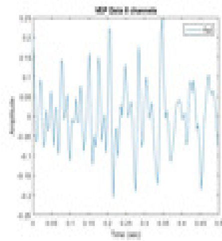
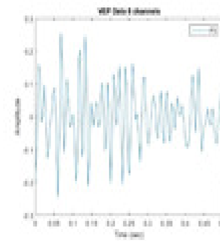
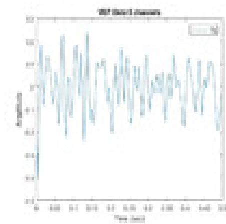
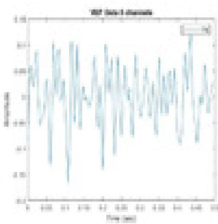
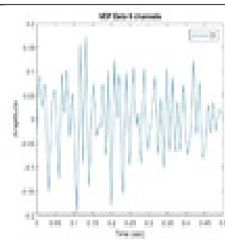
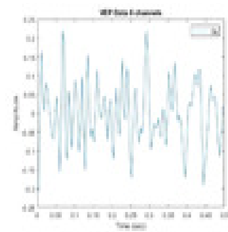
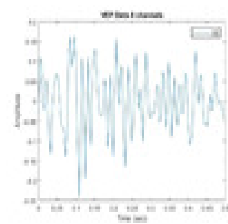
Subject 9: Reverse Spoke Wheel – Oz Sensor

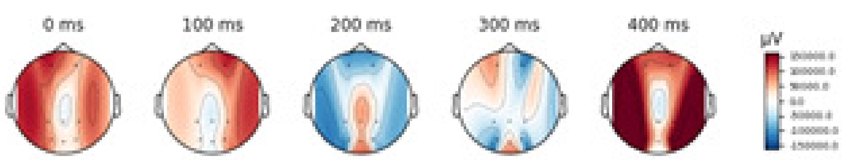
Subject 9	**Fp1**	**Fp2**	**P3**	**Pz**
Reverse Spoke				
	P4	**O1**	**Oz**	**O2**
				

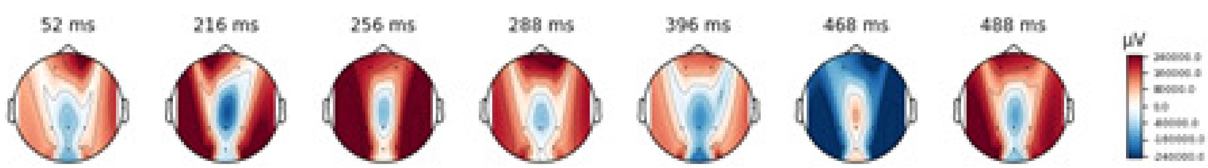




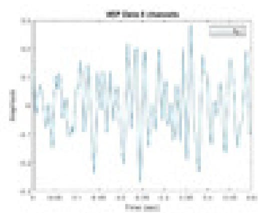
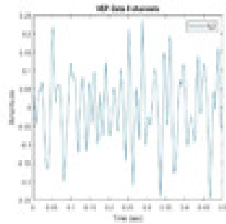
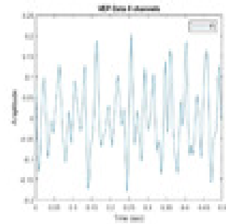
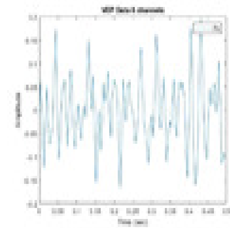
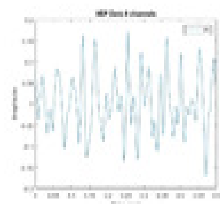
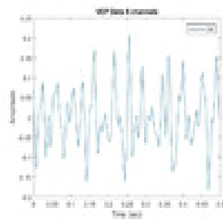
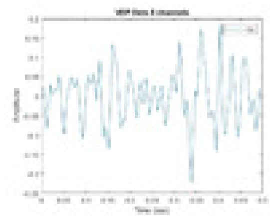
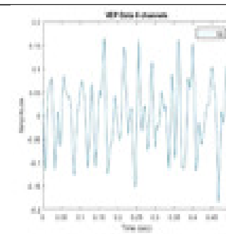
Subject 9: Rotating Snakes Plot – Oz Sensor

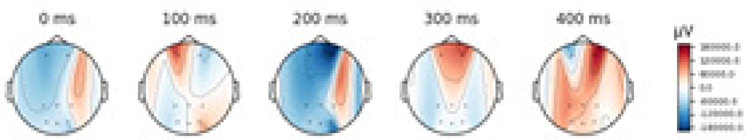
Subject9	**Fp1**	**Fp2**	**P3**	**Pz**
Rotating Snakes				
	P4	**O1**	**Oz**	**O2**
				

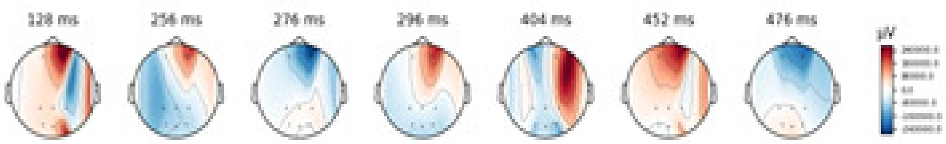




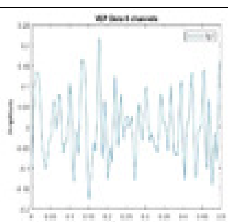
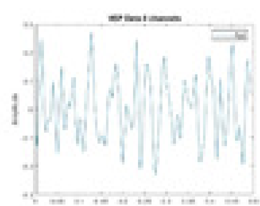
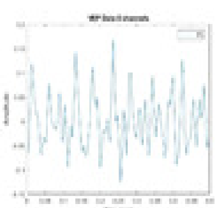
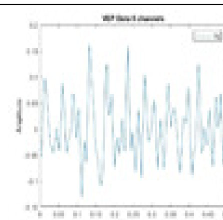
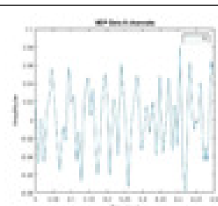
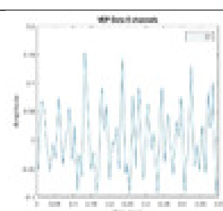
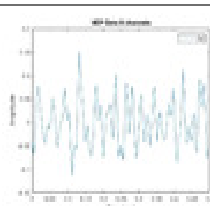
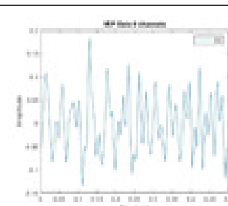
Subject 9: Stepping Feet Plot – Oz Sensor

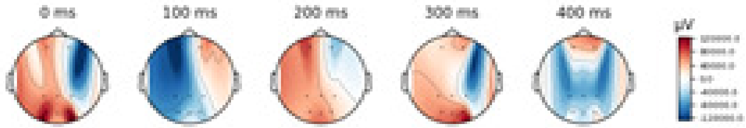
Subject9	Fp1	Fp2	P3	Pz
Stepping Feet				
	P4	O1	Oz	O2
				

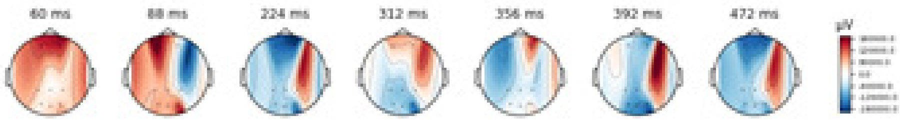




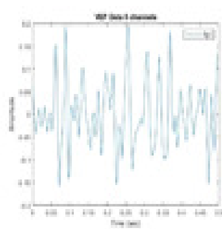
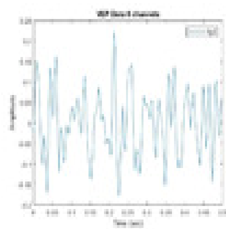
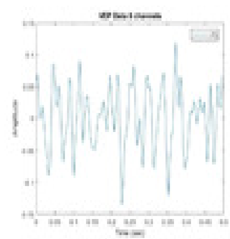
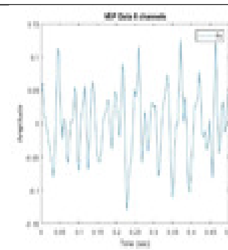
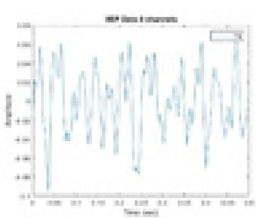
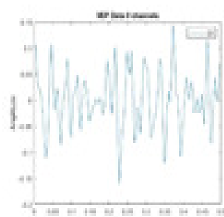
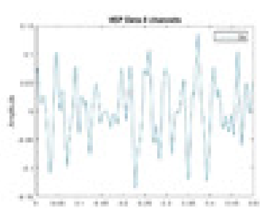
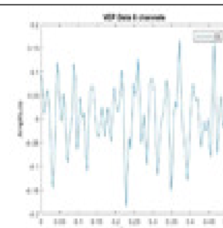
Subject 10: Café Wall Plot – Oz Sensor VEP Segments

