Illusion: An Instrument Propelled by the Mind

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

Doctor of Philosophy

University of Washington
2021

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Program Authorized to Offer Degree:
Digital Arts and Experimental Media

University of Washington

Abstract

Illusion: An Instrument Propelled by the Mind

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This thesis describes *Illusion*, a performance-based sound installation that explores the mind's obscurity employing brain-computer interfaces. The doctoral study investigates the correlation between the human mind and brain waves through interdisciplinary research encompassing neuroscience, computer science, philosophy of mind, and early experimental arts. Furthermore, it presents an audio-visual system that enables both real-time performance and sound installation by simultaneously manipulating images and sounds by selecting particular brain waves. This study results in creating artworks and engaging the public with the new brain-computer interface variant.

This project creates art by designing artistic representation instruments using the brain-computer interface, a direct communication channel between the human brain and the machine. It advocates a neurologic view of the correlation between the human mind and brain waves and pursues Cybernetics' ideal, the co-evolution of humans and machines. Human beings and machines' mutual prosperity through art creation also inherits the vision of early experimental artists who attempted to converge art-oriented science and technology.

Acknowledgments

This dissertation is dedicated to my advisor Richard Karpen. He founded DXARTS, where I could pursue my ideals, and he was willing to lead me into the world of brain-computer music interfaces. I am genuinely grateful to him.
Thank you, Richard.

I also sincerely appreciate the support and inspiration of the following individuals and organizations:

Hae-young Choi
Paul DeMarinis
Thomas Deuel
Joe Freemann
Doug Hall
Jordan Howland
Jian Kang
Sung Koo Kang
Yong Chul Kim
Paul Kos
Sangwook Lee
Julie Martin
Eamon McQuaide
Guy Merrill
Julie Nicoletta
Laetitia Sonami

Marcin Pączkowski
Juan Pampin
Jin Park
Andrew Phillips
Afroditi Psarra
John Roloff
Jewels Rottiers
Yong Deuk Seo
Ian Treasure
Robert Twomey
Bonnie Whiting
Chan Yoo

4Culture
Art+Brain Lap in DXARTS
CoMotion MakerSpace

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1. Introduction

1.1 Motivation

In the 1999 film *Being John Malkovich*, written by Charlie Kaufman and directed by Spike Jonze, puppeteer Craig Schwartz discovers a portal into respected actor John Malkovich's brain. There, he sees the world through Malkovich's eyes and experiences Malkovich's consciousness. Craig succeeds in manipulating Malkovich's body as if playing puppetry with his consciousness. This story recalls Cartesian dualism that the mind and body are distinct substances. How can the immaterial mind and the material body interact with each other? This question has long been a philosophical challenge and a source of artistic imagination.

Despite unprecedented advances in science and technology today, the mind-body problem is still mysterious. However, we have learned that human mental activity is related to the brain's neural process by accumulating much knowledge of the brain's anatomical structures and physiological functions. This research has begun with the question of what brain waves are. How do the electrophysiological signals that occur when neurons, the basic unit of the nervous system, transmit information reflect the human mind?

This dissertation seeks to explore the impenetrable aspects of the human mind through scientific inquiries and artistic metaphors. The project focuses on designing a system that enables visual and auditory devices' simultaneous performance for artistic expression in response to conscious experience. A research tool for implementing this system has employed a brain-computer interface (BCI) that enables direct and immediate communication between the brain and the machine by concurrently processing a series of tasks, such as converting neural oscillations into digital signals, extracting certain features, and operating devices electronically connected to the brain.

This work is significant in that it represents the creative vision of the brain-computer interface. Brain waves, whose frequency or amplitude vary depending on the quality and type of conscious experience, are used as a medium of communication between humans and machines within this system. This research project aims to create an instrument that can manifest the artist's inner self with animated images and cadenced sounds according to brainwave fluctuations.

This paper investigates the philosophical and biological approaches to the human mind. It puts forward the working hypothesis for creative research and artistic practice on the research subject; An Instrument Propelled by the Mind. It also describes the strategies and methods for realizing this idea, and analyzes the resulting performance-based sound installation, Illusion: You can hear, but you cannot see. This project is a journey to ask and find answers about the obscurity of the mind.

Since pioneering American composer, Alvin Lucier converted brain waves into musical sounds in his 1969 piece, Music for Solo Performer, experiments using brain waves as an artistic medium have continued. Furthermore, composing music using brain-computer interfaces has lately become a new paradigm for computer music. Hopefully, this project will bring in-depth questions and answers about the human mind and advanced science and technology in experimental art history.

1.2 Overview

This dissertation is composed of five chapters, and the remainder of it as follows:

Chapter 2: *Background* presents the working hypothesis and philosophical and historical outline by examining three areas: philosophy of mind, neuroscience, and early experimental arts. The quest for the mind has long been a playground for philosophers, but today scientists are biologically exploring the human mind. Cartesian dualism, which raised the question of causality between mind and body, triggered this transition.

The journey to discover the biological basis of consciousness began in the 1990s by Francis and Koch. This thesis work, creating an instrument for artistic expression operated by brain waves, is premised on neuroscientists' hypothesis that mental activities can be reduced to neural processes.

Chapter 3: *Methodology* provides the brain-computer interface (BCI) configuration design and the strategy for selecting the appropriate EEG. Perhaps the most critical strategy is the localization of EEG sources. This method can increase precision and overcome current BCI technology limitations, such as limited CPU throughput, by focusing on specific functions and monitoring EEGs.

A second important strategy is using a specific type of EEG related to visual stimulation as a switch to activate a custom algorithm. Humans mostly rely on vision to sense the world. Also, more sensitive parts of the body occupy a wider area of the cerebra cortex. Thus, the posterior dominant alpha rhythm, which response to the presence or absence of light stimuli, tends to be more pronounced than other EEGs.

Chapter 4: *Results* analyzes this thesis's work by dividing it into three stages of the development process, including the prototype, composition study on soundscape, and premiere, then discusses the aesthetic significance of the research project, *Illusion: You can hear, but you cannot see*.

Finally, Chapter 5: *Conclusion* briefly summarizes the contents of the dissertation and proposes future research topics.

1.3 Contribution

This thesis aims to create artistic metaphors by exploring the inscrutable human mind with a scientific approach. Concerning these research objectives, the study provides a historical survey of the correlation between the human brain and the conscious mind from a scientific perspective. Moreover, it develops an instrument for artistic expression by employing the brain-computer interface, a modern means of electrically connecting the brain and machine to communicate information.

In system design, the project adopts the EEG source localization method to overcome the current limitations of computer information processing capacity and increase the device mechanism's accuracy. Furthermore, it uses EEGs associated with a particular sensory perception as a switch to operate custom algorithms. These methods allow for brain-computer interfaces' artistic application appealing to multiple senses by creating autonomous instruments that manipulate sound sculptures and images by brain wave fluctuations.

Besides, this project implements the ideal of Cybernetics, the mutual prosperity of humans and machines, which also inherits the spirit pursued by the early experimental art movement that incorporates science and technology. It also adds a new sound art model between art and music, time and space, and performances and exhibitions in contemporary art.

2. Background

2.1 Mind-Body Problem

Since being conscious of one's existence, humans have raised the question of whether the subject of self-awareness is mind or body. The mind-body problem is a debate over causality between consciousness and the brain in the field of philosophy of mind. Mathematician and philosopher René Descartes laid the foundation for today's mind-body problem by developing dualism that the mind and brain were separable substances in the 17th century.

Descartes defines that the substance is an entity that does not need other beings to exist in his book, *Meditations on First Philosophy*. In this context, the ultimate substance is God that exists beyond the world that humans can grasp. On the other hand, humans can understand the world created by God, which consists of two kinds of finite substances: the mind (*res cogitans)* and the matter (*res extensa)*.

The essential attribute of the mind lies in thinking, while the essential attribute of the matter lies in being spatially expanded. These two are mutually exclusive. The former is entirely spiritual without material attributes, and the latter is purely physical without mental attributes. Thus Descartes argues that humans are dualistic beings, consisting of two separate entities: the mind and the body.[1]

In Cartesian dualism, the mind and body follow their respective laws. The physical body moves like a precision machine by the law of nature, and the invisible, intangible mind does not

[1] Robinson, Howard. "Dualism." *Stanford Encyclopedia of Philosophy*, Stanford University, 2017, plato.stanford.edu/archives/fall2017/entries/dualism/.

follow the law of nature. If mental events are irrelevant to physical ones or vice versa, how should we understand the causal interaction between the mind and the body?

Descartes proposed the pineal gland as "the principal seat of the soul and the place where our thoughts are formed."[2] In other words, he speculated that the tiny organ in the brain served as a kind of signal transducer, creating a close causal connection between the body and the mind. Figure 2.1 illustrates his thoughts on the role of the pineal gland. But he did not empirically prove his hypothesis.

From a modern physiological point of view, the pineal gland is a tiny endocrine that produces melatonin, which controls sleep patterns in the brain of most vertebrates. American neuroscientist Christof Koch presumes that the corpus callosum, rather than the pineal gland,

Figure 2.1. The pineal gland connects visual stimuli to the nerves in the arm, Drawing by Rene Descartes.
Image source: *L'Homme, et la formation du foetus,* Paris, 1677, archive.org/details/lhommeetlaformat00desc/page/74/mode/2up

[2] Lokhorst, Gert-Jan, "Descartes and the Pineal Gland." *The Stanford Encyclopedia of Philosophy*, 2018, plato.stanford.edu/archives/win2018/entries/pineal-gland/.

enables an integrated consciousness by coordinating the activity of the cerebral hemispheres and facilitating communication.[3] In Figure 2.2 we can identify the anatomical structure of the pineal grand and corpus callousum.

Descartes was mistaken about the pineal gland. However, the brain could gain an equal position with the mind by reaching the Cartesian dualism. By defining the mind and body as separate entities, he advocate the conventional notion of metaphysics that the mind is transcendent while paving the way for studying the brain based on mechanical philosophy.

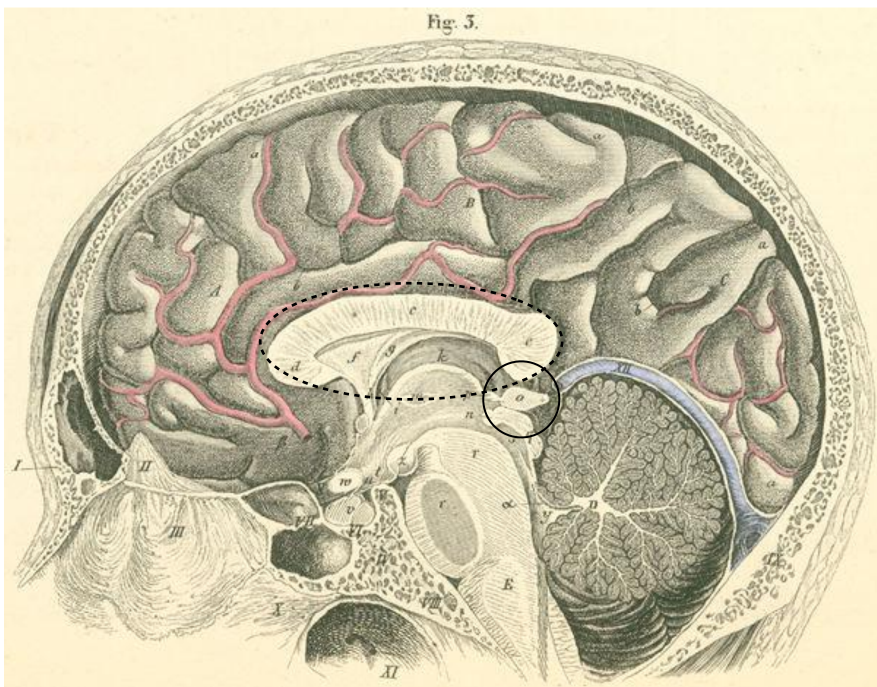

Figure 2.2. Sagittal drawing of the brain by Dr. Carl Ernest Bock, Pineal Gland (o) and Corpus Callosum (c, d, e), *Handbuch der Anatomie des Menschen*, Leipzig, 1841. Image source: Bergman, Ronald. "Atlas of Human Anatomy." *Sagittal section of brain, the surface of the medial half of the right side is seen*, University of Iowa, 27 Jun. 2014, www.anatomyatlases.org/atlasofanatomy/plate24/03sagmedialr.shtm

[3] Koch, Christof. *Consciousness: Confessions of a Romantic Reductionist.* MIT Press, 2012. p 68-70

In addition, Descartes thought that the brain was like automata, so he could explain a complex mental process through mathematics and mechanics. Descartes' question of the causal relationship between the mind and the body and his mechanistic view of the brain have become the driving force for empirical study of the conscious mind to this day.

2.2 Searching for the Biological Basis of Consciousness

Empirical Study of the Brain

The development of microscopes and staining techniques in the late 19th century made it possible to observe the nervous tissue in the brain. Italian physician Camillo Golgi contributed to uncovering the complex structure of neurons by discovering silver staining technique in 1873 when nervous tissue reacted to potassium dichromate and silver nitrate, turning neurons black,[4] as shown in Figure 2.3. This method, called Golgi stain, allowed us to closely observe each nerve cell in the brain tissue.

Spanish pathologist Santiago Ramón y Cajal researched microscopic structure of nervous system using the Golgi stain. Figure 2.4, for example, is one of his drawings that recorded observations after staining pigeon cerebellar tissue via Golgi technique. Cajal argued that the nervous system is composed of a large number of discrete single cells that communicate with each other through contact, this idea known as the neuron doctrine. The discovery of neurons laid the groundwork for the epochal advance of 20th century neuroscience.

[4] Finger, Stanley. Origins of Neuroscience: a History of Explorations into Brain Function. Oxford University Press, 1994. p. 45.

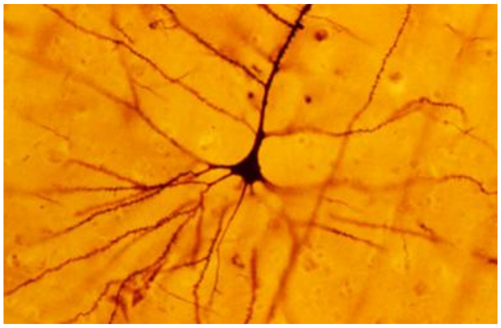

Figure 2.3. A human neocortical pyramidal cell stained via Golgi technique.
Photo by Bob Jacobs in the Laboratory of Quantitative Neuromorphology Department of Psychology Colorado College.

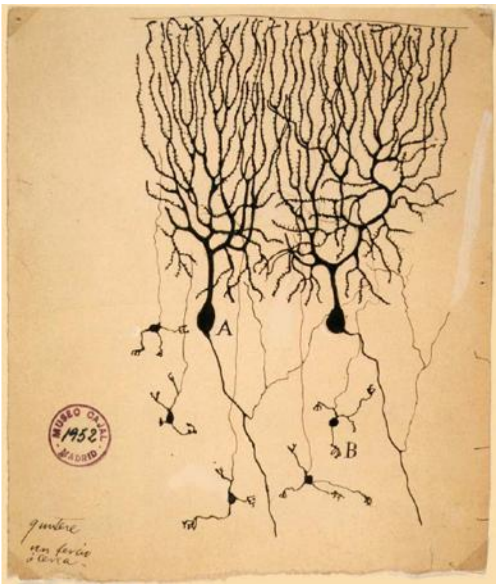

Figure 2.4. Purkinje cells (A) and granule cells (B) from the pigeon cerebellum. Drawing by Santiago Ramón y Cajal, 1899. Instituto Cajal, Madrid, Spain.

A neuron is a functional unit of the nervous system, including the brain, which is an electrically excited cell and consists of three main parts: dendrite, axon, and soma. The functional role of neurons is to convey information about sensory, motor, and cognitive events. The discontinuous junction between neurons is called synapses, where information expressed as electrical pulses is transmitted.