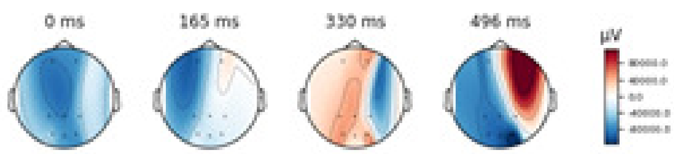
Subject 10	Fp1	Fp2	P3	Pz
CafeWall				
	P4	O1	Oz	O2
				



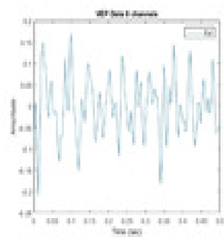
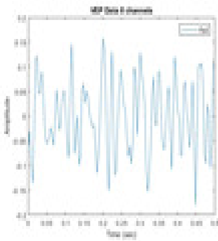
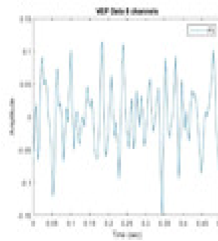
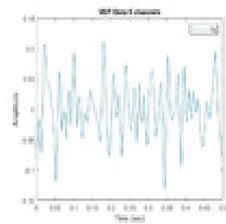
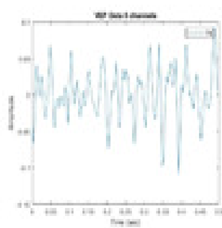
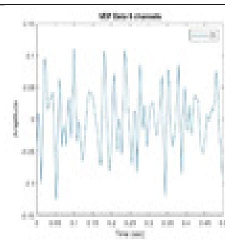
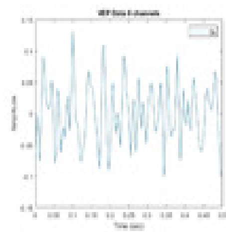
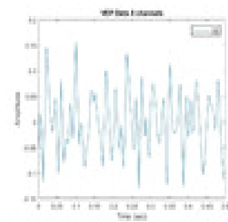


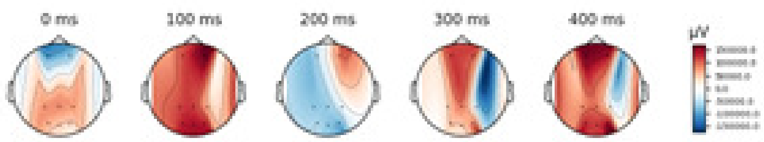
Oz Reverse Spoke

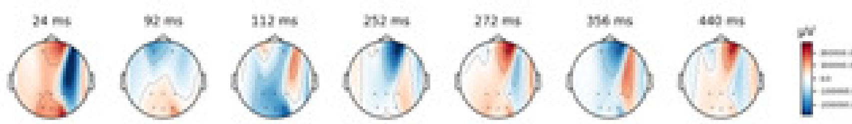
Subject 10	**Fp1**	**Fp2**	**P3**	**Pz**
Reverse Spoke				
	P4	**O1**	**Oz**	**O2**
				



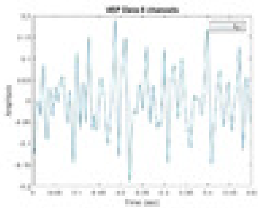
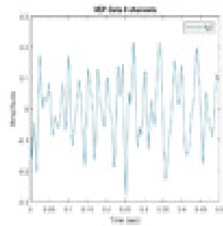
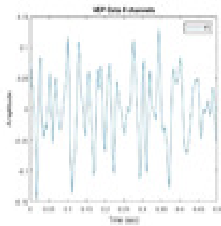
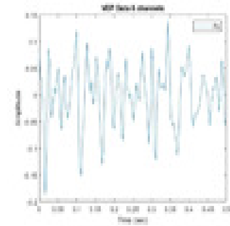
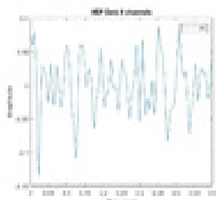
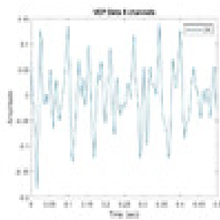
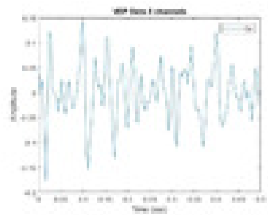
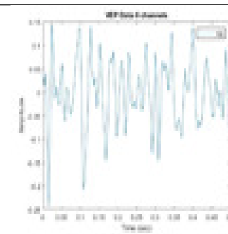
Oz Rotating Snakes

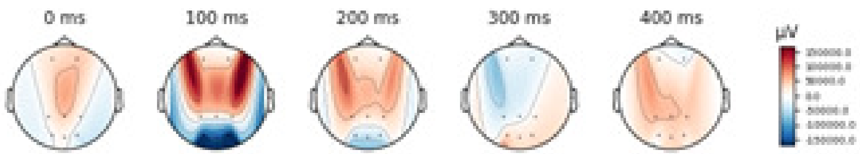
Subject 10	**Fp1**	**Fp2**	**P3**	**Pz**
Rotating Snakes				
	P4	**O1**	**Oz**	**O2**
				

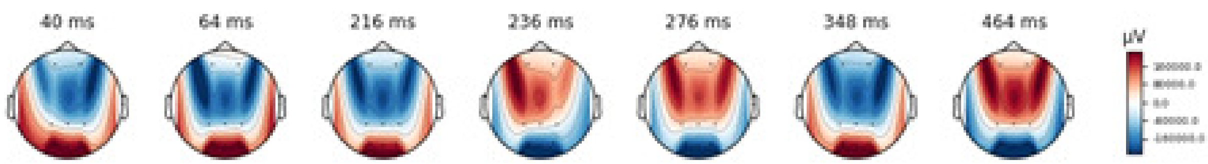




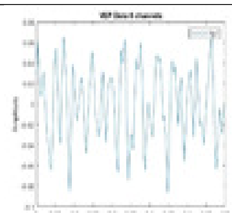
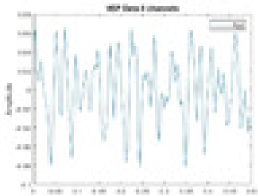
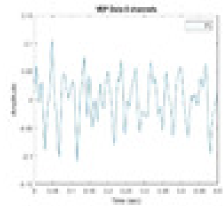
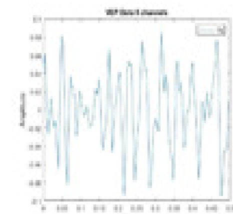
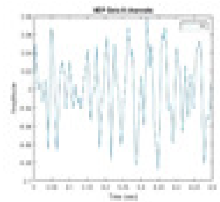
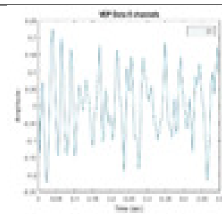
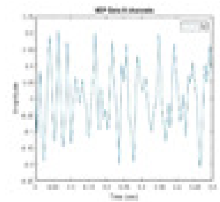
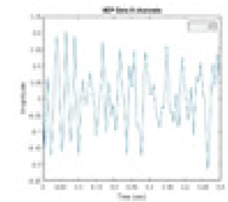
Oz Stepping Feet

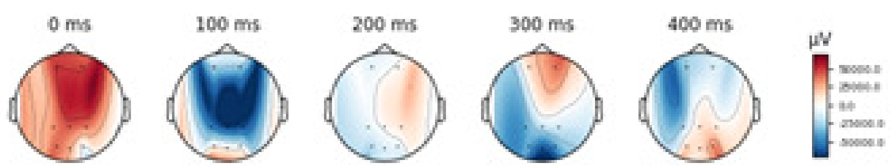
Subject 10	**Fp1**	**Fp2**	**P3**	**Pz**
Stepping Feet				
	P4	**O1**	**Oz**	**O2**
				

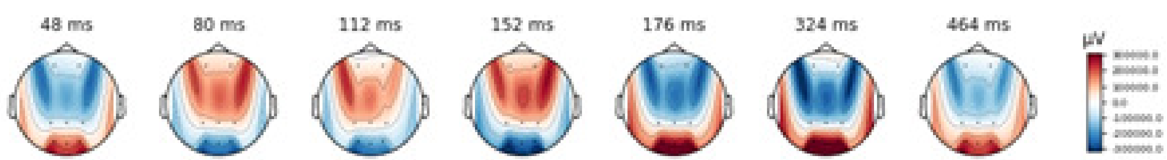




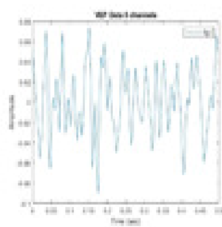
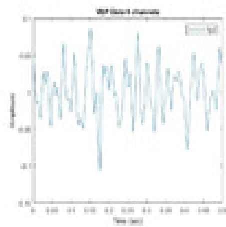
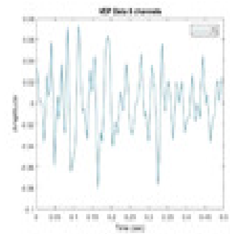
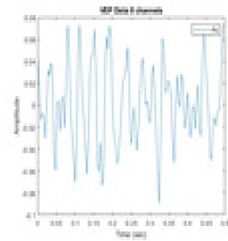
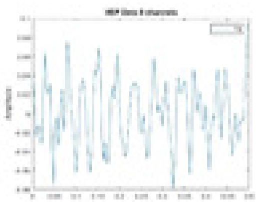
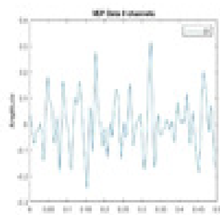
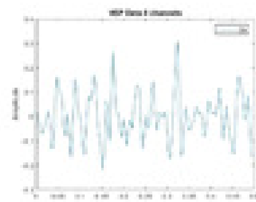
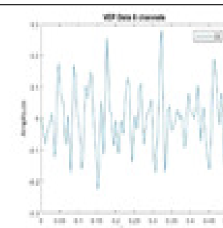
Subject 11: Café Wall Plot – Oz Sensor VEP Segments

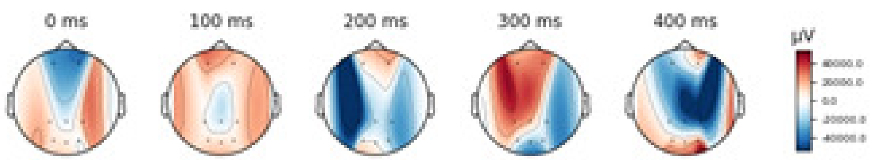
Subject 11	Fp1	Fp2	P3	Pz
CafeWall				
	P4	O1	Oz	O2
				

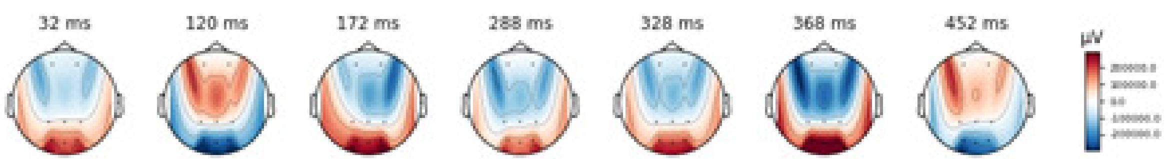




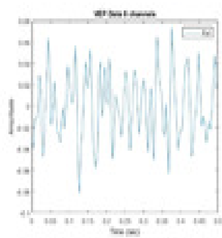
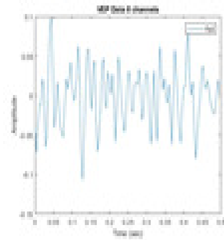
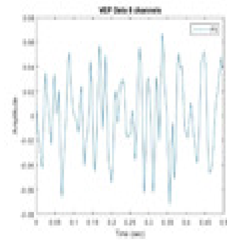
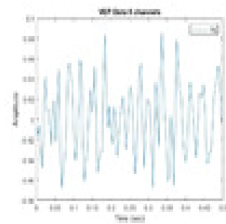
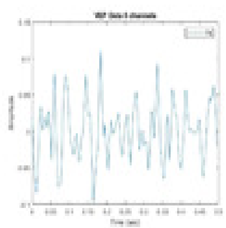
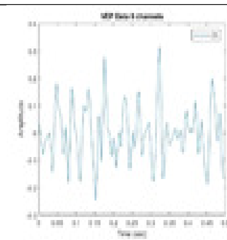
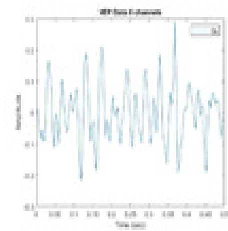
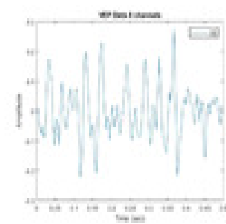
Subject 11: Reverse Spoke Plot – Oz Sensor

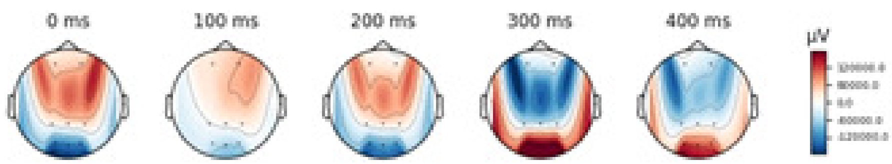
Subject 11	Fp1	Fp2	P3	Pz
Reverse Spoke				
	P4	**O1**	**Oz**	**O2**
				

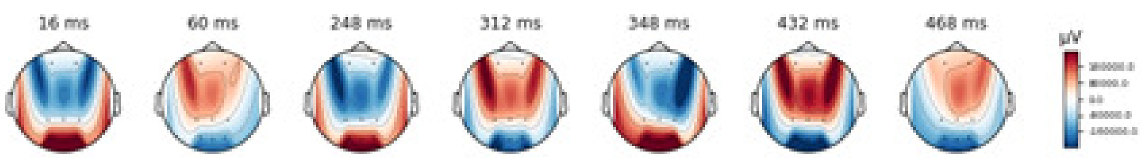




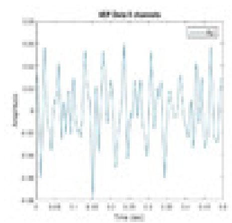
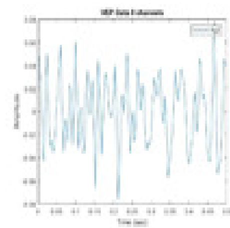
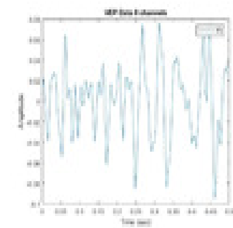
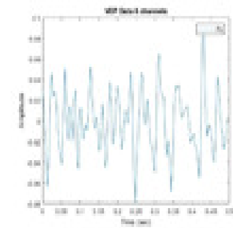
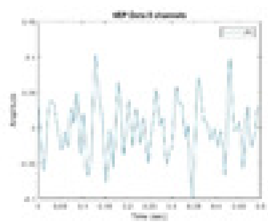
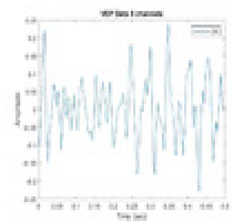
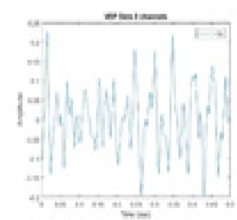
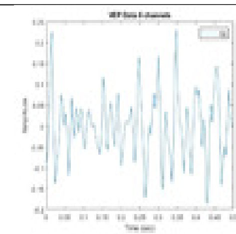
Subject 11: Rotating Snakes Plot – Oz Sensor

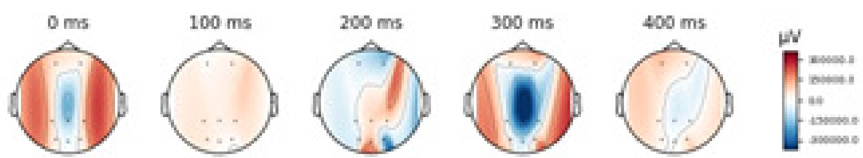
Subject 11	**Fp1**	**Fp2**	**P3**	**Pz**
Rotating Snakes				
	P4	**O1**	**Oz**	**O2**
				



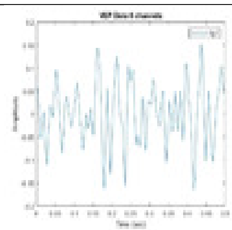
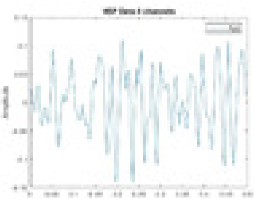
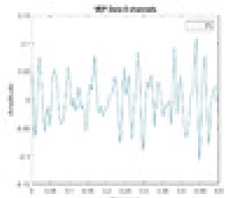
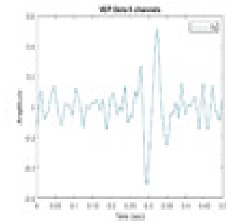
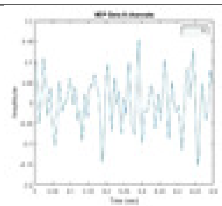
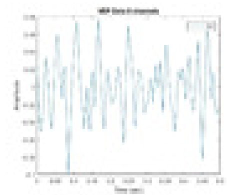
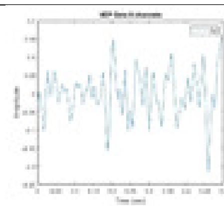
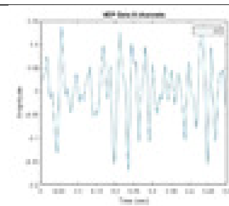


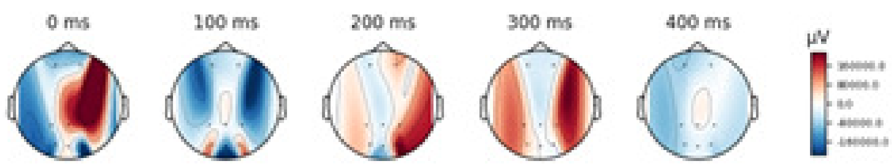
Subject 11: Stepping Plot – Oz Sensor

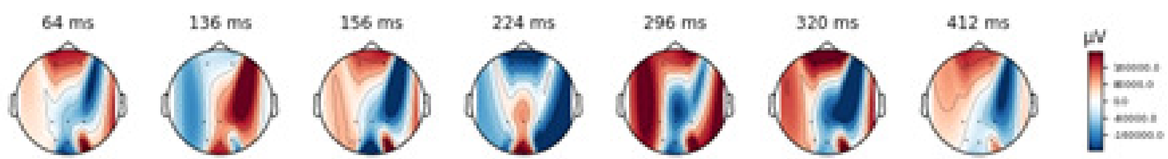
Subject 11	**Fp1**	**Fp2**	**P3**	**Pz**
Stepping Feet				
	P4	**O1**	**Oz**	**O2**
				