The human brain generally contains more than 100 billion neurons, and they make up a thousand times more synapses. These vast number of neurons and synapses form complex neural circuits and transmit information. The electrical signals that a single neuron emit when delivering information can be measured by penetrating micro-electrodes into the brain, which is called single-unit recording.

However, the human mental process is not explained solely by the action potentials of individual neurons. In addition, to quantify human brain activity, planting electrodes in the human brain is neither safe nor moral. To measure neuronal activity in the human brain, non-invasive methods are more realistic than invasive methods so far.

Typical non-invasive methods for measuring human brain activity include electro-encephalography (EEG), magnetoencephalography (MEG), functional magnetic resonance imaging (fMRI), positron emission tomograpohy (PET), and near-infrared spectroscopy (NIRS),[5] whose common purpose is to track the position of electrically activated neurons during certain mental events. Along with the development of such innovative research methods, the field of neuroscience achieved remarkable results over the past hundred years. Notable examples include the discovery of aphasia areas, functional asymmetry of left and right hemispheres, and the discovery of feature detectors. The nerves are no longer became metaphysical phenomena, but physical matter.

From the standpoint of neuroscientists today, all mental activity can ultimately be reduced to neural processes. In other words, the mind can't exist without matter. But little is known about how complex neural circuits in the brain form consciousness, even though much has been revealed about the anatomical structure and physiological function of the brain.

Biological Approach to Consciousness

Neuroscientist Francis Crick and his colleague Christof Koch proposed empirically studying consciousness within the scope of neuroscience on the premise that "consciousness emerges

[5] Axelrod, Julie. "Types of Brain Imaging Techniques." *Psych Central*, Psych Central, 17 May 2016, psychcentral.com/lib/types-of-brain-imaging-techniques/.

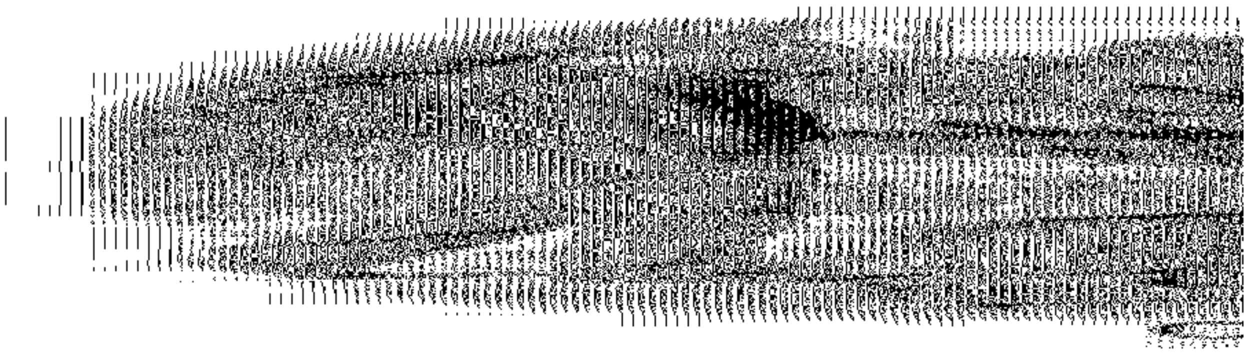

Figure 2.5. The Neuronal Correlates of Consciousness (NCC).
Image source: Koch, Christof, *The Quest for Consciousness : a Neurobiological Approach*. Roberts and Co., 2004. p.16

from the neuronal features of the brain."[6] If the biological basis of consciousness is discovered, it could explain the gap between neural events and mental events.

According to Crick and Koch's hypothesis, the neuronal correlates of visual consciousness (NCC) are the "minimal set of neuronal events and mechanisms jointly sufficient for a specific conscious percept."[7] The NCC is the physical carrier corresponding to any mental events related to the action potential emitted when the pyramidal neurons in the cortex are excited, as shown in Figure 2.5. Koch seeks to discover the NCC through an in-depth investigation of diverse and numerous neurons' interconnected neural networks. He focuses on visual awareness, excluding the self-referential aspects of consciousness associated with language or emotion to achieve such research objectives.

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[6] Koch, Christof. *The Quest for Consciousness : a Neurobiological Approach*. Roberts and Co., 2004. p.10

[7] Crick, Francis, and Koch, Christof. "A Framework for Consciousness." *Nature Neuroscience*, vol. 6, no. 2, 2003, pp. 119–126.

Visual cortex occupies the largest area of the human brain. The images detected in the retina are transmitted to the visual cortex through the lateral geniculate body (LGN). The secondary visual area is functionally divided into about thirty areas processing specific aspects of visual information, such as vertical or horizontal lines, colors, motions, or human faces.[8] The deeper visual information flows into the visual cortex, the greater the complexity of neuronal representation. For example, neurons in the primary visual cortex react selectively to partial lines of a shape, whereas neurons in the secondary visual areas respond to a full shape and neurons in the visual association cortex respond to familiar faces.

Koch deduces that the NCC, which conjures up the visual consciousness, is located somewhere in the forebrain.[9] [10] According to his hypothesis, the human becomes aware of visual representations as the visual cortex and the frontal lobe area are periodically co-activated by the neural backpropagation.[11] In particular, vivid visual perception is due to feedback loops from the higher cortical layer to the lower visual cortex.

Scientifically Investigable Problems of Consciousness

Today we know more about brain function than ever, and consciousness has become the subject for scientific research. However, we have yet to resolve the causal relationship between the human brain and the mind. The difficulty of empirical research on consciousness stems from

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[8] Bortfield, Heather. "Approach to the Mind: Introduction to Cognitive Science." *Visual Pathways*, Departments of Psychology and Cognitive & Linguistic Sciences, Brown University, 2000, cog.brown.edu/courses/cg0001/lectures/visualpaths.

[9] This thesis categorizes the human brain into three parts: forebrain, midbrain, and hindbrain. The forebrain, known as a significant part of human thinking, is divided into five parts: thalamus, hypothalamus, corpus callosum, hippocampus, and cerebral cortex.

[10] Ziolecki, Austin. "Forebrain." *Structures of the Brain*, thebrainstructure.weebly.com/forebrain.

[11] Koch, Christof, 2004.

the subjective aspect of conscious experience. For example, it is impossible to quantify introspective feelings when looking at red. This inner experience is often referred to as Qualia in the field of philosophy of mind, which is a phenomenal feature of the perceived sensation accessible only from a first-person perspective, and we cannot observe it objectively.[12]

Philosopher David Chalmers suggests dividing mental phenomena into easy and hard ones to enable scientific investigation of consciousness in his 1995 paper, *Facing Up to the Problem of Consciousness.* The hard problem of consciousness is scientifically impenetrable as it arises from Qualia that corresponds to the quality of consciousness experience. On the other side, easy problems are scientifically understandable mental phenomena.

A complete list of the relatively easy problems of consciousness, which is quantitatively researchable, presented by Chalmers is as follows:

- the ability to discriminate, categorize, and react to environmental stimuli
- the integration of information by a cognitive system
- the reportability of mental states
- the ability of a system to access its internal states
- the focus of attention
- the deliberate control of behavior
- the difference between wakefulness and sleep.[13]

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[12] Tye, Michael, "Qualia." *The Stanford Encyclopedia of Philosophy, Stanford University,* Summer 2018, Edward N. Zalta (ed.), plato.stanford.edu/archives/sum2018/entries/qualia/.

[13] Chalmers, David J. *Facing up to the problem of consciousness*. Journal of Consciousness Studies 2(3): 200-19, 1995, consc.net/papers/facing.html.

2.3 Related Works

2.3.1 Cybernetician's dream

Cybernetics

The radical development of neuroscience has inspired other research fields. As a case in point, the investigation of the human central nervous system facilitated the implementation of artificial neural networks. Neurophysiologist Warren McCulloch and logician Walter Pitts have created the first computational model of the neural network. They premised that the neuron activity is an all-or-none process, and presented the communication process of the neuron as a model of binary logic circuits consisting of 0 and 1.[14]

Meanwhile, mathematician Norbert Wiener, along with neurophysiologist Arturo Rosenblueth and engineer Julian Bigelow, published a paper that interpreted the physiological concept of homeostasis using engineering feedback circuits.[15] While McCulloch and Pitts' work modeled the human brain as a logical device, their work interpreted human behavior as a feedback circuit in the machine.

Wiener formulated the theory of cybernetics in his 1948 book *Cybernetics: or Control and Communication of Animals and Machines.* From the perspective of cybernetics, which sought to find universal principles that apply to any regulatory systems through comprehensive research on communication and control and information processing, humans and machines are systems that maintain homeostasis by the feedback mechanism that circulate information.

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[14] McCulloch, Warren, and S. Pitts. "A Logical Calculus of the Ideas Immanent in Nervous Activity." *The Bulletin of Mathematical Biophysics*, vol. 5, no. 4, 1943, pp. 115–133.

[15] Rosenblueth, Arturo, et al. "Behavior, Purpose and Teleology." *Philosophy of Science*, vol. 10, no. 1, 1943, pp. 18–24.

In Cybernetics, the human and machine pursue symbiotic relationships that cooperate through close communication, not vertical relationships in which either side controls the other. This mutual prosperity between humans and machines will eventually improve human life quality in a technologically progressive society where reliance on machines increases in daily human life.[16]

Coevolution of Man and Machine in Art

The scope of the theory of cybernetics, which began with the study of the autonomous systems of living organisms and machines, has expanded to social systems and influenced art. Nam June Paik, known as the founder of video art, has presented artworks on the co-evolution between humans and machines.[17] Paik has created an anthropomorphic robot with the aid of electronics engineer Shuya Abe and presented it at the 1964 New York Avant-Garde Festival. The *Robot K-456,* named after Mozart's Piano Concerto No. 18, was designed to act like a human being by excreting beans or playing a recording file of Kennedy's inaugural address.[18]

Paik has intended to surprise passersby by letting the *Robot K-456* walk down the street with pedestrians or spurting beans to them, as if in a Fluxus[19] performance. In a retrospective exhibition at the Whitney Museum in 1982, Paik has staged a performance that the robot was hit

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[16] Wiener, Norbert. *The Human Use of Human Beings : Cybernetics and Society*. Da Capo Press, 1988.

[17] LEE, Sooyoung, ed. NJP Reader #7 *Coevolution: Cybernetics to Posthuman*. Yongin: Nam June Paik Art Center, 2017.

[18] Hoggett, Reuben. "Robots in Art." *1964 – Robot K-456 – Nam June Paik & Shuya Abe*, 1 September 2010, cyberneticzoo.com/robots-in-art/1964-robot-k-456-nam-june-paik-korean-shuya-abe-japanese/

[19] Fluxus is the most radical experimental art movement of the 60s, which experimented with various art media and disciplines and sought the artistic process rather than the finished result. Fluxus artists believed that the aesthetic shock element caused viewers to question their reasoning and awaken them from the intuitive lethargy fostered by habit.

Figure 2.6. Staged accident with the *Robot K-456* in front of the Whitney Museum of American Art, New York, 1982. Image courtesy © Estate of Nam June Paik.

and destroyed by a car accident at the intersection of 75th Street and Madison Avenue in Manhattan, called "the catastrophe of technology in the twentieth century," as shown in Figure 2.6.

The *Robot K-456*, which can move, speak, excrete, and die like a human being with 20-channel radio-control, contains Paik's thoughts on the convergence of human-centered art and technology. This robot needs human beings to keep working, and Paik uses the robot to awaken conventional intuition's lethargy. He says that "the real problem of art and technology is not to invent new scientific toys but to find out a way to humanize technology."[20] Moreover, he has

[20] LEE, Sooyoung, ed. op. cit., pp. 393-394.

MANIFESTOS

by Nam June Paik

Cybernated art is very important, but **art for cybernated life** is more important, and the latter need not be cybernated.

(Maybe George Brecht's simplissimo is the most adequate.)

But if Pasteur and Robespierre are right that we can resist poison only through certain built-in poison, then some specific frustrations, caused by cybernated life, require accordingly cybernated shock and catharsis. My everyday work with video tape and the cathode-ray tube convinces me of this.

Cybernetics, the science of pure relations, or relationship itself, has its origin in karma. Marshall McLuhan's famous phrase "Media is message" was formulated by Norbert Wiener in 1948 as "The signal, where the message is sent, plays equally important role as the signal, where message is not sent."

As the Happening is the fusion of various arts, so cybernetics is the exploitation of boundary regions between and across various existing sciences.

Newton's physics is the mechanics of power and the unconciliatory two-party system, in which the strong win over the weak. But in the 1920's a German genius put a tiny third-party (grid) between these two mighty poles (cathode and anode) in a vacuum tube, thus enabling the weak to win over the strong for the first time in human history. It might be a Buddhistic 'third way,' but anyway this German invention led to cybernetics, which came to the world in the last war to shoot down German planes from the English sky.

The Buddhists also say

Karma is samsara

Relationship is metempsychosis

We are in open circuits

Figure 2.7. Nam June Paik's Manifesto, *We are in Open Circuits*.
Image source : Ay-o, and Something Else Press. *Manifestos*. [Something Else Press], 1966, www.ubu.com/historical/gb/manifestos.pdf

stressed the role of art to restore humanity in a technologically advanced society in his 1965 manifesto; “Cybernated art is very important, but art for cybernated life is more important,” as shown in Figure 2.7.

The mutual prosperity of machines and humans begins from creating a new junction between man and machine, rather than machine dominates human or vice versa. Paik proposed the coevolution of man and machine through art creation. Ultimately, the notion is how the convergence of art and technology contributes to humanity’s interests. This thesis seeks to fulfill our will to build a human-centered technological progressive society through the artistic application of brain-computer interfaces in Nam June Paik’s footsteps.

2.3.2 Early Experimental Arts with Electroencephalography

Electroencephalography (EEG)

German psychiatrist Hans Berger recorded the electric field of the human brain in 1924 and named it electroencephalogram.[21] Figure 2.8 shows the first recording of this spontaneous electrophysiological activity measured on the brain. The top trace is the first human EEG, and the bottom one is a 10 Hz frequency reference. The first EEG waveform, called alpha waves, has about 8 to 13 cycles per second. Most EEGs' frequency range is between 0.5 and 500 Hz, and the typical adult EEGs' amplitude is about 10 to 100 µV when measured on the scalp.[22]

EEG waveforms can be characterized based on their location, amplitude, frequency, morphology, continuity, synchrony, symmetry, and reactivity. However, the most commonly used method for classifying EEG waveforms is by frequency.[23] Neuroscience generally studies these waveforms separately for several frequency bands, including delta (0.5-4 Hz), theta (4-7 Hz),

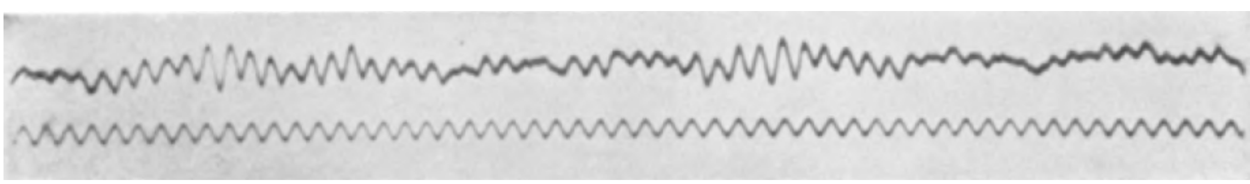

Figure 2.8. The first human EEG recorded by Hans Berger in 1924, the bottom one is a 10 Hz frequency reference.
Image source : Berger, Hans. "Über Das Elektrenkephalogramm Des Menschen." *European Archives of Psychiatry and Clinical Neuroscience*, vol. 94, no. 1, 1931, pp. 16–60.