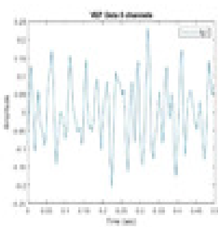
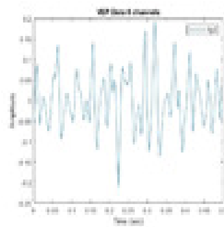
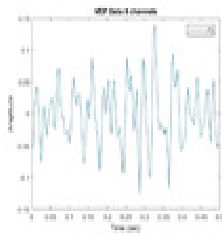
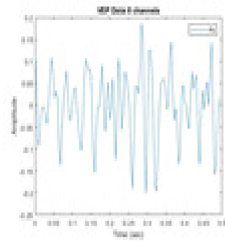
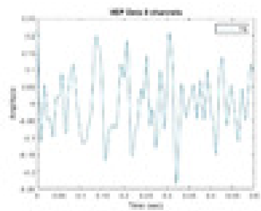
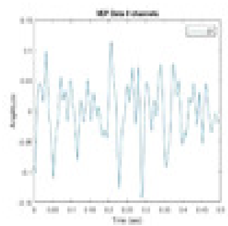
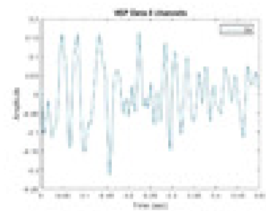
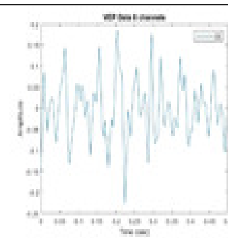
Subject 12: Café Wall Plot – Oz Sensor VEP Segments

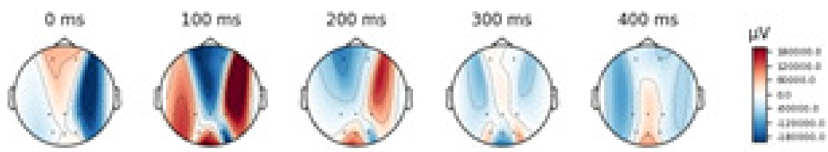
Subject 12	**Fp1**	**Fp2**	**P3**	**Pz**
CafeWall				
	P4	**O1**	**Oz**	**O2**
				

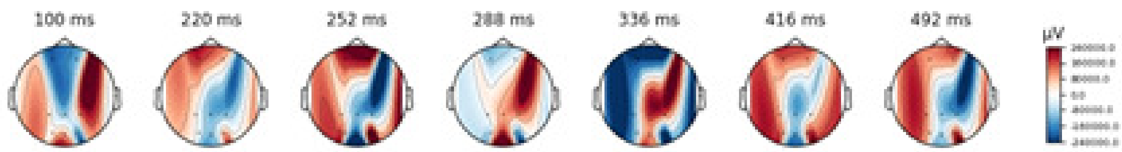




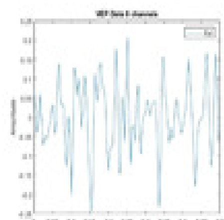
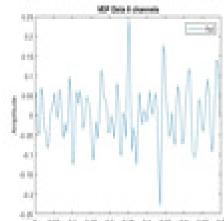
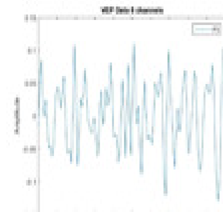
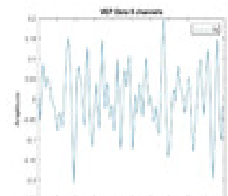
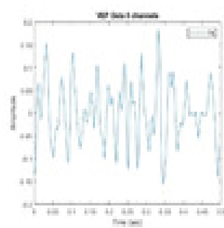
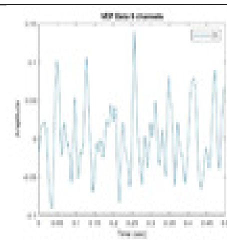
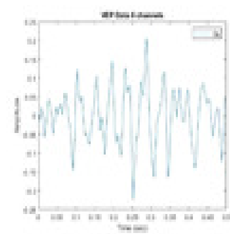
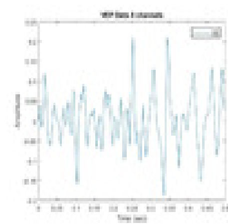
Subject 12: Reverse Spoke Wheel Plot – Oz Sensor

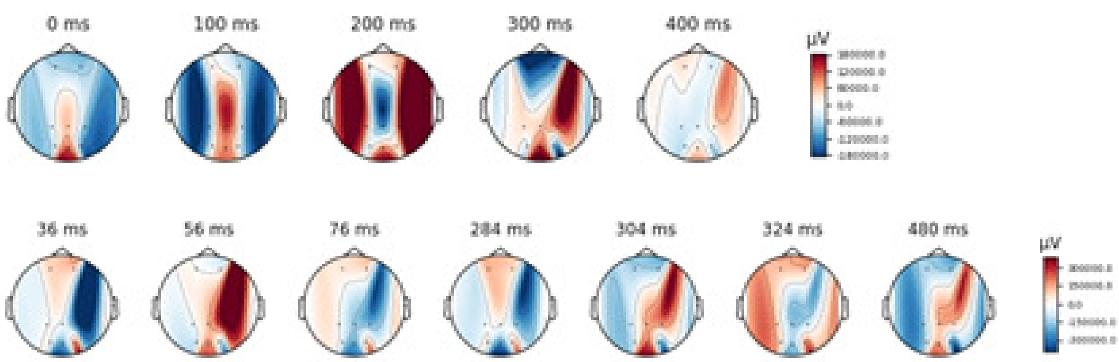
Subject 12	**Fp1**	**Fp2**	**P3**	**Pz**
Reverse Spoke				
	P4	**O1**	**Oz**	**O2**
				



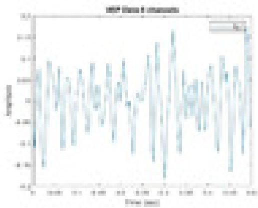
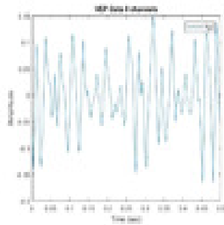
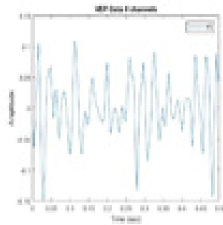
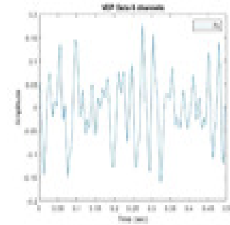
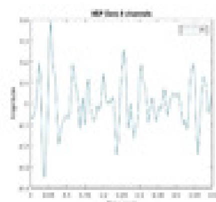
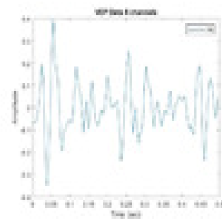
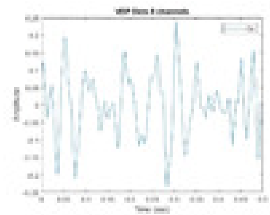
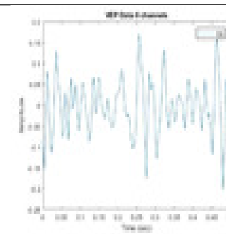


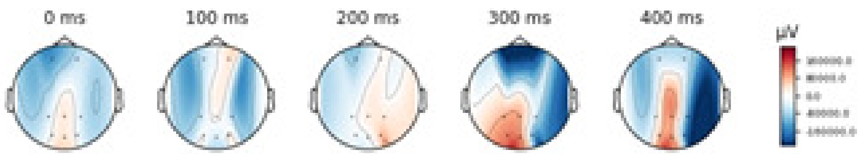
Subject 12: Rotating Snakes Plot – Oz Sensor

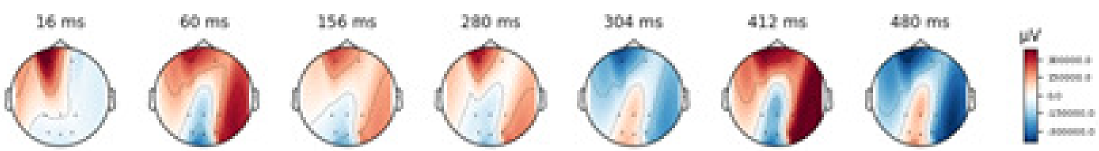
Subject 12	**Fp1**	**Fp2**	**P3**	**Pz**
Rotating Snakes				
	P4	**O1**	**Oz**	**O2**
				



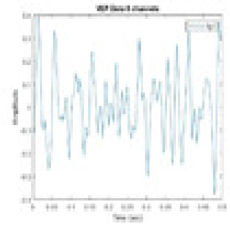
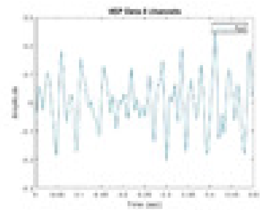
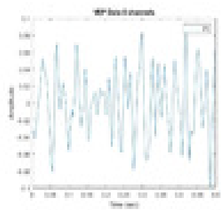
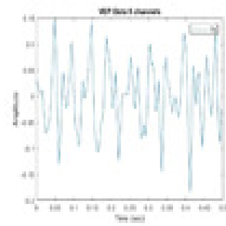
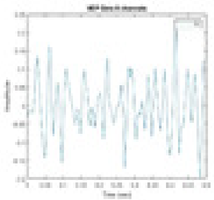
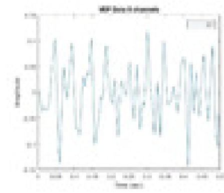
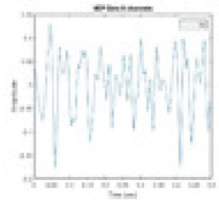
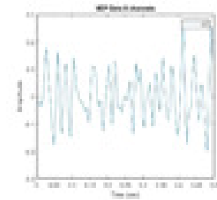
Subject 12: Stepping Feet Plot – Oz Sensor

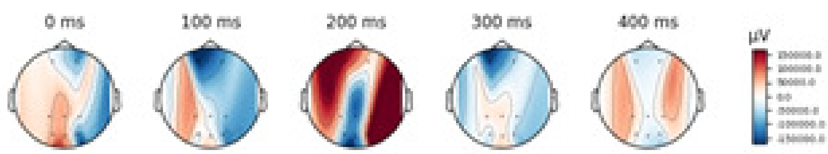
Subject 12	**Fp1**	**Fp2**	**P3**	**Pz**
Stepping Feet				
	P4	**O1**	**Oz**	**O2**
				

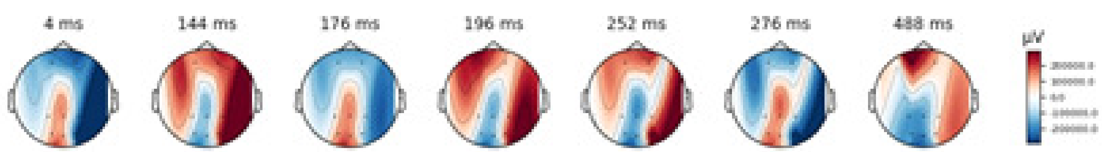




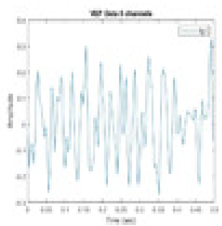
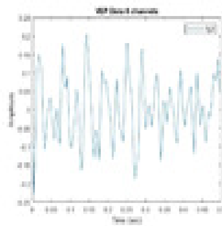
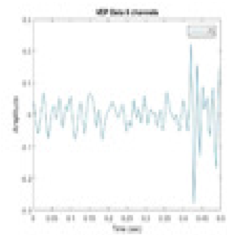
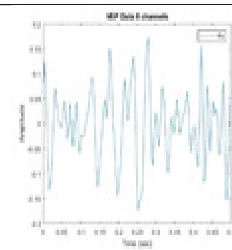
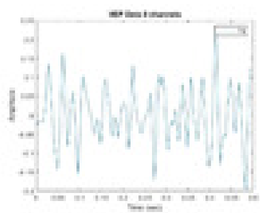
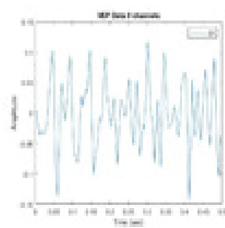
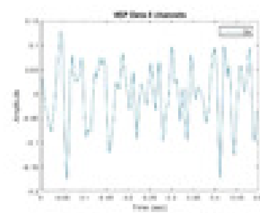
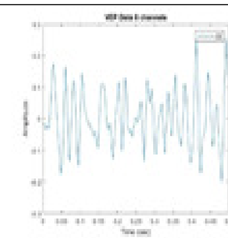
Subject 13: Café Wall Plot – Oz Sensor VEP Segments

Subject 13	**Fp1**	**Fp2**	**P3**	**Pz**
CafeWall				
	P4	**O1**	**Oz**	**O2**
				

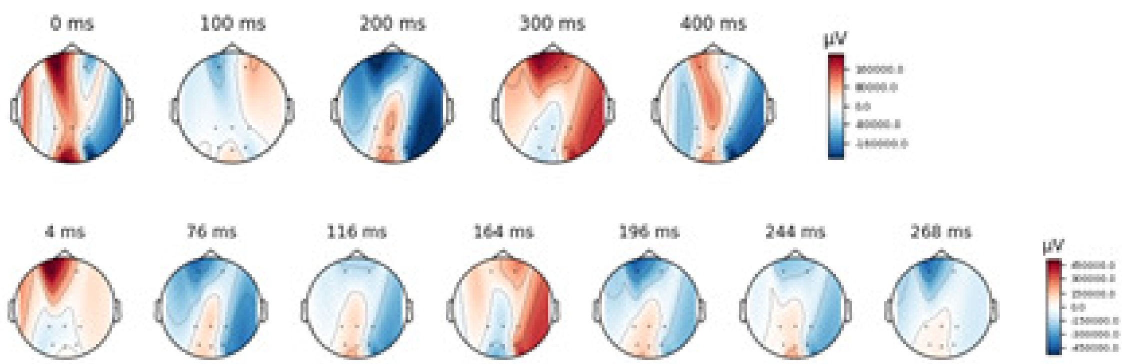


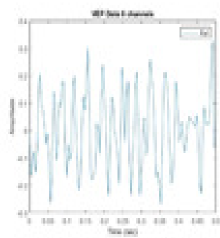
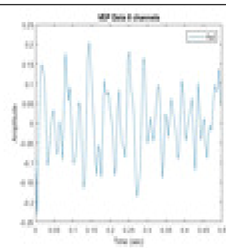
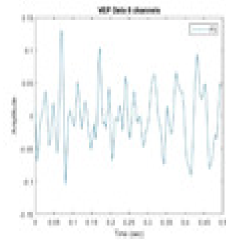
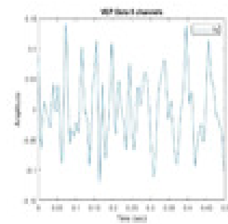
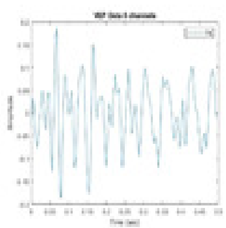
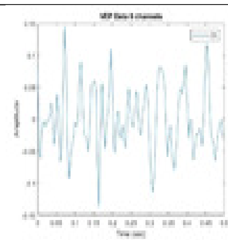
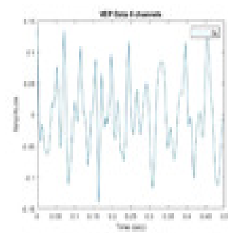
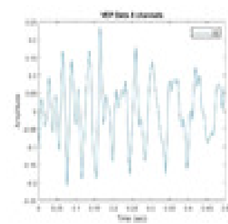


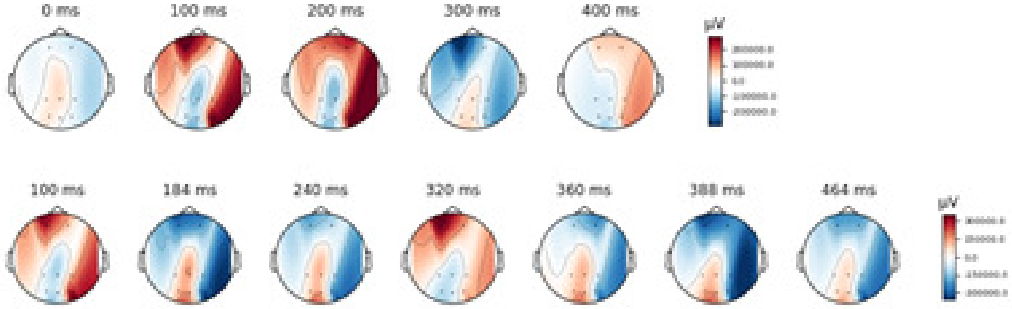
Subject 13: Reverse Spoke Wheel Plot – Oz Sensor

Subject 13	**Fp1**	**Fp2**	**P3**	**Pz**
Reverse Spoke				
	P4	**O1**	**Oz**	**O2**
				

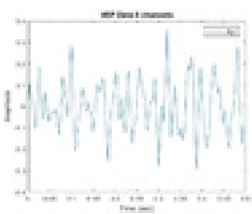
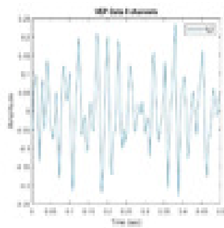
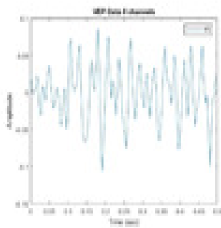
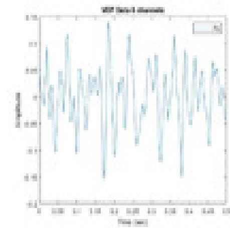
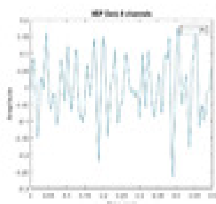
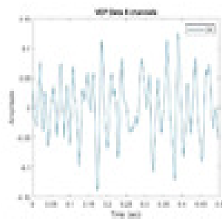
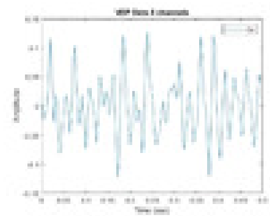
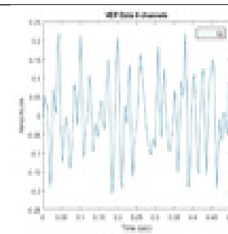
Subject 13: Rotating Snakes Plot – Oz Sensor