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[21] Millet, David. *The Origins of EEG.* 3 June 2002, www.bri.ucla.edu/nha/ishn/ab24-2002.htm

[22] Aurlien, H, et al. "EEG Background Activity Described by a Large Computerized Database." *Clinical Neurophysiology*, vol. 115, no. 3, 2004, pp. 665–673.

[23] Nayak, Chetan S., et al. "EEG Normal Waveforms." StatPearls Publishing, 2020, www.ncbi.nlm.nih.gov/books/NBK539805/

alpha (8-12 Hz), beta (13-30 Hz), and gamma (30 Hz or higher). This type of research led avant-garde artists to use EEG as an artistic medium in the 1960s.

Music for Solo Performer

American composer Alvin Lucier was inspired by physicist Edmund Dewan's research[24] on EEGs and created *Music for Solo Performer,* which is considered the first piece to convert brain waves into music. This pioneering work of art, which amplified the brain waves into the audible frequency band and then sent them to the loudspeakers so that percussion instruments make sounds by the vibration, premiered in 1965 at the Rose Art Museum of Brandeis University in Waltham, Massachusetts.[25]

Lucier employed a neurological device with three silver electrodes, differential amplifiers and low-pass filters to obtain EEGs. Scalp electrodes were fixed on the forehead using paste and a headband, and the recorded EEG data transmitted to several loudspeakers via amplifiers and filters. The cone part of the speaker vibrates and makes sounds by beating various drums and other objects.[26]

Later, Lucier suggested the composition of the musical instruments to perform this piece as follows: 1 mixer with 16 outputs, 16 12-inch radius speakers, 2 bass drums, 2 snare drums, 2 timpani, 2 cymbals, 2 triangles, 1 tambourine, 1 tam tam, 1 gong, 1 grand piano, 1 cardboard box, 1 metal trash container, and 1 CD player. The CD player is for prerecorded alpha rhythms,

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[24] "1964: Brainwave control device by Edmond Dewan (1964)." *YouTube,* uploaded by The Retronaut, 18 Sep. 2014, www.youtube.com/watch?v=nCGcY6sQjcM.

[25] "Alvin Lucier - Music For Solo Performer (1965)." *YouTube,* uploaded by Carlos Conceição, 27 Nov. 2010, www.youtube.com/watch?v=bIPU2ynqy2Y.

[26] Wolf, Daniel James. "NO IDEAS BUT IN THINGS - Music For Solo Performer (1965)." 1 Jul. 2013, www.alvin-lucier-film.com/solo_performer.html.

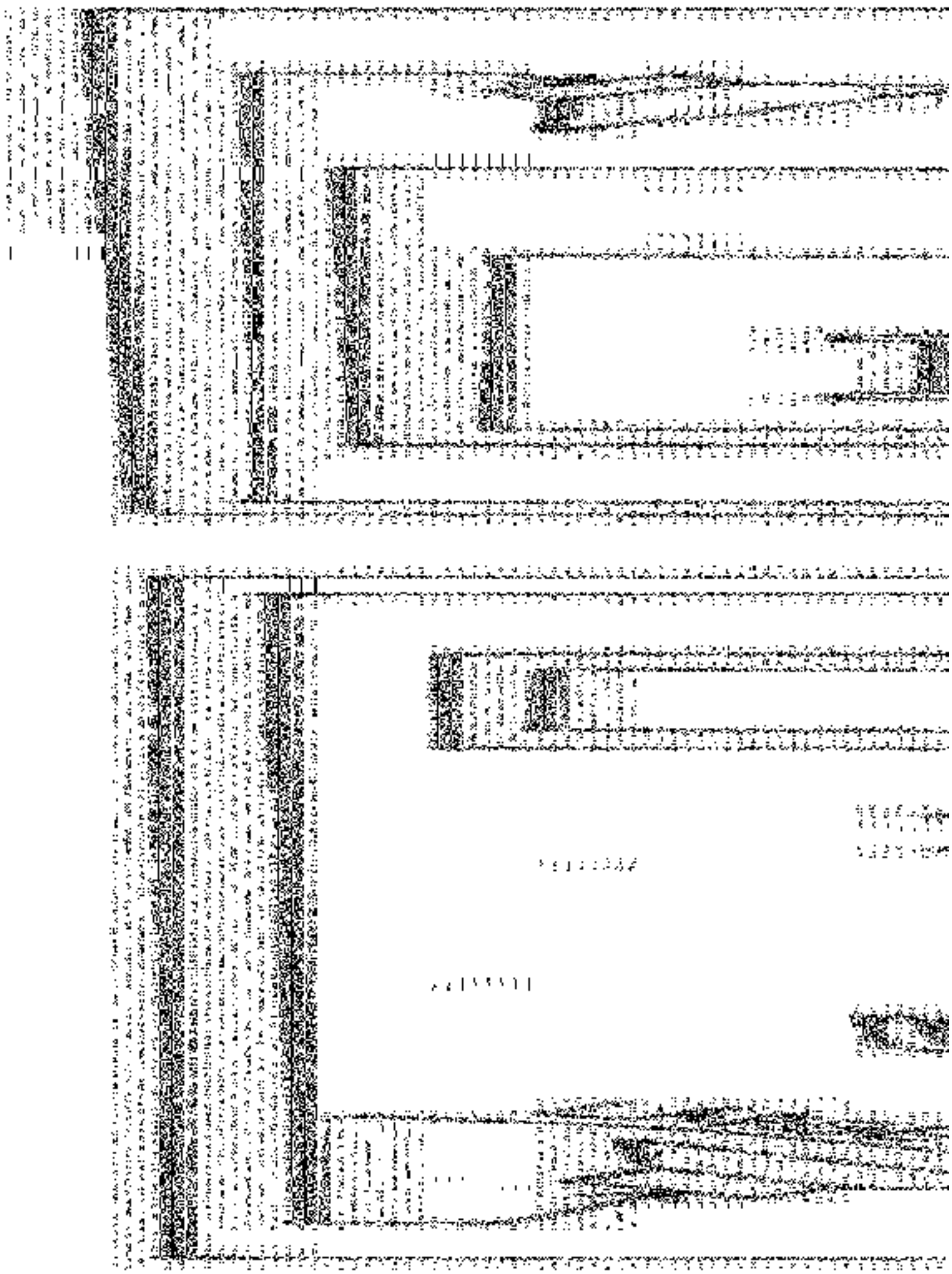

Figure 2.9. Scheme for *Music for Solo Performer* drawn by Alvin Lucier to illustrate the suggested connections for the performance.
Image source: Lucier, Alvin, et al. *Reflections : Interviews, Scores, Writings 1965-1994 = Reflexionen : Interviews, Notationen, Texte* 1965-1994. Zweite erweiterte und überarbeitete Auflage. ed., MusikTexte, 2005.

which modulated to the range of audible frequencies and played back through stereo speakers.[27] We see his idea in a scheme for *Music for Solo Performer* drawn by Alvin Lucier to illustrate the suggested connections for the performance, as shown in Figure 2.9.

Grass Field

American artist Alex Hay has designed a performance that explores the kinetic nature of human by converting brain waves, muscle activity and eye movements into sounds. It technically adopted the same principle as *Music for Solo Performer*. The electrophysiological signals recorded using electrodes such as EEG, electromyogram (EMG), and electrooculography (EOG) turn into musical sounds through differential amplifiers, voltage-controlled oscillators, transmitters, and speakers.[28]

The performance, *Grass Field,* premiered as part of *9 Evenings: Theatre and Engineering*, The 69th Regiment Armory, New York, NY, October 13-22, 1966. Alex Hay, Robert Rauschenberg, and Steve Paxton performed, David Tudor was in charge of sound.[29] Fred Waldhauer and Cecil Corker developed a portable FM transmitter with battery power in the form of a backpack.[30] In addition, outstanding engineers from Bell Telephone Laboratories and artists from various fields participated.

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[27] Straebel, Volker, and Thoben, Wilm. "Alvin Lucier's Music for Solo Performer: Experimental Music beyond Sonification." *Organised Sound : an International Journal of Music Technology*, vol. 19, no. 1, 2014, pp. 17–29.

[28] "Grass Field." *Media Art Net*, www.medienkunstnetz.de/works/grassfield/images/2/

[29] Bonin, Vincent. "Alex Hay, Grass Field: Performance." Daniel Langlois Foundation, 2006, www.fondation-langlois.org/9evenings/e/alex-hay/performance.html

[30] Deoksun, Park. *E.A.T.(Experiments in Art and Technology): Open-ended*, National Museum of Modern and Contemporary Art, 2018. pp.13

Hay placed sixty four pieces of skin colored fabric in a grid with attaching electrodes to his head and body and carrying the apparatus invented by the engineers on his back, which captured and wirelessly transmitted electrophysiological signals that occur while Hey is moving on stage or sitting down and observing the movements of the other performers. A decoder received these signals through FM radio and converted to musical sounds.

In Figure 2.10, the top part of the drawing is related to sound and the bottom part is for images and lightings. In particular, the top right corner is for the mobile device that Hay carried

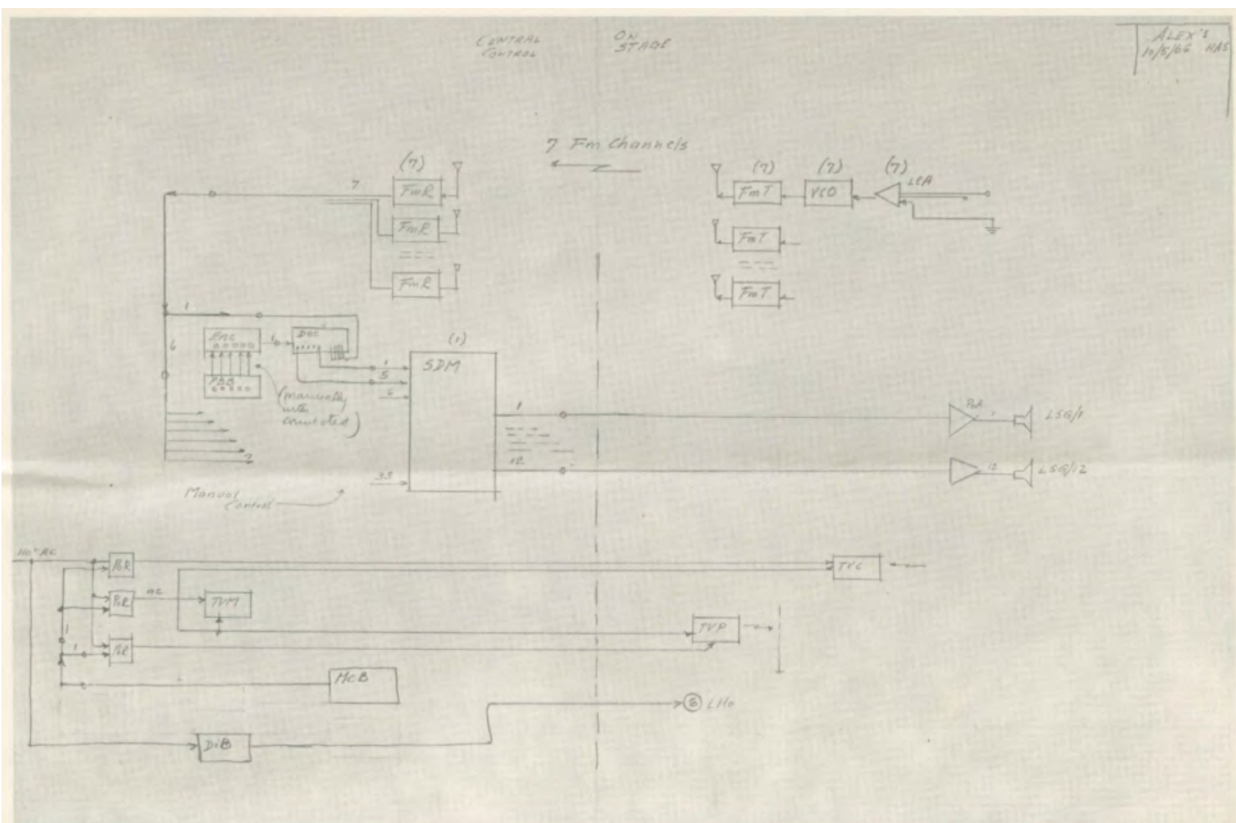

Figure 2.10. 9 Evenings Engineer Drawing for Alex Hay's *Grass Field* by Herb Schneider, 1966.
Graphite on graphic paper, 11x17 inches.
Image courtesy © Robert Rauschenberg Foundation.

on his back. They used electrodes from Grass Instrument Company, the first U.S. to market EEG equipment, and the title came from here.[31]

2.3.3 Evolution of Brain-Computer Music Interface

David Rosenboom extended Lucier's challenge of using human EEGs as an artistic medium to biofeedback arts. Rosenboom organized the *New York Biofeedback Quartet*, a multi-agent biofeedback ensemble. In the 1970s, he produced two works, *Portable Gold and Philosophers Stones works*, the first with the subtitle *Music with Trill*, and the second with the subtitle *Music from Brains in Four*. In the second work, rather than tracking several frequency bands in one performer's brain for musical results, he advanced a significant BCMI paradigm by analyzing and processing EEGs detected in four performers' brains.

In the 1980s, Hugh Lusted and Benjamin Knapp invented a new type of musical instrument that drives a keyboard synthesizer by analyzing bioelectrical signals such as Electromyography (EMG), Electrocardiography (ECG), Electrooculography (EOG) as well as EEG.[32] This instrument, called the *BioMuse*, was widely known in the 1990s when Atau Tanaka played on the Sensorband.[33]

With the spread of digital technology, the interface development for musical expression has also taken a new turn. Computers have become a tool to aid or generate music compositions by

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[31] Bardiot, Clarisse. "Alex Hay, Grass Field: Diagram." Daniel Langlois Foundation, 2006, www.fondation-langlois.org/9evenings/e/alex-hay/diagram.html

[32] Lusted, Hugh S, and Knapp, R. Benjamin. "Biomuse: Musical Performance Generated by Human Bioelectric Signals." *The Journal of the Acoustical Society of America*, vol. 84, no. S1, 1988, p. S179, asa.scitation.org/doi/10.1121/1.2025994.

[33] "Sensorband performing at Paradiso in Amsterdam on 21 August 1994," *eContact! Online Journal for Electroacoustic Practices,* Video by d.g. graber 1995, econtact.ca/14_2/tanaka_gallery.html

introducing digital signal processing technology. The brain-computer music interface, which converts brain waves into digital signals and modulates and synthesizes them to create music simultaneously, has become a new paradigm of computer music.

Rosenboom, who has been continuously exploring biofeedback arts since the 1970s, collaborated with Tim Mullen and Alex Khali to produce *Ringing Minds* in 2014. This work adopted a hyperscanning technique to analyze multi music listener's brains.[34] This technique allows the simultaneous recording of different subjects' brain activity, allowing the study of inter-brain correlations between a group of interacting subjects' cerebral activities a unique system.[35]

The second version of *Ringing Minds* was on stage at the 2015 Whitney Museum's Rosenboom retrospective. This version added moving images in cooperation with Matt Wachter and Glenn Snyder. These images show an artistic visualization of the corresponding components of the EEG analysis and music generation system.

Two recent works, *The Encephalophone and Human Subjects*, most closely influenced the *Illusion* project. Neurologist Thomas Deuel's *Encephalophone*[36] premiered at the 2015 Megapolis Audio Art Festival in Oakland and San Francisco. It is a musical instrument controlled by the posterior dominant rhythm (PDR) and mu rhythm. Both rhythms belong to the same alpha frequency band but differ in the areas detected. PDR is recorded in the visual cortex

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[34] "David Rosenboom: Propositional Music - 2015 Retrospective at the Whitney, Day 2." *Vimeo*, uploaded by David Rosenboom, 2017, whitney.org/events/david-rosenboom-ringing-minds

[35] Babiloni, Fabio, and Astolfi, Laura. "Social Neuroscience and Hyperscanning Techniques: Past, Present and Future." *Neuroscience and Biobehavioral Reviews*, vol. 44, 2014, pp. 76–93.

[36] "Encephalophone - Direct Brain Music Interface Instrument." *Deueling Thumbs StudioLab*, www.deuelingthumbs.com/brain-music-instrument/

Figure 2.11. Still image from the documentation film “Human Subjects.”
Image sauce: “Human Subjects.” Directed by Laura Stayton and Adam Hogan, *Amazon Prime Video*, 4 Dec. 2020. www.amazon.com/Human-Subjects-Richard-Karpen/dp/B08P1PV8LK

and mu in the motor cortex. With this instrument, a musician can improvise, and patients with a motor disability are healed and entertained by playing music with brain waves.[37]

Deuel’s research directly affected DXARTS’ Art+Brain Lab at the University of Washington. Composers Richard Karpen and Juan Pampin collaborated with the JACK Quartet to explore new algorithmic composition methods and extended performance techniques based on brain and nervous system sensing. As a result, *Human Subjects*[38] has premiered at the Meany Hall - Katharyn Alvord Gerlich Theater on May 18, 2019, as shown in Figure 2.11.

Human Subjects, created through a three-year generative process, acquires JACK members’ EEG and their electromyography (EMG) data while playing their instruments. During the live

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[37] “Meany_TownHall_Combined_Final_4.” *Vimeo*, uploaded by Thomas Deuel, 11 Nov. 2019, vimeo.com/372516748

[38] “Human Subjects.” Directed by Laura Stayton and Adam Hogan, *Amazon Prime Video*, 4 Dec. 2020, www.amazon.com/Human-Subjects-Richard-Karpen/dp/B08P1PV8LK

performance, massive amounts of data collected from four EEG headsets and eight EMG armbands are streamed in realtime to algorithms running in SuperCollider, a music/audio programming language, to expand the quartet's performative sonic capabilities.

2.3.4 Brain-Computer Interface in Contemporary Art

Brain-computer interfaces (BCI) was used not only to produce music but also to manipulate images. Mariko Mori created Wave UFO in 2003 using BCI as an artistic tool. Three participants can lie down in her installation, called UFO, and their brain waves transform images projected onto walls and ceilings. The brain waves detected in the participant's left and right hemispheres show each of the six orbs in different colors depending on their frequency. For example, delta and theta waves are yellow, beta waves are pink, and alpha waves are blue. And when all three participants' brain waves are in sync, some small orbs become brightened.[39]

Recently, various noninvasive EEG-based BCI devices have been on the market along with low-cost entry-level models such as Muse or NeuroSky, and the entry barrier of BCI technology has also been relatively low. Artists have more choice of tools. Therefore, works using brain waves as an artistic medium have also diversified. For example, Lisa Park transformed brain waves into ripples in her 2013 *Eunoia*,[40] Maurice Benayoun into 3d prints in his 2016 *Brain Factory*,[41] and Emanuel Gollob into ciliation's smooth movements in his 2019 *Doing Nothing with AI*.[42]

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[39] Nijholt, Anton. Brain Art: Brian-Computer Interfaces for Artistic Expression. Springer, 2019. pp.16

[40] "Eunoia." *Lisa Park*, www.thelisapark.com/work/eunoia

[41] "The Brain Factory." *YouTube*, uploaded by Maurice Benayoun, 14 Mar. 2018, www.youtube.com/watch?v=GrLA9kaWBPc&feature=emb_logo&ab_channel=MauriceBenayoun

[42] "Doing Nothing with AI 1.0." 2020, www.emanuelgollob.com/doing-nothing-with-ai/

On the other hand, SymbioticA at the University of Western Australia and Neuroengineering Lab at Georgia Institute of Technology jointly conducted the neurorobotics project *MEART* in the early 2000s. They built a drawing machine controlled by a neural network of the rat cortex cultured in an *in vitro* microelectrode array (MEA), as shown in Figure 2.12. This project seems to embody Cartesian dualism that the mind and body are separate substances in a unique way.

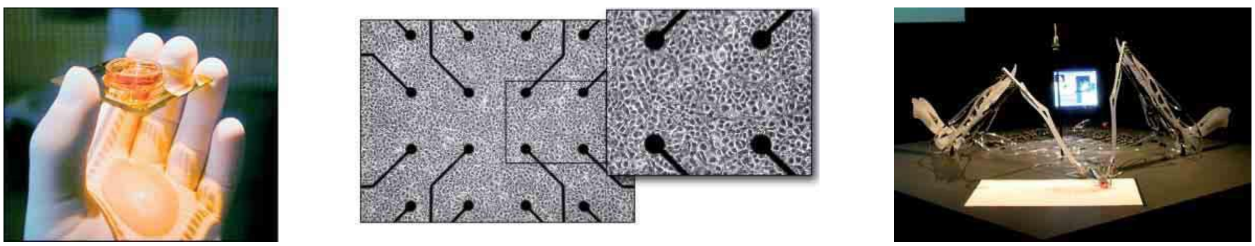

Figure 2.12. MEART's Brain (left), MEA (middle), and Body (right).
Image sauce: Bakkum, Douglas J, et al. "MEART: The Semi-Living Artist." *Frontiers in Neurorobotics*, vol. 1, 2007, p. 5.

MEART's brain, a network of rat cortical neurons, lives in an MEA culture dish in Potter's lab in Atlanta. Fifty-nine micro-electrodes enable the brain to communicate with its body by recording neural activity in an MEA culture dish extracellularly or evoking it by electrical stimulation. *MEART's* body, two perpendicular robot arms with a charge-coupled device camera, can produce 2D drawings in any place, including Melbourne, Bilbao, New York, Moscow, and Shanghai. Pneumatic artificial muscles actuate the arms. *MEART's* brain and body communicate in real-time over the internet, store memories digitally, and draw images through these learning and memories.

This work integrates 'Wetware' – neurons from embryonic rat cortex grown in a culture dish, 'Hardware' – the robotic drawing arm, and 'Software' – that interfaces between the wetware and the hardware.[43] The *MEART* project responds to Descartes and Cybernetics' questions while raising numerous questions about the mind and the artificial and living things. Above all, this work suggests that humans can create "thinking entities."

[43] Shanken, Edward A. *Art and Electronic Media*. Phaidon Press, 2009.

3. Methodology

3.1 Strategies

3.1.1 EEG Source Localization

The project monitors brainwaves only in the local area related to visual perception, based on the hypothesis of localization of the brain function. For example, damage to parts of the brain that are responsible for language causes aphasia.[44] If different parts of the brain are related to different functions, it is necessary to monitor the EEG source associated with a specific task for the purposes, not the whole brain.

The functional areas of the cerebral cortex are generally divided into three categories: sensory, motor, and association. The sensory areas receive and process data from the senses and include the primary visual cortex located in the occipital lobe. The motor areas are related to the spontaneous movement of the body, and the association areas are involved in the higher functioning of the brain, such as storing information or abstract thinking.

German anatomist Korbinian Brodmann defined the cerebral cortex of primates into 52 regions, as shown in Figure 3.1, by examining their neural tissue in 1907. This classification by Brodmann is known to be related to various cortical functions today. For example, Brodmann area 4 is the primary motor cortex and area 17 is the primary visual cortex. In this way the cerebral cortex is locally associated with different cognitive and behavioral functions.

[44] French physician Pierre Paul Broca dissected two aphasia patients after their death and found that the same part of the cerebral cortex was lesioning. This region associated with the language processing in the frontal lobe was named Broca's area after him.

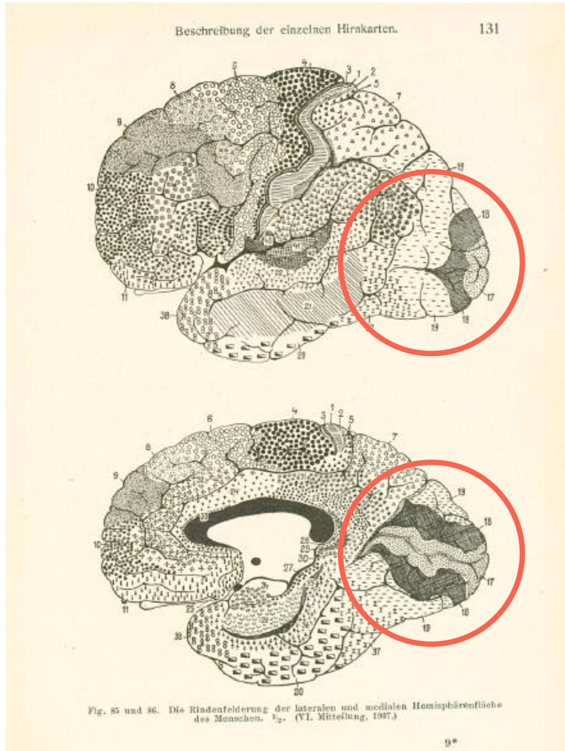

Figure 3.1. Brodmann Areas.
Image source: Brodmann, K. *Vergleichende Lokalisationslehre der Großhirnrinde,* Leipzig: Barth, 1909, digital.zbmed.de/physische_anthropologie/content/pageview/711836

Areas specifically relevant to visual perception are those marked with red circles corresponding to 17, 18, and 19 in Figures 3.1. Visual information is passed directly on to Brodmann Area 17 via the thalamus, then moved to 18 and 19, forming a more complex neural network to process more detailed information. This project records EEGs only in these cerebral cortex areas directly related to the processing of visual information.

The brain's electrophysiological response to light stimulation serves as a switch for turning sound on and off in a system for artistic expression applied with brain-computer interface technology. Such a methodology is a strategy to create synesthetic metaphors that appeal to hearing through visual images or vice versa, as in the title of the work supported by this dissertation, *Illusion*: *you can hear, but you can't see.*

3.1.2 Closed-loop Interaction

The brain-computer interface (BCI), in general, connects the brain to a computer electronically, converting physiological signals that occur when neurons transmit information into digital signals, allowing the computer to interpret them. The EEG-based BCI adopted in this paper consists of EEG data collection, analog to digital signal transformation, data analysis, and feature selection. This project adds sound to these standard EEG-based BCI configurations.

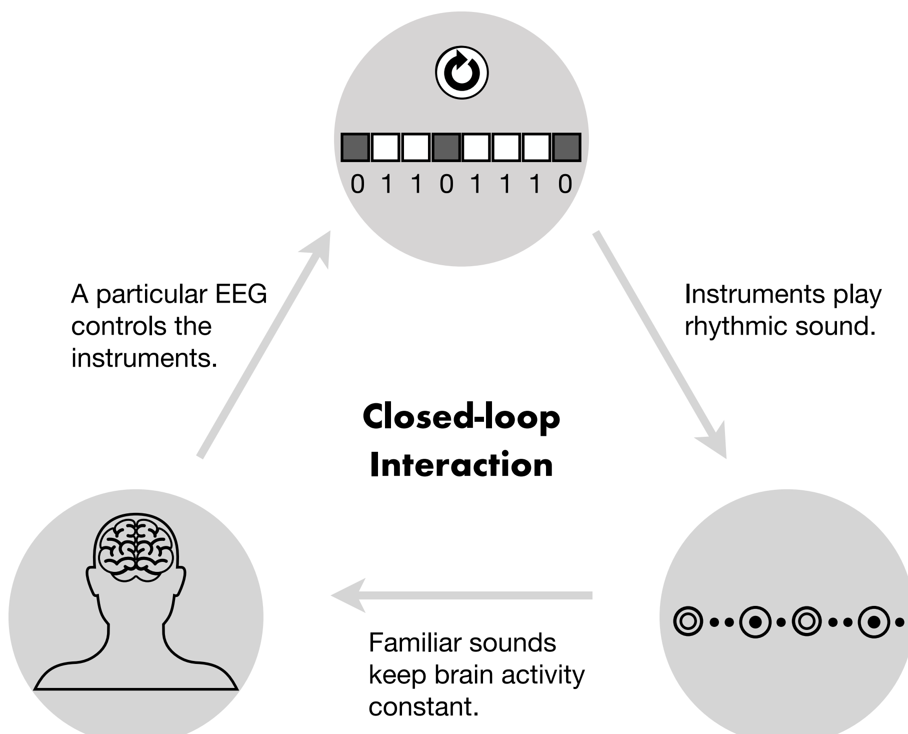

Figure 3.2. Closed-Loop EEG Biofeedback Mechanism (Image © Haein Kang.)

Sound is one of the most emotive materials in creating art. The brain-computer music interface can use the affective component of sound as a closed-loop method to steady emotions or an open-loop method to induce various emotions. This project strategically adopts the closed-loop interaction method to maintain constant brain activity with feedback on familiar sounds, as shown in Figure 3.2. Therefore, the gradually changing soft tapping sound acts as a mediator between the mind and the machine, allowing the performer to provide stable EEG information to the BCI system.

The three elements of human, instrument, and sound constitute the closed-loop EEG biofeedback mechanism that circulates energy sequentially. In the system designed by this thesis, a specific EEG operates sound devices, and the instruments play rhythmic sounds that vary with algorithms, and the sounds that vary with algorithms keep the performer's brain activity constant. The closed-loop EEG biofeedback mechanism using sound is a strategy to enable the performer's specific EEG to act more accurately as a switch.

3.1.3 Posterior Dominant Rhythm as an Actuator

This project's BCI is an on-off control system that coordinates external devices by specific EEG data in terms of technology. When the visual stimulus is blocked while still conscious, particular brain waves appear. These neural oscillations, especially in the frequency range of about 8-13 Hz observed in the occipital lobe, is called Posterior Dominant Alpha Rhythm (PDR) in neuroscience. This project's algorithm is designed to activate the sound mechanism when detecting the PDR.

On the artistic side, this method of inducing PDR leads to the performer's motion. To block visual stimuli, the performer makes the most routine and static movement, blinking their eyes.

The performer is sitting in a chair, and sound devices set behind the performer. The instrument makes a gentle tapping sound or silence following the movement of opening and closing their eyes. When you close your eyes, you can hear but not see.

3.2 System Configuration

This project employs an electroencephalography-based brain-computer interface (hereafter EEG-based BCI) as a research tool. The method of obtaining EEG data is divided into two, depending on the location of the electrode. They are invasive techniques that attach electrodes directly to the cerebral cortex and non-invasive techniques that attach electrodes onto the scalp. The non-invasive technique is less resistant than invasive methods and more portable than fMRI, making it suitable for performance arts.