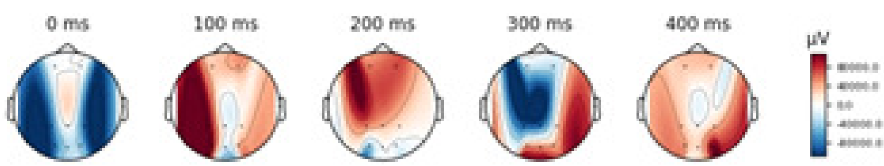


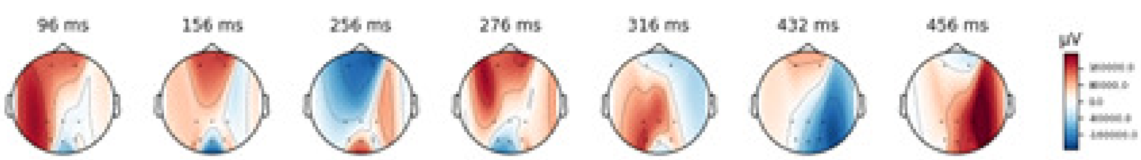
Subject 13	**Fp1**	**Fp2**	**P3**	**Pz**
Rotating Snakes				
	P4	**O1**	**Oz**	**O2**
				



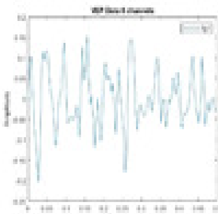
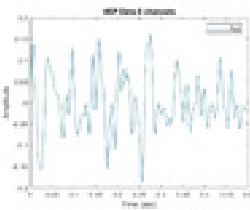
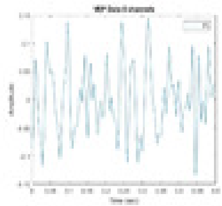
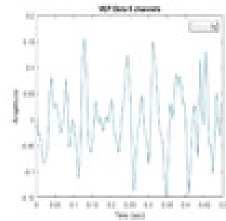
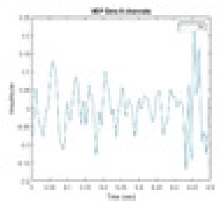
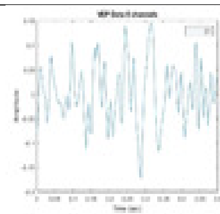
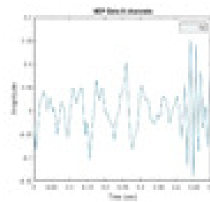
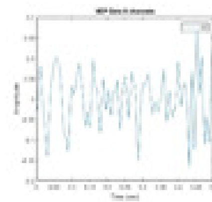
Subject 13: Stepping Feet Plot – Oz Sensor

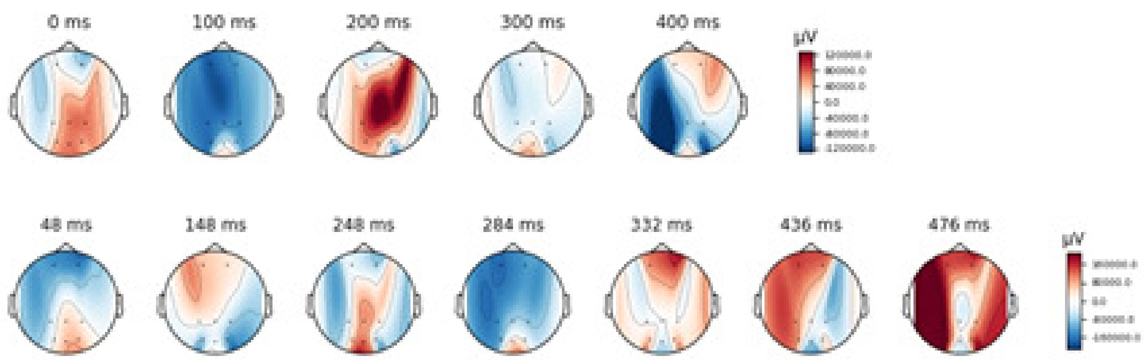
Subject 13	**Fp1**	**Fp2**	**P3**	**Pz**
Stepping Feet				
	P4	**O1**	**Oz**	**O2**
				



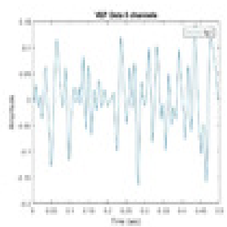
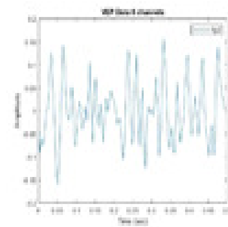
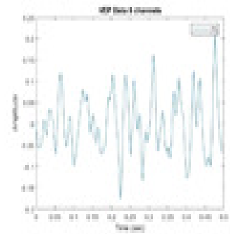
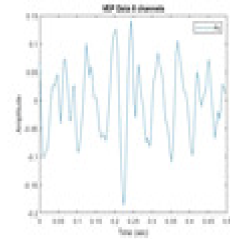
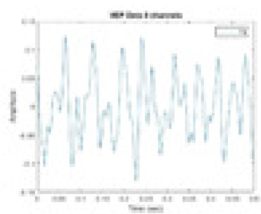
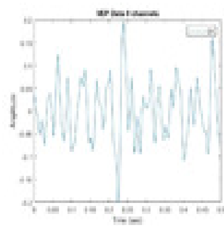
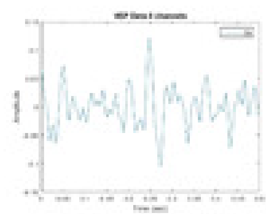
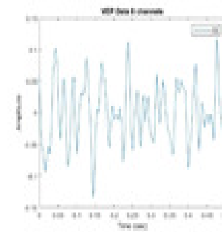


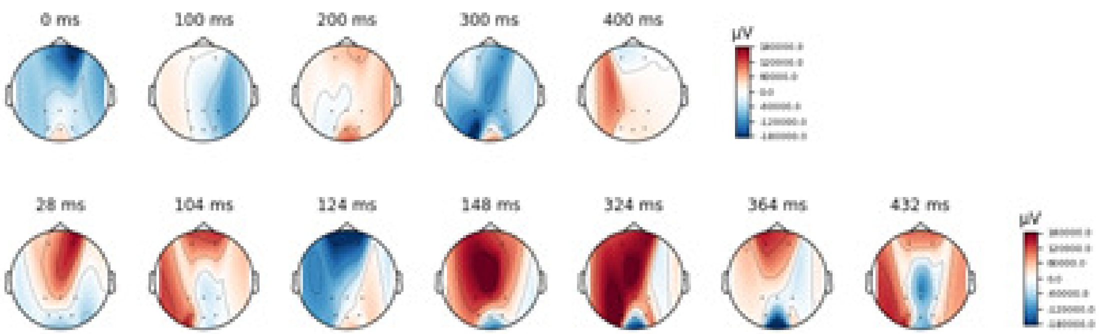
Subject 14: Café Wall Plot – Oz Sensor VEP Segments

Subject 14	**Fp1**	**Fp2**	**P3**	**Pz**
CafeWall				
	P4	**O1**	**Oz**	**O2**
				

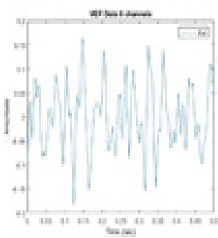
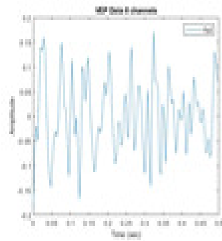
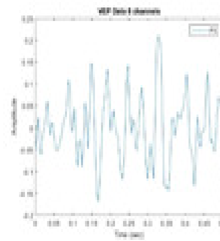
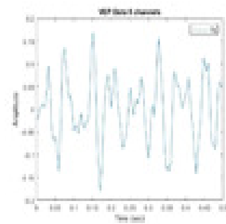
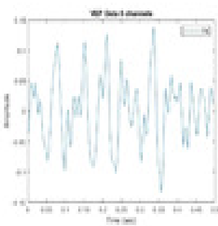
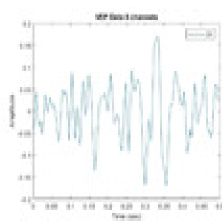
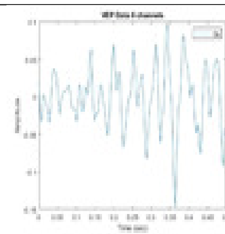
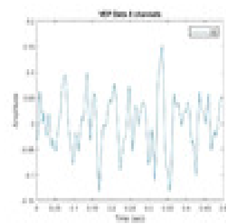


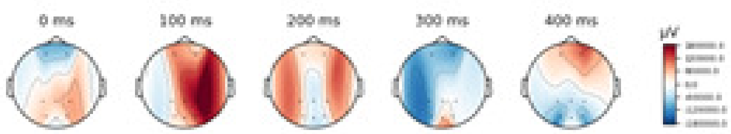
Subject 14: Reverse Spoke Wheel Plot – Oz Sensor