This project's BCI configuration consists a total of four stages: EEG data acquisition and analog-to-digital conversion, digital signal processing, feature selection, and external mechatronic device control, as shown in Figure 3.3. The first phase acquires EEG data with a

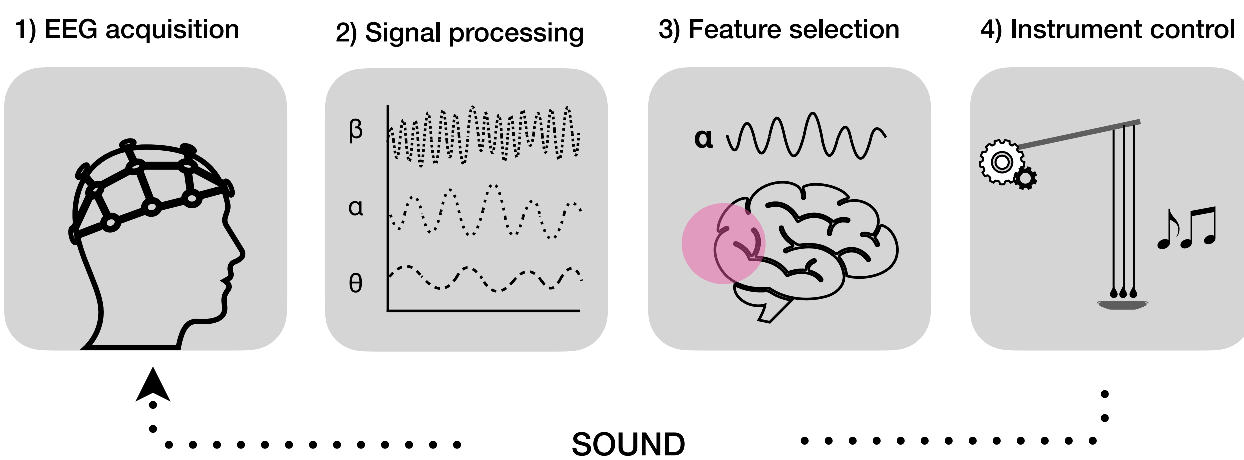

Figure 3.3. BCI Configuration of *Illusion* (Image © Haein Kang.)

non-invasive technique, and the second phase applies filters to the EEG data converted into digital signals. In the other two phases, custom algorithms and mechatronics have been designed to monitor individual brain waves' appearance and make intended sounds. In the third phase, Feature Selection, the custom algorithm detects the emergence of PDRs. Finally, in the fourth phase, eight modules of custom percussion instruments that communicate through wireless communication produce cadenced sounds. As a result, the BCI system produces rhythmic sounds that induce the performer to generate consistent EEG data.

3.2.1 EEG Data Acquisition

This project uses a high-quality open-source BCI system provided by OpenBCI. For the first phase EEG data collection, the headwear is 3D-printed using STL files provided by OpenBCI.[45] A Cyton board is equipped on the headwear's backside, an Arduino compatible, eight-channel neural interface with a 32-bit processor. This board amplifies, digitalizes, and transmits the raw EEG data to the OpenBCI GUI to process digitized EEG data to reduce artifacts and facilitate the extraction of specific features.

The first step in the EEG-based BCI is to place electrodes in the scalp to detect subtle analog signals. The 3D-printed EEG headwear, both Ultra-Cortex Mark III-Nova and Ultra-Cortex Mark IV, is designed to mount dry EEG electrodes in the required location according to the International 10-20 system. The dry electrode coated with conductive Ag/AgCl (Silver/Silver Chloride) does not require conductive gel, making it more convenient for the performer and more durable for long-term performance.

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[45] Ultra-Cortex Mark III-Nova is used for the prototype and Ultra-Cortex Mark IV for Gallery 4 Culture's opening performance. Mark IV's STL files for 3d printing are available from https://github.com/openbci-archive/Docs/tree/master/assets/MarkIV/STL_Directory

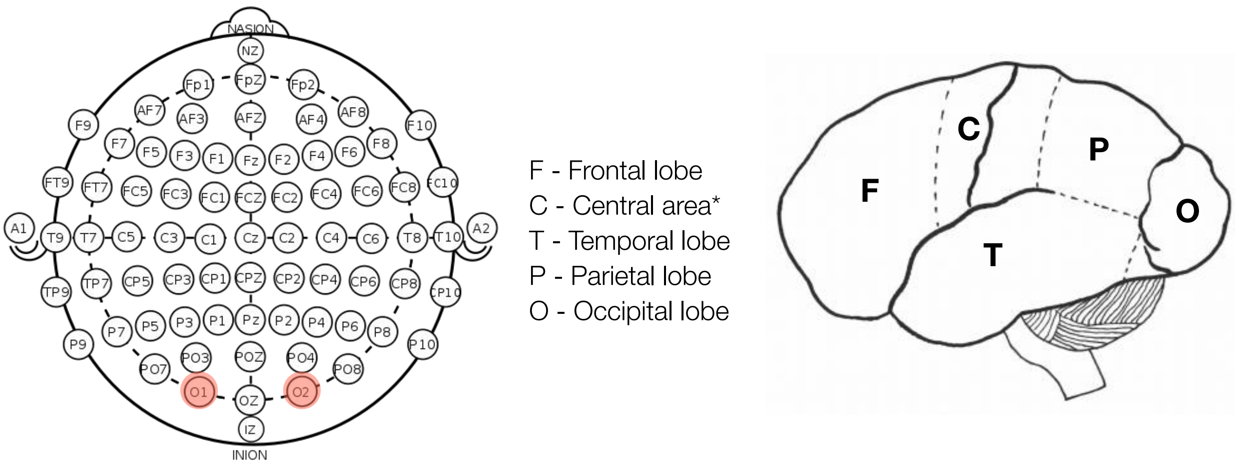

Figure 3.4. Relationship between the location of electrodes in the International 10-20 system and the area of the cerebral cortex

As shown in Figure 3.4 Left, the International 10-20 system is an internationally approved method for placing electrodes onto the scalp in non-invasive EEG research. The 10-20 system allows us to obtain EEG data from relatively identical positions from several subjects. It is also possible to systematically analyze and compare EEG data recorded in repetitive experiments.

Besides, the naming code for electrode locations in the 10-20 system is related to the structural classification of the cerebral cortex. As shown in Figure 3.4 Right, the letter F refers to the frontal lobe, T to the temporal lobe, P to the parietal lobe, and O to the occipital lobe. The central lobe does not exist, and the central area means the cortical area around the central sulcus, including the primary motor cortex and the primary sensory cortex.

This project limits EEG source to the primary visual cortex to obtain EEG data that respond to the light stimuli. These electrode locations are O1 and O2 in the 10-20 system, as shown by the red dots in Figure 3.4. Thus, the project collects the performer’s raw EEG data from EEG electrodes mounted in O1 and O2 positions in the EEG headwear. In theory, we can obtain similar EEG data from both sides. However, there is a high possibility that artifacts will be added depending on electrode and scalp contact.

3.2.2 Signal Processing

In the second phase, signal processing, the OpenBCI GUI receives and processes digitized EEG data to reduce artifacts and facilitate the extraction of specific features. Raw EEG data recorded from the scalp is a very subtle analog signal. The application of computer technology requires amplification and digitalization of the raw data. The Cyton board, a biosensing board, mounted on the back of the Ultra-Cortex Mark III and IV EEG headwear, amplifies and digitizes the raw EEG data and transmits it to software embedded on the main computer.

This project uses the graphical user interface (GUI) provided by OpenBCI as software for signal processing. The OpenBCI GUI is designed for intuitive observation by selectively applying filters such as a notch filter, a bandwidth filter, and a fast Fourier transform (FFT) plot to EEG data. This GUI is also run on Processing Integrated Development Environment (IDE) environment, facilitating data sharing with other software and hardware that make up the project's audiovisual system.

Perhaps the most crucial part of signal processing is artifact elimination. Since the non-invasive EEG technique acquires EEG data above the skull, it contains many biological and environmental artifacts, unlike the intracranial EEG obtained directly from the cerebral cortex. Biological artifact means an electrical signal detected in the scalp due to eye movement, heartbeat, facial muscle movement. The OpenBCI GUI has built-in functions for eliminating artifacts, such as a 60 Hz notch filter and a bandpass filter.

The environmental artifact may also be added to EEG data due to the subject's movements, inferior grounding electrodes, or adjacent electronic equipment. The subject should be located at least 70 centimeters or 27.5 inches away from electronic equipment, including computers, to avoid such environmental artifact.

3.2.3 Feature Selection

EEG studies generally analyze the amplitude or frequency of EEG, spontaneous electrical activity of neurons. The project collects EEG data from the scalp and focuses on the scalp EEG frequency acquired in the visual cortex area. The fast Fourier transform (FFT) algorithm converts EEG data from a time domain to a frequency domain. After applying the FFT algorithm to the digitalized EEG data in the OpenBCI GUI, the data with frequency information is sent to a custom algorithm designed to monitor PDR and operate sound mechanisms through the protocol, Open Sound Control (OSC).[46]

PDRs are generally known as 7.5 to 15 Hz, but EEGs vary by age, gender, and individual. The tolerance for PDR is 7.5-15 Hz. The older the age, the slower the EEG is, and the faster this trend is for men than women. EEG data for young people under the age of 26 is not yet mature. For example, PDR can be slower than 8 Hz for young children. Therefore, it is essential to pre-calibrate the code by examining the scope of the performer's PDR.

If the PDR is true, the custom algorithm moves on to the next stage to activate the sound mechanism and change the image. Otherwise, the workflow returns to the data collection stage and repeats the previous process of purifying the data and extracting the features. Figure 3.5

[46] Open Sound Control (OSC) is a protocol for communication between computers and other multimedia devices, developed by UC Berkeley Center for New Music and Audio Technology, 2002, opensoundcontrol.org/spec-1_0

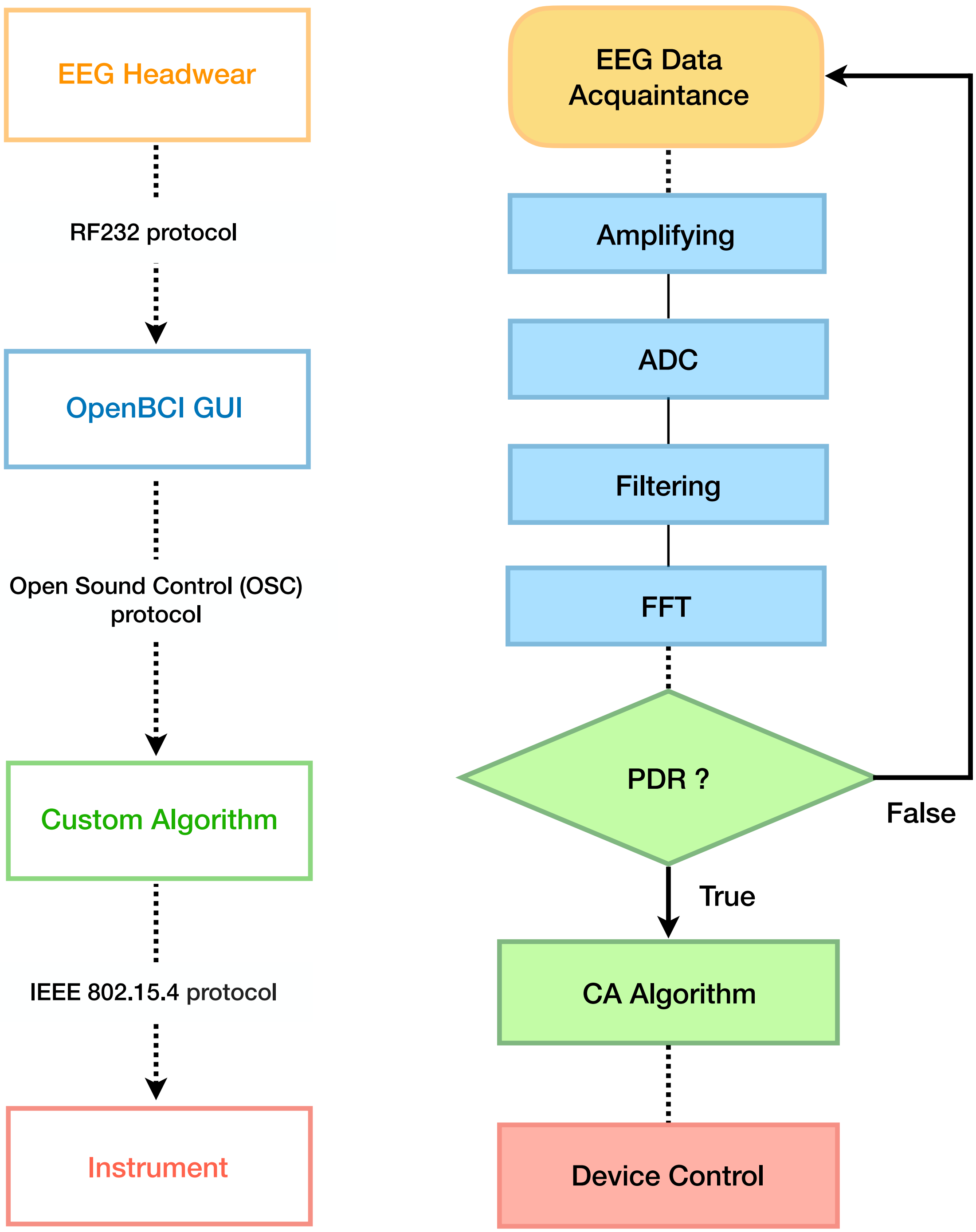

Figure 3.5. Flowchart of an EEG Data Processing Algorithm for *Illusion*.
(© Haein Kang.)

illustrates the EEG data processing procedure for the project.

3.2.4 External Device Control

The custom algorithm running on the main computer determines which of the eight percussion modules will be activated when the BCI detects a PDR. The computer transmits signals to eight custom mechatronic devices via the Xbee RF module that enable wireless communication using the IEEE 802.15.4 protocol. A total of nine Xbee modules are connected and communicated in a star network[47] topology method, combining one coordinator mounted on the main computer and eight receivers mounted on the eight instruments.

The presence of PDR also changes the image. Image switching is an aesthetic solution to unify various elements such as sound, performance, kinetic sculpture, and brainwave. When the performer closes their eyes, a closed-eye image appears with a soft tapping sound, and when they open their eyes, an opened-eye image appears in silence.

3.3 Sound Mechanism

This project falls into the brain-computer music interface (BCMI) category. While typical BCMI converts EEG data directly into electronic sounds, the project selects a particular EEG data to play its custom-made percussion instruments. Eight modules of mechatronic devices produce acoustic sounds by tapping various materials according to the one-dimensional cellular automata algorithm. The soft tapping sound, represented the raindrops, leads a journey into the inner world.

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[47] A star network is a simple form of computer network topology in which all hosts are connected to one central hub. This central hub acts as a channel for message delivery.

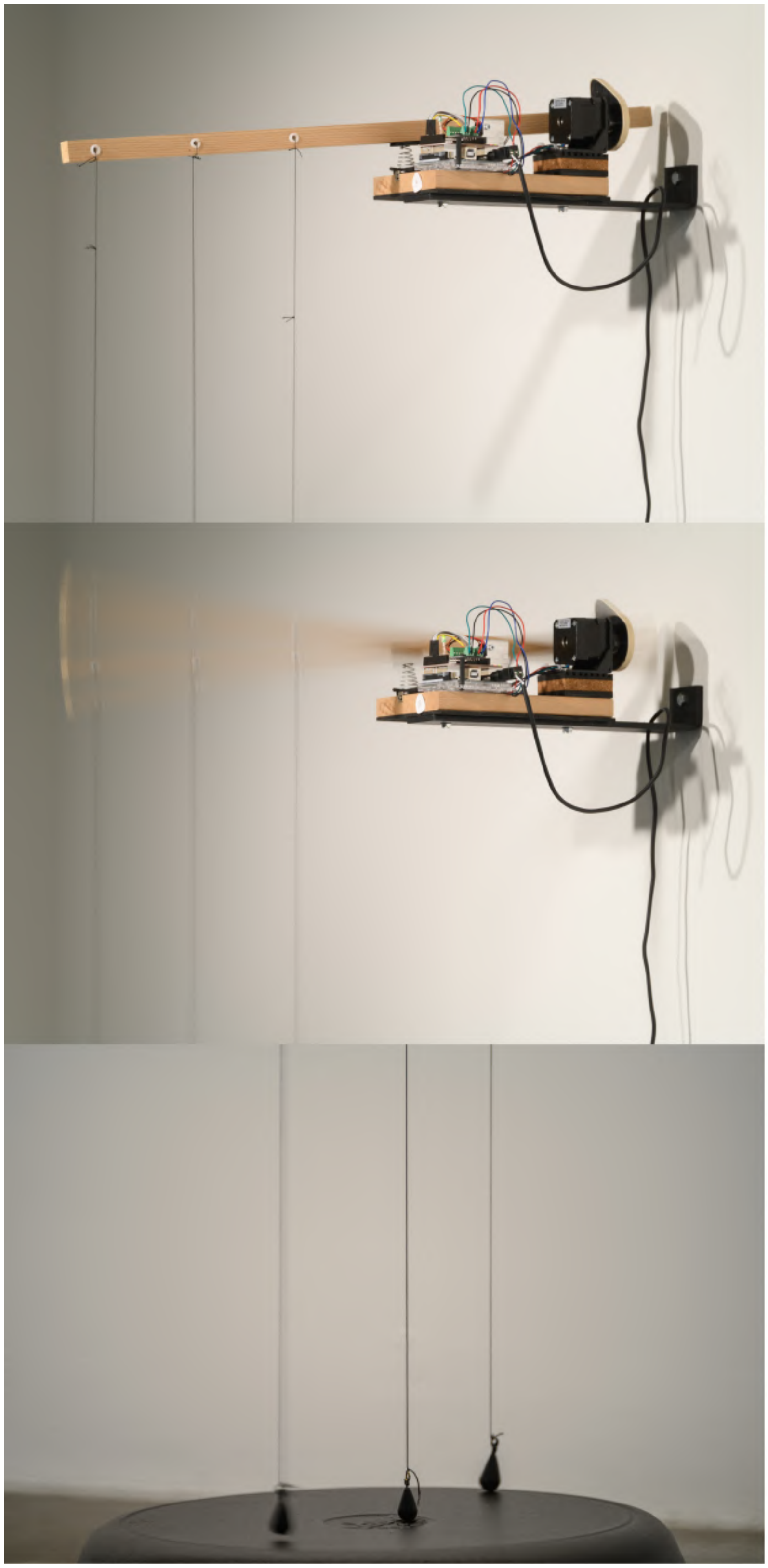

Figure 3.6. Details of the Sound Mechanism (Photo by Joe Freemann.)

3.3.1 Custom Percussion Instruments

The sound mechanism consists of eight custom automated percussion instruments. Each instrument has a microcontroller, a cam-mounted stepper motor, and a rudimentary arm with several weights hanging down from the elastic threads. Figure 3.6 illustrates the details of the sound mechanism. This automated control system consists of an Arduino Uno board, a motor driver, and an Xbee module to receive operating signals from the central computer and activate the stepper motor.

When the motor shaft starts to rotate, the egg-shaped cam rotates and hits the arm. The arm's 3/4 point is fixed to the rotation axis, and the two springs bounce the arm like a seesaw. As these eight arms go up and down, rubber-coated fishing weights dangling from the end of them beat different eight objects to make sounds. These objects found in everyday life have different tones respectively.

Figure 3.7. Custom Percussion Instruments (Photo: Joe Freemann.)

The objects that make up the instrument are a wooden tray, a thin iron pan, a glass dome, a tom-tom drum, a tin lid, a ceramic plate, a thick iron pan, and an apple box in turn from the left, as shown in Figure 3.7. According to the classification criteria of traditional percussion instruments, the tom-tom drum is a membranophone, and the other seven percussions are idiophones. Their arrangement considers the harmony of individual timbre and loudness. The objects with similar timbre place symmetrically, while louder items place outward.

In the early stages of the Illusion project, the weights dangling from the robot's arms knocked on the floor, vibrating the space to make sounds. However, the encounter with percussionist Bonnie Whiting led to various objects' collection and experiment to produce adjustable and musical sounds. Her studio was full of miscellaneous things, and she showed practical principles for vibrating multiple items to make and control sounds.

Composer Jonty Harrison made a piece of electroacoustic music out of the attack or resonant sounds recorded by tapping or rolling the lids of two earthenware casseroles on the bowls in 1982 *Klang.*[48] Composer and instrument creator Harry Partch created a unique custom-made instrument in 1950, *Cloud-Chamber Bowls,*[49] *a* percussion instrument that suspends fourteen bowls made by cutting off 12-gallon Pyrex carboys on a wooden frame.[50]

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48 “Klang.” *YouTube,* uploaded by Jonty Harrioson, 3 Aug. 2015, www.youtube.com/watch?v=_iOV7LSqLUE&ab_channel=JontyHarrison-Topic

49 “Cloud-Chamber Bowls” *YouTube,* uploaded by Harry Parch - Topic, 8 Nov. 2014, www.youtube.com/watch?v=OfZrNaLxH-0&ab_channel=HarryPartch-Topic

50 Partch, Harry. Genesis of a Music : an Account of a Creative Work, Its Roots and Its Fulfillments. 2d ed., enl. ed., Da Capo Press, 1979.

In addition, a Korean Music genre, *Samulnori*,[51] musically expresses weather changes by tapping four percussion instruments, namely Kkwaenggwari, Janggu, Buk, and Jing, respectively, meaning thunder, rain, cloud, and wind. The combination of DXARTS' experimental music and Koreans' ethnic cultural heritage has given the idea of tapping everyday objects to express the sound of raindrops musically.

3.3.2 Generative Rhythm Algorithm

The sound mechanism design focuses on embodying the artistic metaphor both in hardware and software: "If we close our eyes, raindrops fall on the roof, the window, the desk, and everything in the universe, knocking on the mind." When the performer closes their eyes, the algorithm calculates the next-generation rhythm set and enables instruments to play autonomously. The gradually changing rhythmical sound is an integral part of the close-droop musical biofeedback, which appeals to the performer's sensibility. The project designs an algorithm to produce the gentle tapping sounds continuous but with different tones each time by applying an elementary cellular automaton developed by Stephen Wolfram.[52]

According to this one-dimension cellular automaton theory, each cell has two possible states; 0 and 1. The state combination of three cells, two adjacent and one reference cells, determine the next-generation cell's state.[53] In this project, if we replace each sound device with a single cell, it

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[51] "[Open Stage 2018: Samulnori] 40th Anniversary Special Video." *YouTube,* uploaded by Korean Cultural Center New York, 2 Feb. 2018, www.youtube.com/watch?v=qcNGtWVhdgk&ab_channel=KoreanCulturalCenterNewYork

[52] Wolfram, Stephen. "Statistical Mechanics of Cellular Automata." Reviews of Modern Physics, vol. 55, no. 3, 1983, pp. 601–644, www.stephenwolfram.com/publications/academic/statistical-mechanics-cellular-automata.pdf

53 Weisstein, Eric W. "Elementary Cellular Automaton." *MathWorld*, mathworld.wolfram.com/ElementaryCellularAutomaton.html

Current State	On-On-On	On-On-Off	On-Off-On	On-Off-Off	Off-On-On	Off-On-Off	Off-Off-On	Off-Off-Off
New State	Off	On	On	Off	On	On	On	Off

Table 3.1. Elementary Cellular Automata - Rule 110 (© Haein Kang.)

	Device 1	Device 2	Device 3	Device 4	Device 5	Device 6	Device 7	Device 8
Gen 00	Off	On	On	Off	On	On	On	Off
Gen 01	On	On	On	On	On	Off	On	Off
Gen 02	On	Off	Off	Off	On	On	On	On
Gen 03	On	Off	Off	On	On	Off	Off	Off
Gen 04	On	Off	On	On	On	On	Off	On
Gen 05	On	On	On	Off	Off	On	On	On
Gen 06	Off	Off	On	Off	On	On	Off	Off
Gen 07	Off	On	On	On	On	On	Off	Off
Gen 08	On	On	Off	Off	Off	On	Off	Off
Gen 09	On	On	Off	Off	On	On	Off	On

Table 3.2. Cellular Automata Evolutionary Case for Sound Device Control - First Ten Generations (© Haein Kang.)

becomes a one-dimensional array of cellular automata consisting of eight cells. At this point, the device state becomes ON or OFF, respectively.

The rhythm generation algorithm sets the cellular automata rule-110 (01101110) as the initial state of eight sound devices, as shown in Table 3.1. The cellular automata evolve by this rule to create a new set of rhythms. Table 3.2 shows the first ten step-by-step evolution cases of cellular automata for controlling sound devices. Cellular automata evolve by this rule to create a new set of rhythms. In this way, the total number of possible rhythm sets is 256 since each of the eight cells has two states, two to the eighth.

When checking the state of adjacent cells on both sides, the first and last cells have only one adjacent cell. We can solve this issue according to periodic boundary conditions (PBCs)[54] for one-dimension. PBCs are a set of boundary conditions for estimating an extensive system by using a unit cell. Periodic boundaries are obtained by periodically extending the lattice. In other words, assuming that the cell array is circularly connected, the cells at both first and last cells are considered adjacent cells, as shown in Figure 3.8.

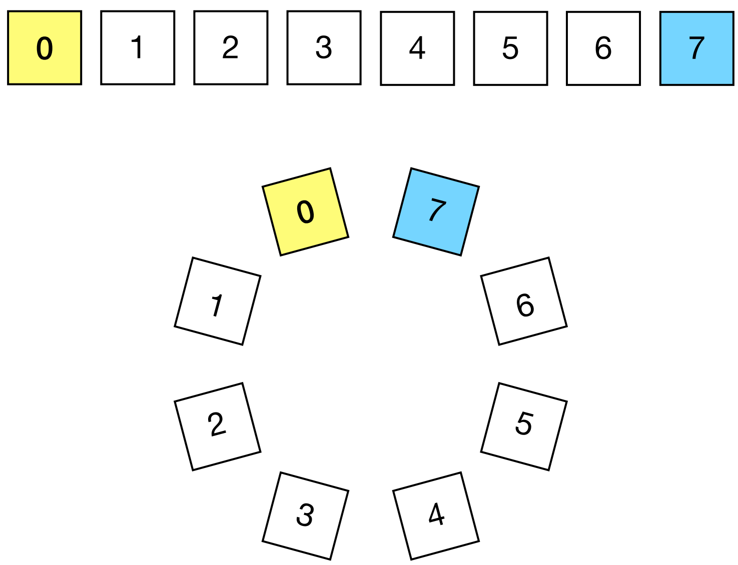

Figure 3.8. One-Dimensional Periodic Boundary Conditions (© Haein Kang.)

[54] Weimar, Jörg R. "Boundary Conditions." *Modeling with Cellular Automata*, Technical University Braunschweig, 2002, www.jcasim.de/main/node6.html

4. Results

Figure 4.1. Prototype of *Illusion* (© Haein Kang.)

4.1 Prototype

The prototype of *Illusion*, in Figure 4.1- 4, realizes the artistic application of EEG-based BCI technology by creating a space where interactive music devices, video projection, and performance events unfold. In the space like a monologue stage, one can control the music devices with their brainwaves to make sounds and experience sound-based biofeedback.

A chair is placed in the center of a black room where natural light and noise are completely blocked. Eight modules of custom percussion instruments are behind the chair, as shown in Figure 4.2, and a screen is in front of the chair. All devices for the performance are arranged in a

Figure 4.2. Instrument Arrangement for the prototype of *Illusion* (© Haein Kang.)

Figure 4.3. Installation View of the prototype of *Illusion* (© Haein Kang.)

circle around the performer, like the oracle of ancient Greece, as shown in Figure 4.3.

The deployment of music and video devices takes into account functionality favorable to neurofeedback as well as aesthetic aspects. Each mechatronic apparatus that makes up a percussion instrument is mounted on a sturdy microphone stand, and an object resonating sound is placed on the floor. Eight percussion instruments are arranged in a semicircle so that the person at the center of the circle can immerse themselves in the sound.

The images projected on the screen are set up to induce alpha rhythm by stimulating a person's eyes with light. The person sitting with the EEG headwear closes their eyes while watching the projected images. When visual stimulation is blocked, the brain triggers PDR and plays the musical instrument.

An environment has been created for the poetic use of the EEG-based BCI system. When a participant sits on a chair wearing an EEG headwear and closes the eyes, custom percussion instruments produce rhythmic sounds, and when they open their eyes, the instruments stop and be quiet, as shown in Figure 4.4.

One question was raised while a 12-year-old boy demonstrated the prototype system. His PDRs were distinguished but were detected between 4-8 Hz. The reference value for the alpha band is 8-13Hz, and the tolerance is 7.5-15Hz. His EEG data are not only slower than the norm but also belong to another frequency band, theta. The PDR is slower than 8 Hz in young children.[55]

The brain is known to grow until its late 20s and to age after its 30s. As a result, the range of alpha rhythms can vary depending on age. Sometimes the brain changes after the age of 30 as the

[55] Niedermeyer, E. "Alpha Rhythms as Physiological and Abnormal Phenomena." *International Journal of Psychophysiology*, vol. 26, no. 1-3, 1997, pp. 31–49.

part of the nerve that transmits signals continues to form. However, EEG examinations are typically targeted at subjects in their 30s, during which time the brain is mature, and EEG data is considered relatively reliable.

EEG data varies from person to person, especially in age and gender. Women, for example, have more delta activity than men, and men have more age-related decline than women. Besides, clear PDRs are detected in 20-25% of the subjects of investigation. Therefore, it was concluded that the effective range of EEGs should be pre-calibrated whenever a participant changes in an EEG-based BCI system that uses the PDR as a switch.

In the process of solving the problem, the project has shifted its perspective from the interactive artwork that everyone participates in a one-person performance piece. The aesthetic aspect of the project has become the crux of the matter. What sound is that? Is the gesture beautiful? Or is the movement of the machine inspiring?

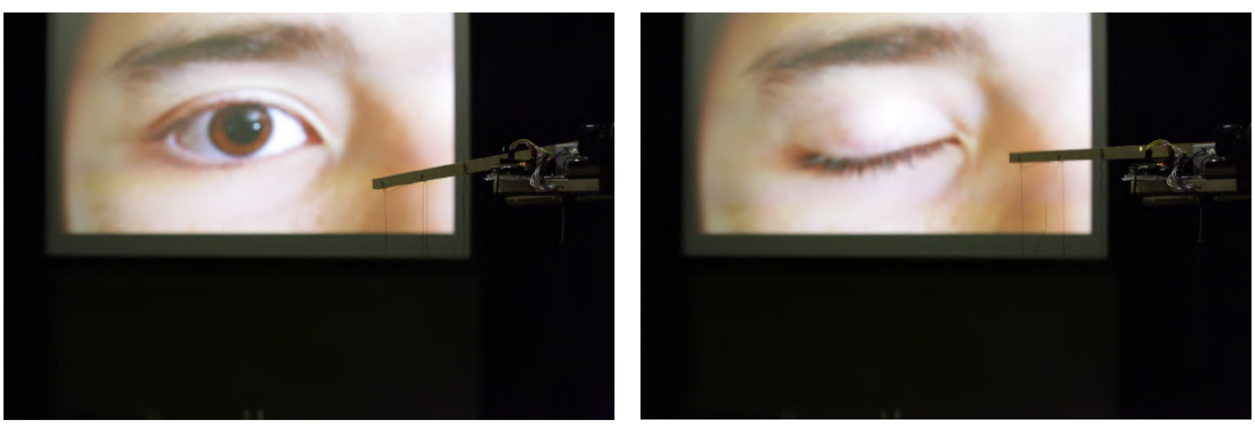

Figure 4.4. Installation details of Prototype (© Haein Kang.)

4.2 Composition Study on Soundscape

The second study focuses on refining musical composition to refine sound by creating a time-based performance. This acoustic research aims to create an auditory landscape where the audience can feel the sense of space using various EEGs following the guiding principles set out below.

> Using your recent work, Illusion, go much further with the use of EEG by making your brain the only activator of the motors. Focus on Mu Rhythm as a primary source of signals to activate and control the action, but you can use other signals as well. The emphasis should be on your ability to have real control over the Illusion modules. Based on this control, create an aural cinema landscape so that the listener, sitting or staring at the edge of the semi-circle of the collection of your eight modules, senses, with their eyes closed, perspectives of distance and elevation. The work should explore sight-deprivation by enhancing the sonic experience of the user also through composition and algorithmic control of the modules. The duration of the "landscape" performance should be between 8-12 minutes.