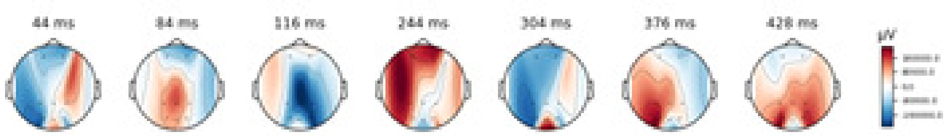
Subject 14	Fp1	Fp2	P3	Pz
Reverse Spoke				
	P4	**O1**	**Oz**	**O2**
				



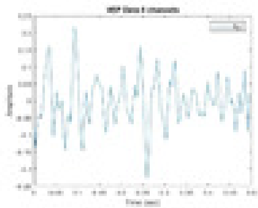
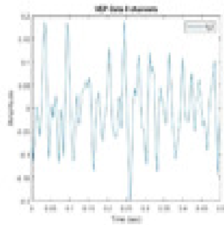
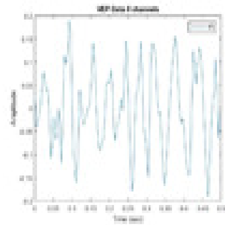
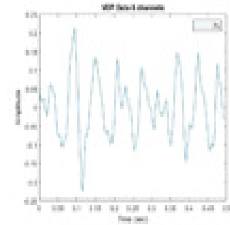
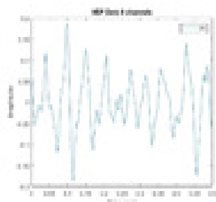
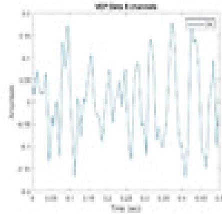
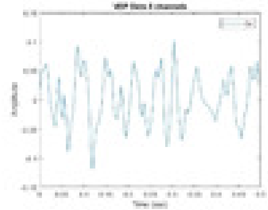
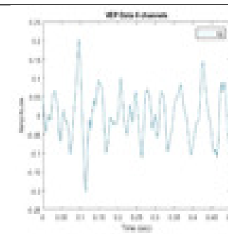
Subject 14: Rotating Snakes Plot – Oz Sensor

Subject 14	Fp1	Fp2	P3	Pz
Rotating Snakes				
	P4	O1	Oz	O2
				





Subject 14: Stepping Feet Plot – Oz Sensor

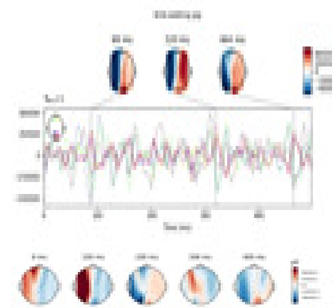
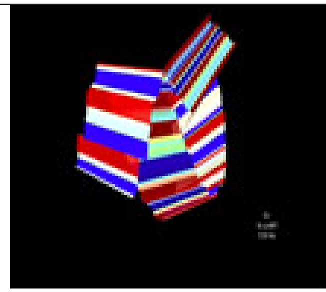
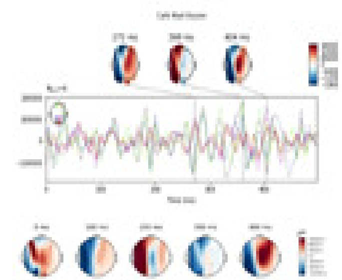
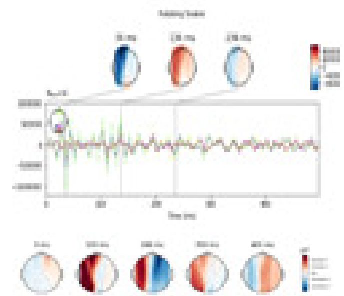
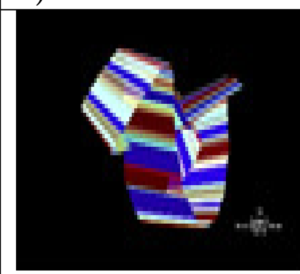
Subject 14	**Fp1**	**Fp2**	**P3**	**Pz**
Stepping Feet				
	P4	**O1**	**Oz**	**O2**
				

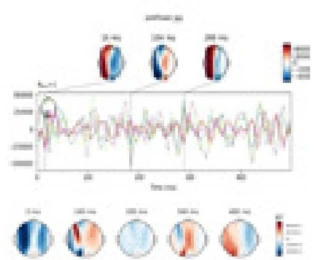
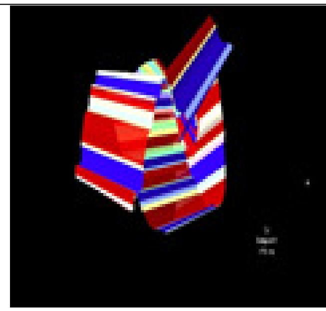
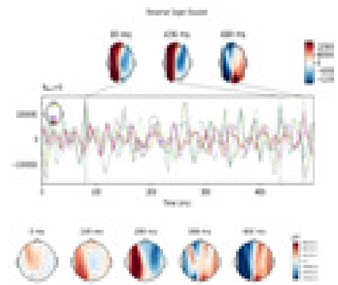
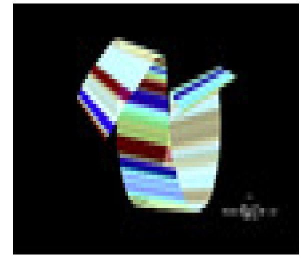
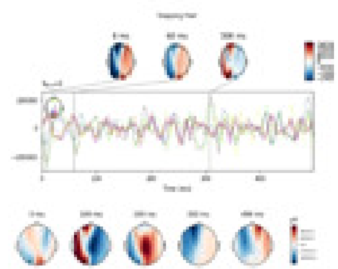
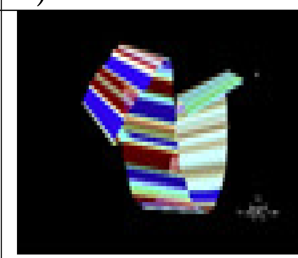
Appendix D

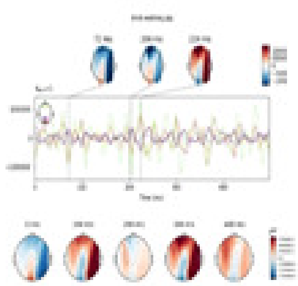
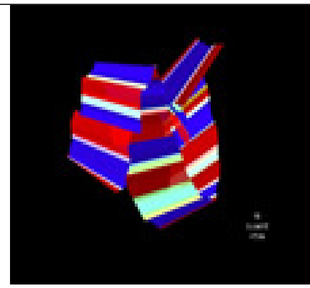
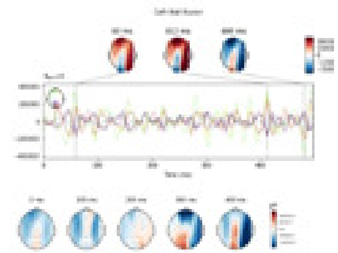
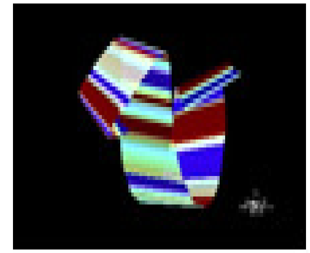
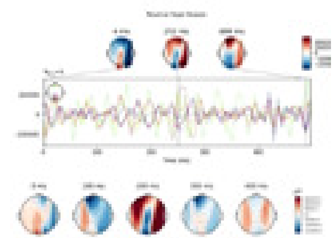
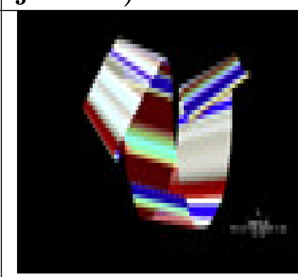
This appendix shows the comparison between the non-illusion (Stage 1) vs. illusion (Stage 2) images. It presents the scientific plotting versus the Aspecta artistic rendering of the same data. The non-illusion images are still images with no illusions or alterations. The illusion images are the optical illusions used in the experiment. The purpose is to compare Stage 1 with Stage 2 of the experiment (see Chapter 5). The subjects shown below are those who were most able to distinguish between the different types of images.