Prompt 1. The Prompt for Composition Study on Soundscape.

The core keyword of the second study is a soundscape, a compound word of sound and landscape. The term generally refers to the sonic environment that humans perceive by hearing. Still, in modern music, it refers to a musical form that expresses a particular situation using electroacoustic music techniques, such as field recording and granular synthesis.[56] For example, *Presque Rien n°1* [57] by French composer Luc Ferrari.

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56 Berry Truax, Acoustic Communication, 1984. Norwood, NJ: Ablex./Curtis Roads, *Microsound,* 2001. Cambridge: MIT Press.

57 "Presque Rien n°1." *PRESQUE RIEN*, uploaded by Luc Ferrari, Jun. 2006, lucferrari.com/en/analyses-reflexion/presque-rien-ou-le-lever-du-jour-au-bord-de-la-mer/.

The concept of soundscape sought in this study is more like the latter. However, rather than recording a situation and then transforming it musically, the study invents a musical instrument that makes timbre to conjure up the memories of an environment. Notably, a set of percussion instruments is designed to produce sounds reminiscent of raindrops falling on windows and roofs in the early morning.

Each device moves two or three thin elastic strings up and down to produce sound by gently tapping an object with its vibration. The acoustic composition study examined eight tones and categorized them into five groups, then relocated eight custom percussion modules. In most cases, according to resonant materials, they were classified as follows: wood, iron, glass, tin-containing springs and screws, and skin.

If the instrument's position is indexed to the left by number one and the right by number eight, three pairs of objects with similar loudness and timbre are placed in positions 1 and 8, 2 and 7, and 3 and 6 respectively. The louder objects are placed closer to the performer. Then the other two objects with distinct timbre from others are placed in the middle positions of 4 and 5, as shown in Table 4.1.

Index	1	2	3	4	5	6	7	8
Object	**Apple box**	**Iron pan**	**Ceramic plate**	**Tin with screws**	**Skin**	**Glass dome**	**Iron plate**	**Wood tray**
Loudness	3	4	4	3	1	5	4	3
Material	X	O	^	++	///	^	O	X
Duration	3	1.5	1	1	4	1.5	1	2
Num of pendulum	3	2	3	3	3	1	2	3

Table 4.1. Analysis and classification of acoustics for instrument placement, (© Haein Kang.)

Scientific methods of using software such as EASE Focus[58] or Smaart[59] were considered for acoustic measurement and analysis. However, the sound analysis was ultimately determined by the musical ear or sensory intuition. Emotional response to auditory stimuli is a subjective matter, like Qualia. For example, listening to the sound of knocking on wood, one person thinks of a woodpecker, and another person recalls a dance hall.

In the second study, instruments are activated using theta, gamma, and mu frequency bands in addition to the alpha rhythm, PDR. Theta is relatively slow EEGs between 4 and 8 Hz, appearing throughout the scalp when concentrating. Gamma is fast EEGs of 40 Hz or more and

Name	Frequency (Hz)	Region	Event
Delta	Under 4	Frontal Lobe in adults, Occipital Lobe in children, Thalamus	- Deep sleep.
Theta	4-8	All over the cerebral cortex, Hippocampal	- Drowsiness, idleness. - Actively trying to repress a response or action. - Performing cognitive tasks. (Fz)
Alpha	8 - 13 tolerance 7.5-15	Occipital lobe Frontal lobe (REM sleep)	- Relaxed with closing eyes. (O7-O8) - Rapid eye movement in sleep. (Fz)
	9-13 (Mu)	Motor cortex	- Rest state of motor neurons. (C3-C4)
Beta	13-30	Mostly frontal lobe and Central area	- Problem solving, concentration, decision making. - Ronald beta. (C3-C4)
Gamma	Over 30 around 40 Hz	Somatosensory Cortex	- Short term memory matching. - Coherent perception. e.g.) Tallon-Baudry's visual search task. (O7-O8) - Recall long term memories.

Table 4.2. Primary EEG Frequency Bands

58 "Easy Focus 3." *AFMG Technologies GmbH*, focus.afmg.eu/index.php/fc-features-en.html

59 "Smaart v8." *Rational Acoustics LLC*, www.rationalacoustics.com/smaart/smaart-v8/

observed in the somatosensory cortex. It is known to be caused by coherent perception, short-term memory matching, and long-term memory recall.[60] Mu rhythm is the same as the frequency of the 8-13 Hz alpha rhythm and is activated in the primary sensory and motor cortexes by resting state of motor neuron. Table 4.2 shows the primary EEG frequency bands and features.

More electrodes are added to detect theta, gamma, and mu rhythms. The more sensitive part of the body occupies a broader area of the cerebral cortex. For example, in a neurological map of the proportion of the human brain devoted to handling motor functions, the region activated by the movement of the fingers rather than by the arm is greater, as shown in Figure 4.5, Cortical Homunculus. EEG data by the hand movement can be detected at electrode positions C3 and C4 in the international 10-20 system.

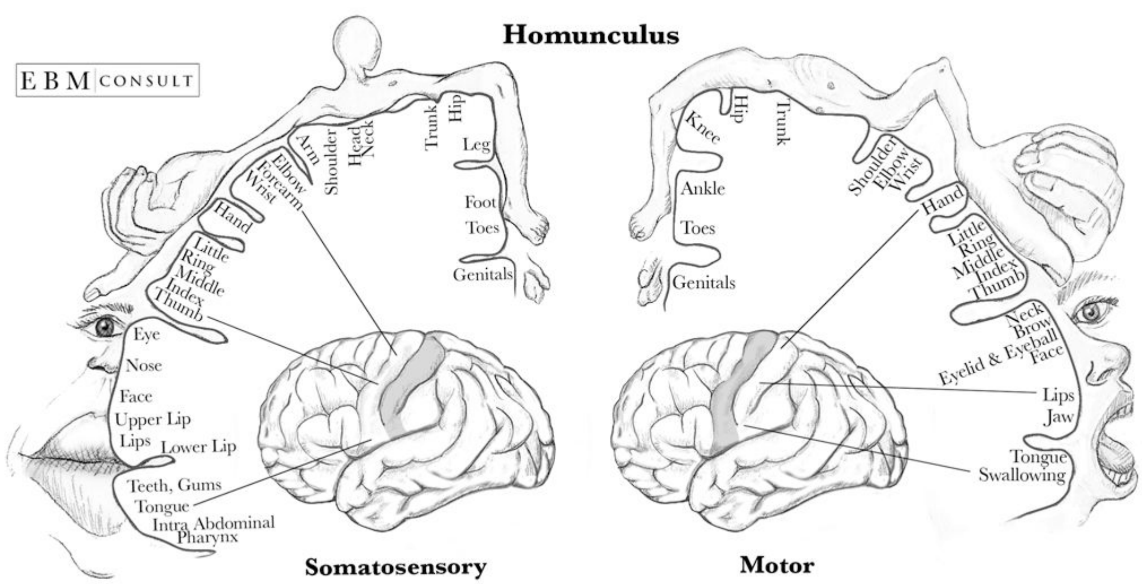

Figure 4.5. Cortical Homunculus.
Image Courtesy © EBM Consult, LLC, www.ebmconsult.com/articles/homunculus-sensory-motor-cortex

[60] Tallon-Baudry, Catherine, et al. "Oscillatory γ-Band (30–70 Hz) Activity Induced by a Visual Search Task in Humans." *The Journal of Neuroscience*, vol. 17, no. 2, 1997, pp. 722–734.

PDR sensing uses electrode position O1 used in the first study, and other EEGs sensing uses electrode position C3. Right-handed people are known to show dominant EEGs in the left hemisphere of the brain, while left-handed people are known to be the opposite. The performer is right-handed. The performer's gesture induces each frequency band EEG to play music. When the performer closes their eyes while looking at the candle, PDR occurs in the primary visual cortex. When they move their fingers and relax limbs, the mu rhythm appears in the primary motor cortex. If they are forced to stay still, the theta rhythm appears.

While the performer's PDR and theta rhythm were evident, it was not easy to induce mu and gamma rhythms. The performer attempted gestures to trigger EEGs in the order of Theta, Mu, Gamma, and PDR. These four EEGs play different tempo and timbre, as shown in Table 4.3. When EEGs outside these frequency bands are detected, the percussion instruments stop playing and become silent.

EEG	Gesture for inducing EEGs	Tempo	Choice of Instruments
Theta (θ)	Actively trying to repress their actions.	Adagio	Wood
Gamma (γ)		Presto	Iron & Ceramic
Mu (μ)	Move fingers and then relax limbs.	Andate	Tin & Membrane
PDR	Look at the candle and then close the eyes.	Moderato	Selected by CA

Table 4.3. EEG, Gesture, and Instrument. (© Haein Kang.)

4.3 Premiere

Based on two previous studies on space and acoustic, my doctoral study has attained its aim of poetic utilization of BCI technology and unveiled it to the public under the title, *Illusion: You can hear, but you cannot see*. The premiere took place in October 2018 at Gallery 4Culture[61] in Seattle. The opening performance lasted for about an hour and a half, and the BCI system operated during the one-month exhibition by recorded EEG data recorded at that time. The video-recorded live performance was played on the monitor with a loop and alluded that the devices were operated by the performer's EEGs, as shown in Figure 4.6.

The exhibition is an intermedia format that encompasses performance, sound art, and multimedia installation based on the audiovisual system for artistic expression using EEG-based BCI. Device placement had to be tailored to the L-shaped gallery space's characteristics and adjusted for image projection and sound, considering the natural light and noise from the streets.

Figure 4.6. The Exhibition Scene (Photo by Joe Freemann.)

[61] "Illusion." *Gallery 4Culture*, 2018, www.4culture.org/gallery_work/haein-kang/

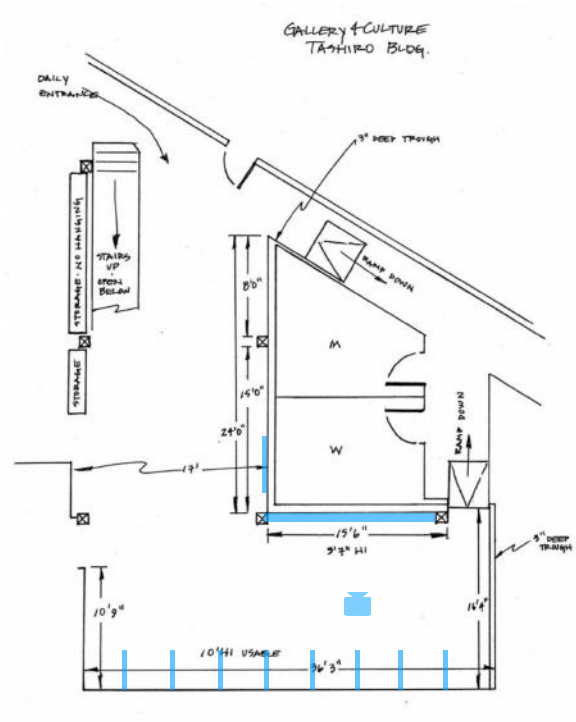

Figure 4.7. Floor Plan of Gallery 4Culture

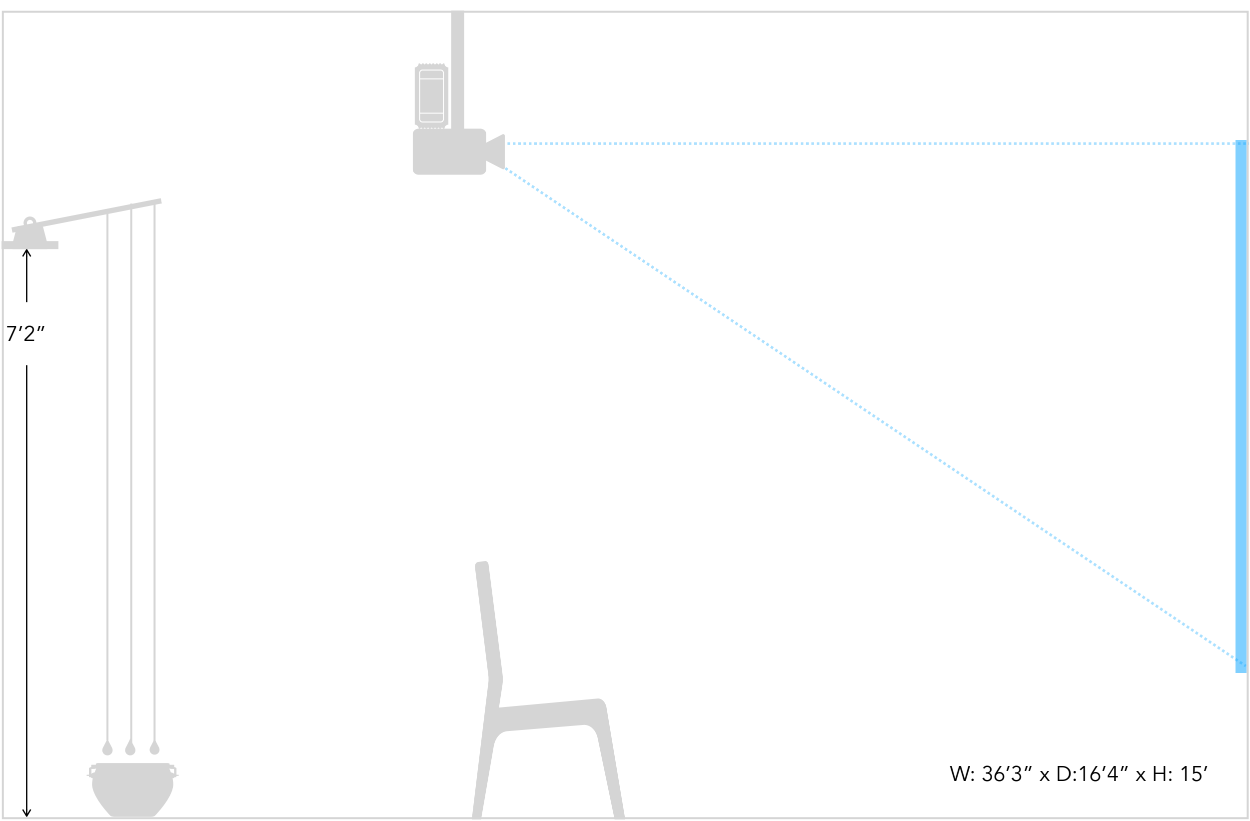

Figure 4.8. Diagram for Instrument Placement (© Haein Kang.)

Figure 4.9. Performance Still Image (Photo by Jian Kang.)

Figure 4.10. Performance Still Image (Photo by Jian Kang.)

This work was installed in a 36’3” (width) x 16’4” (depth) x 15’ (height) space within the Gallery 4Culture, as shown in Figure 4.7.

The eight rudimentary robotic arms are mounted using an L-bracket on the longest wall located at the rear of the gallery at 7.2 feet and 4 feet apart. Install the short-throw projector with the central computer on the ceiling above the performer's chair and project the images onto the short wall facing the long wall mounted with the robotic arms. Figure 4.8 provides a layout for these equipment deployments.

In the premiere, a performer sits in the middle of a room wearing an EEG headwear, as shown in Figure 4.9. The custom percussion instruments are behind the performer, and the projected image of one eye zooming is in front of the performer, as shown in Figure 4.10. The performer operates the sound mechanism with a static movement that blinks in the eyes while an audience walks around space or sits down in the exhibition to appreciate the instrument's movement and sound.