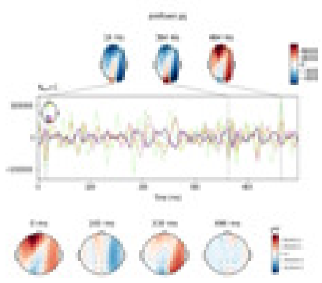
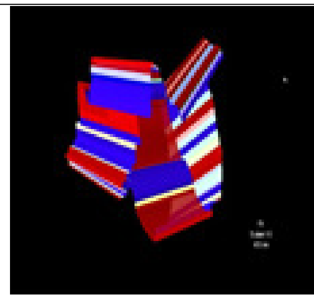
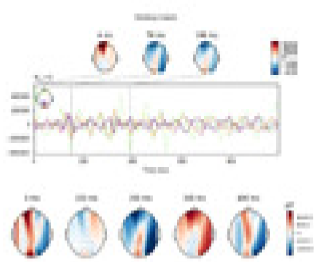
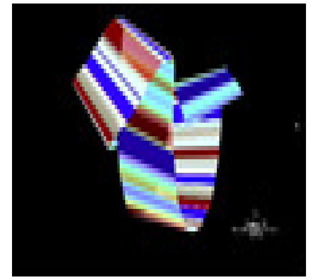
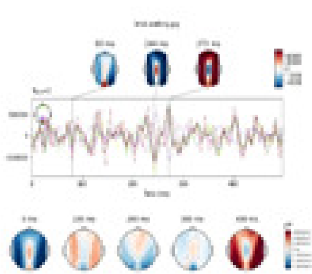
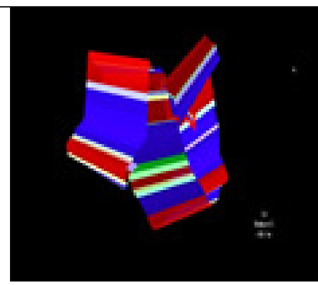
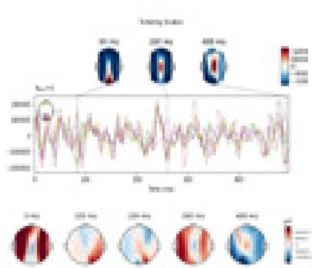
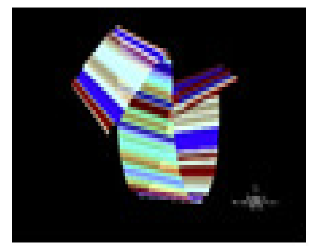
D.0.1 Illusion vs. Non-illusion Visualization Comparisons

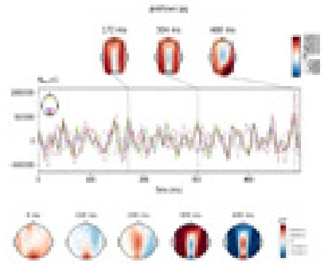
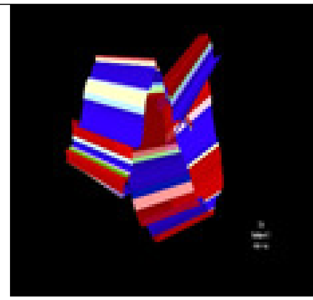
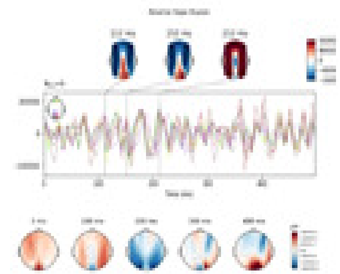
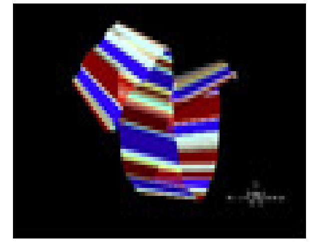
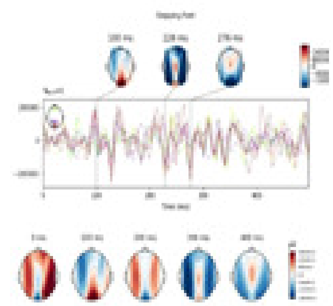
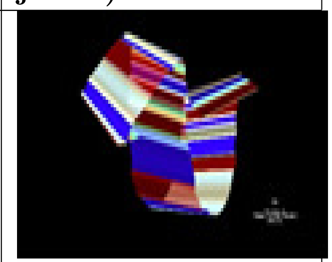
Non-Illusion (NI) brisk walk **(Subject 8)**	*Aspecta* processed NI **(Subject 8)**	Illusion Café wall (CW) **(Subject 8)**	*Aspecta* processed CW Illusion **(Subject 8)**

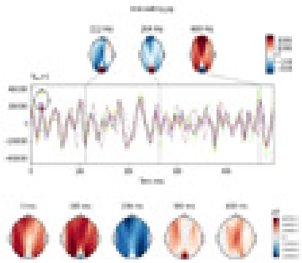
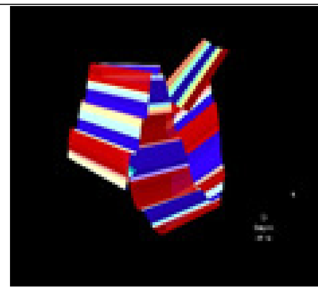
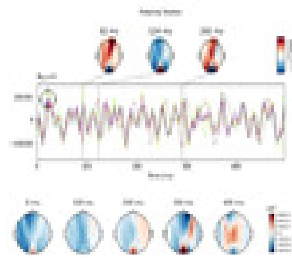
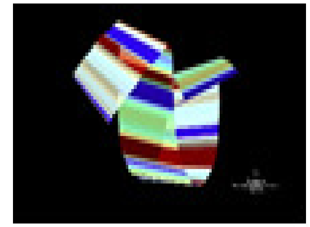
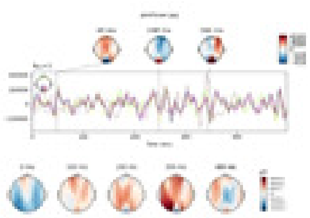
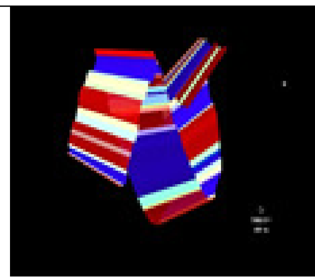
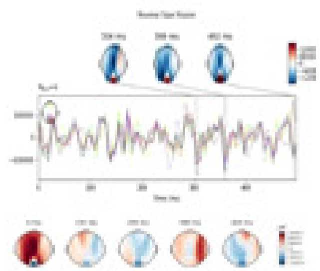
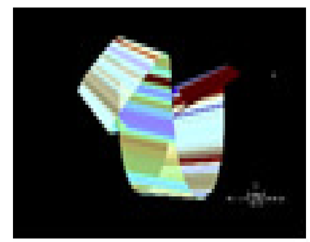
			
–	–	Illusion Rotating Snakes (RS) **(Subject 8)**	*Aspecta* processed Illusion RS **(Subject 8)**
–	–		
Non-Illusion (NI) pink flower **(Subject 8)**	*Aspecta* processed NI **(Subject 8)**	Illusion Reverse Spoke (RevS) **(Subject 8)**	*Aspecta* processed Illusion RevS **(Subject 8)**

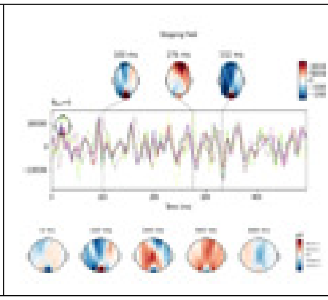
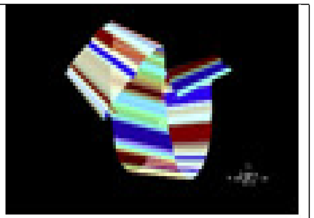
			
–	–	Illusion Stepping Ft (SF) **(Subject 8)**	*Aspecta* processed Illusion SF **(Subject 8)**
–	–		
Non-Illusion – brisk walking **(Subject 13)**	Aspecta processed NI **(Subject 13)**	Illusion Café wall (CW) **(Subject 13)**	*Aspecta* processed Illusion CW **(Subject 13)**

			
–	–	Illusion **(Subject 13)** Rev. Spoke (RevS)	*Aspecta* processed Illusion RevS **(Subject 13)**
	–		
Non-Illusion Pink flower **(Subject 13)**	Aspecta processed NI **(Subject 13)**	Illusion Rot Snakes (RotS) **(Subject 13)**	*Aspecta* processed Illusion RotS **(Subject 13)**

			
Non-Illusion – Brisk walking **(Subject 3)**	Aspecta processed NI **(Subject 3)**	Illusion Rot. Sn **(Subject 3**)	*Aspecta* processed RotS Illusion **(Subject 3)**
			
Non-Illusion Pink Flower **(Subject 3)**	Aspecta processed NI **(Subject 3)**	Illusion Rev. Sp **(Subject 3**)	Aspecta processed RevS Illusion **(Subject 3)**

			
–	–	Illusion Step Ft **(Subject 3)**	Aspecta processed SF Illusion **(Subject 3)**
–	–		
Non-Illusion Brisk walking **(Subject 4)**	Aspecta processed NI **(Subject 4)**	Illusion Rot. Snake (RotS) **(Subject 4)**	Aspecta processed RotS Illusion **(Subject 4)**

			
Non-Illusion Pink flower **(Subject 4)**	Aspecta processed NI **(Subject 4)**	Illusion Rev. Spoke (RevS) **(Subject 4)**	Aspecta processed RevS Illusion **(Subject 4)**
			
–	–	Illusion Step. Ft. (SF) **(Subject 4)**	Aspecta processed SF Illusion **(Subject 4)**

—	—		

Appendix E

This Appendix presents the Open Sound Control (OSC) Specification for the Visum Interface.

E.0.1 OSC - Specification

The OSC data streamed by Visum is sent out through Port 8000. By default, Visum outputs a single value for each parameter.

Item	**OSC Path**	**Value**
Stream*	/stream*/parameter	f (One Float value)

*** indicates stream number.** For example, /stream1/lp sends out one float value for the low pass filter for stream 1.

Parameters (Visum)
Grain Size /stream*/grain
Pan (pan) /stream*/pan
Pitch Shift (pitch) /stream*/pitch
Low Pass Filter (lp) /stream*/lp
Delay (delay) /stream*/del
Feedback /stream*/feed
Mix /stream*/mix
Reverb /stream*/rev
Reverb Mix /stream*/revm
Time Stretch /stream*/tmsrtch
On/Off /stream*/onoff

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