The *Illusion* alternately stimulates hearing and vision, creating synesthesia images in mind. When we close our eyes, we can see the world imaged by the sounds. The brain-computer interface’s artistic application explores the obscurity of the mind as an instrument propelled by the mind. The results and methodologies of this study have been presented and shared in numerous international academic venues in the form of installation, performance, workshop, and artist talks, including International Computer Music Conference-New York City Electroacoustic

Music Festival,[62] IEEE - Game Entertainment & Media,[63] International Symposium on Electronic Art,[64] CODAME Art+Tech Festival,[65] SIGGRAPH-ASIA,[66] and Immersive Storytelling Open Seminar at Harvard.[67]

4.4 Discussion on *Illusion: You can hear, but you cannot see*

This thesis approaches consciousness in a scientific manner that monitors neural activity by using EEG-based BCI technology. The customized BCI developed for artistic expression produces cadenced sounds externally manifesting the performer's inner state. The performer controls the sound mechanism with their brain waves in the sense of unity with the rhythm.

The sound also guides the audience on their journey into consciousness by recalling memories and evoking illusions. In the context of the psychology of perception, an illusion is a distortion of the senses. The human brain distorts the perception of reality in the process of organizing and interpreting sense data. Most people share this internal cognitive experience.[68]

Philosopher Ludwig Wittgenstein analyzes two different ways of seeing an ambiguous image in his book, *Philosophical Investigations*. When looking at the duck-rabbit illusion in Figure

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[62] Connors, Teresa Marie. "Illusion:you can hear, but you cannot see." *ICMC-NYCEMF 2019/ Reports+Reviews*, pp.24-25, www.computermusic.org/media/documents/array/ array_special_ICMC2019.pdf

[63] "Illusion: an instrument propelled by the mind." *IEEE-GEM Special Events*, 2019, www.ieee-gem.space/special-events

[64] "Haein Kang." *ISEA Symposium Archives*, 2019, isea-archives.siggraph.org/person/haein-kang/

[65] "ILLUSION." *CODAME Art+Tech Festival*, 2019, codame.com/projects/illusion

[66] "Haein Kang." *ACM SIGGRAPH Art Show Archives*, 2019, digitalartarchive.siggraph.org/person/haein-kang/

[67] "Gentle Introduction to EEG." *Immersive Storytelling Using Mixed Media*, Harvard University, 2019, tdm.fas.harvard.edu/event/immersive-storytelling-tdm-169l-open-seminar-haein-kang

[68] Solso, Robert L. Cognitive Psychology. 3rd ed., Allyn and Bacon, 1991

Figure 4.11. The earliest known version of the Duck-Rabbit Illusion.
Image source: “Duck-Rabbit Illusion.” *Fliegende Blätter,* 23 Oct. 1892, digi.ub.uni-heidelberg.de/diglit/fb97/0147/image

4.11, one sees this image as a duck at first sight. However, the next moment, some of them may recognize that they can also see the image as a rabbit. Wittgenstein calls the unexpected awareness ‘the dawning of an aspect.’ The aspect switching is not the awareness of newly emerging features in the object, but the unforeseen perception of internal relationships that already existed on the object. That is, the exterior appearance of the image has not changed, but the human perception change the aspect from duck to rabbit or vice versa.

Art historian Ernst Gombrich considers the psychology of perception as a critical issue in the development of art. In his 1960 book, *Art and Illusion,* Gombrich refers to Wittgenstein’s analysis of the duck-rabbit illusion to discuss visual perception in the artistic representation. To Gombrich, the perception is beyond ‘seeing it as ~.’ Artists project what they see into what they know. The sensory data accepted in artists’ retina are not visual experiences in themselves.

Artists organize, identify, and interpret their sensory information to represent as an artistic form what they see.

In terms of a perceptual strategy, the brain recognizes objects through the phenomenon of projecting the data accepted by sensory organs into the data stored in memory. This unique trait of perception is the illusion. We can deliberately try Wittgenstein's idea, 'the dawning of an aspect.' In this case, 'seeing it as ~' is replaced by 'trying to see it as~.' At this point, the concept of aspect and the concept of imagination are nearly related. In other words, the concept of 'I now see it as ~' is a close relationship with 'I imagine it now.'[69]

All art is illusory. Music creates illusions by sound, while art makes illusions by form. This innovative research and art practice create synesthetic illusions at the intersection of formative art and music, and arts and science.

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[69] Wittgenstein, Ludwig. *Philosophical Investigations*. Basil Blackwell, 1968, pp. 365-377

5. Conclusion

5.1 Conclusion

The quest for the human mind began in ancient times. Since Descartes raised the mind-body dualism, exploring the mind has shifted slowly but surely from the realm of philosophy to science. In order to study consciousness empirically, contemporary philosopher David Chalmers suggested dividing the problem of consciousness into scientifically explainable and unexplainable ones. Neuroscientists today seek to discover the biological basis of consciousness based on the brain's anatomical structure and physiological function. This dissertation has aimed to create instruments for artistic expression that interact with the conscious mind, following the principle of neuroscience that all mental activities can be reduced to neural processes.

A neuron, the basic unit of the nervous system, is an electrically excited cell that emits action potential when transmitting the information. Brain waves, which are voltage fluctuations caused by ion currents in neurons, were used as artistic media by Alvin Lucier for the first in his 1965 *Music for Solo Performer*. This thesis's work follows the pioneering artist's footsteps while using the latest technology, a non-invasive electroencephalography (EEG)-based brain-computer interface (BCI).

The non-invasive EEG-based BCI was a natural choice as a research tool for achieving this research objective. This technique converts brain waves into digital signals, applies the digital computer's capability to extract specific features, and controls external devices connected electronically to the brain, enabling direct communication between the brain and the machine.

Moreover, its portability and affordability make it suitable for experimenting with BCI's creative capabilities and performing arts practices.

This research project has adopted the EEG source localization strategy, which increases consistency and precision by recording EEG only in the cerebral cortex areas associated with specific sensory perception. Thus, the algorithm can effectively extract the posterior dominant alpha rhythm, and this particular EEG in the 8-13 Hz frequency band, which appears in the primary visual cortex when the visual stimuli are blocked, can act as an actuator of the sound mechanism.

If the performer closes their eyes, custom percussion instruments play cadenced sounds, and if the performer opens their eyes, it becomes quiet. As the cellular automata algorithm creates a new generation, it gradually changes the timbre of the soft rhythmic sounds by tapping the combination of different objects.

In conclusion, this thesis has presented the performance-based sound installation, *Illusion: You can hear, but you cannot see*, which simultaneously responses to the brainwave fluctuation that can be considered the manifestation of conscious experience. When we close our eyes, we see images drawn by sound in the dark. *Illusion* is a journey into the obscurity of the mind.

5.2 Future Directions

The next project is to aesthetically improve the *Illusion* by strengthening artistic elements such as sound, image, and movement of the performer. The audiovisual systems for artistic representation using EEG-based BCI presented in this paper have the various creative potential to express sophisticated poetic sensibilities. Moreover, the current system consists of visual, auditory, and BCI devices connected by wireless communication, making it easy to develop each module separately and expand it quantitatively and qualitatively.

For example, by doubling the current system, two performers' brains can manipulate different sounds and images to create a duet. Formal extensions naturally result in semantic changes. When a solo becomes a duet, the possibility of variation increases further. The two people facing each other on stage have a silent conversation with their eyes and hands. The brain's physiological reactions to their communication will be translated into color and music by BCI.

Developing a system that can increase psychological immersion by combining BCI with other immersive technologies such as augmented reality, surround sound, and gesture detection is also an interesting topic of further research. The combination of the physical world and digital reality can maximize the experience of artistic illusion.

It would be a valuable study to predict a future that is not yet approaching by looking far into the long run. When discovering the biological basis of consciousness and solving the causal relationship between the mind and body, that point will be the ultimate singularity of human civilization. The advances in neuroscience and computer technology will lead to improvements in BCI function, then this technology, a direct means of communication between the brain and the machine, will change the world.

Currently, Elon Musk's *Neuralink* is developing a system to implant micro AI chips with electrodes attached to the cerebral cortex for treatment purposes such as epilepsy and severe depression. BCI technology, a communication channel that directly connects the brain and machine, has tremendous potential to enhance human life. However, we must prepare for ethics as long as someone develops the technology to implant AI chips in the brain. Envisioning such a future through the lens of art is a social obligation as an artist who wants to design a positive future for humanity with science and technology development.

It is my honest belief that sooner or later, the brain-computer interface will permeate deeper into our daily lives, and humans and machines will be more closely connected and communicated. It is my sincere hope that this paper will be of some use to those who explore the creative potential of BCI.

BIBLIOGRAPHY

"1964: Brainwave control device by Edmond Dewan (1964)." *YouTube,* uploaded by The Retronaut, 18 Sep. 2014, www.youtube.com/watch?v=nCGcY6sQjcM.

"Alvin Lucier - Music For Solo Performer (1965)." *YouTube,* uploaded by Carlos Conceição, 27 Nov. 2010, www.youtube.com/watch?v=bIPU2ynqy2Y.

"Cloud-Chamber Bowls" *YouTube,* uploaded by Harry Parch - Topic, 8 Nov. 2014, www.youtube.com/watch?v=OfZrNaLxH-0&ab_channel=HarryPartch-Topic

"David Rosenboom: Propositional Music - 2015 Retrospective at the Whitney, Day 2." *Vimeo*, uploaded by David Rosenboom, 2017, whitney.org/events/david-rosenboom-ringing-minds

"Doing Nothing with AI 1.0." 2020, www.emanuelgollob.com/doing-nothing-with-ai/

"Easy Focus 3." *AFMG Technologies GmbH*, focus.afmg.eu/index.php/fc-features-en.html

"Encephalophone - Direct Brain Music Interface Instrument." *Deueling Thumbs StudioLab*, www.deuelingthumbs.com/brain-music-instrument/

"Eunoia." *Lisa Park*, www.thelisapark.com/work/eunoia

"Gentle Introduction to EEG." *Immersive Storytelling Using Mixed Media*, Harvard University, 2019, tdm.fas.harvard.edu/event/immersive-storytelling-tdm-169l-open-seminar-haein-kang

"Grass Field." *Media Art Net*, www.medienkunstnetz.de/works/grassfield/images/2/

"Haein Kang." *ACM SIGGRAPH Art Show Archives*, digitalartarchive.siggraph.org/person/haein-kang/

"Haein Kang." *ISEA Symposium Archives*, 2019, isea-archives.siggraph.org/person/haein-kang/

"Human Subjects." Directed by Laura Stayton and Adam Hogan, *Amazon Prime Video*, 2020, www.amazon.com/Human-Subjects-Richard-Karpen/dp/B08P1PV8LK

"Illusion: an instrument propelled by the mind." *IEEE-GEM Special Events*, 2019, www.ieee-gem.space/special-events

"ILLUSION." *CODAME Art+Tech Festival*, 2019, codame.com/projects/illusion

"Illusion." *Gallery 4Culture*, 2018, www.4culture.org/gallery_work/haein-kang/

"Klang (1982)" *The San Francisco Tape Music Festival program*, 2002, sfsound.org/tape/Harrison.html

"Klang." *YouTube,* uploaded by Jonty Harrioson, 3 Aug. 2015, www.youtube.com/watch?v=_iOV7LSqLUE&ab_channel=JontyHarrison-Topic

"Meany_TownHall_Combined_Final_4." *Vimeo*, uploaded by Thomas Deuel, 11 Nov. 2019, vimeo.com/372516748

"[Open Stage 2018: Samulnori] 40th Anniversary Special Video." *YouTube,* uploaded by Korean Cultural Center New York, 2 Feb. 2018, www.youtube.com/watch?v=qcNGtWVhdgk&ab_channel=KoreanCulturalCenterNewYork

"Presque Rien n°1." *PRESQUE RIEN*, uploaded by Luc Ferrari, Jun. 2006, lucferrari.com/en/analyses-reflexion/presque-rien-ou-le-lever-du-jour-au-bord-de-la-mer/.

"Sensorband performing at Paradiso in Amsterdam on 21 August 1994," *eContact! Online Journal for Electroacoustic Practices,* Video by d.g. graber 1995, econtact.ca/14_2/tanaka_gallery.html

"Smaart v8." *Rational Acoustics LLC*, www.rationalacoustics.com/smaart/smaart-v8/

"The Brain Factory." *YouTube*, uploaded by Maurice Benayoun, 14 Mar. 2018, www.youtube.com/watch?v=GrLA9kaWBPc&feature=emb_logo&ab_channel=MauriceBenayoun

Aurlien, H, et al. "EEG Background Activity Described by a Large Computerized Database." Clinical Neurophysiology, vol. 115, no. 3, 2004, pp. 665–673.

Axelrod, Julie. "Types of Brain Imaging Techniques." *Psych Central*, Psych Central, 17 May 2016, psychcentral.com/lib/types-of-brain-imaging-techniques/.

Ay-o, and Something Else Press. *Manifestos*. [Something Else Press], 1966, www.ubu.com/historical/gb/manifestos.pdf

Babiloni, Fabio, and Astolfi, Laura. "Social Neuroscience and Hyperscanning Techniques: Past, Present and Future." *Neuroscience and Biobehavioral Reviews*, vol. 44, 2014, pp. 76–93.

Bakkum, Douglas J, et al. "MEART: The Semi-Living Artist." *Frontiers in Neurorobotics*, vol. 1, 2007, p. 5.

Bardiot, Clarisse. "Alex Hay, Grass Field: Diagram." Daniel Langlois Foundation, 2006, www.fondation-langlois.org/9evenings/e/alex-hay/diagram.html

Berger, Hans. “Über Das Elektrenkephalogramm Des Menschen.” *European Archives of Psychiatry and Clinical Neuroscience*, vol. 94, no. 1, 1931, pp. 16–60.

Bergman, Ronald. “Atlas of Human Anatomy.” *Sagittal section of brain, the surface of the medial half of the right side is seen,* University of Iowa, 27 Jun. 2014, www.anatomyatlases.org/atlasofanatomy/plate24/03sagmedialr.shtm

Berry Truax, Acoustic Communication, 1984. Norwood, NJ: Ablex./Curtis Roads, *Microsound,* 2001. Cambridge: MIT Press.

Bonin, Vincent “Alex Hay, Grass Field: Performance.” Daniel Langlois Foundation, 2006, www.fondation-langlois.org/9evenings/e/alex-hay/performance.html

Bortfield, Heather. “Approach to the Mind: Introduction to Cognitive Science.” *Visual Pathways*, Departments of Psychology and Cognitive & Linguistic Sciences, Brown University, 2000, cog.brown.edu/courses/cg0001/lectures/visualpaths.

Brill, Dorothée. *Shock and the Senseless in Dada and Fluxus*. Dartmouth College Press : Published by University Press of New England, 2010.

Brodmann, K. *Vergleichende Lokalisationslehre der Großhirnrinde,* Leipzig: Barth*,* 1909, digital.zbmed.de/physische_anthropologie/content/pageview/711836

Broeckmann, Andreas. *Machine Art in the Twentieth Century*. The MIT Press, 2016.

Berger, Hans. “Über Das Elektrenkephalogramm Des Menschen.” *European Archives of Psychiatry and Clinical Neuroscience*, vol. 94, no. 1, 1931, pp. 16–60.

Carter, Rita. *Exploring Consciousness*. University of California Press, 2002.

Chalmers, David J. *Facing up to the problem of consciousness*. Journal of Consciousness Studies 2(3):200-19, 1995, consc.net/papers/facing.html.

Chŏng, Yong, et al. *1.4 K'illogŭraem ŭi Uju, Noe* : Sin'gyŏng ŭihak esŏ Nyuro Mak'et'ing Kkaji Yunghap Noe Kwahak ŭi hyŏnjang. 1판..; 1-p'an. ed., Saiŏnsŭ Puksŭ; 사이언스 북스, 2014.

Connors, Teresa Marie. “Illusion:you can hear, but you cannot see.” ICMC-NYCEMF 2019/ Reports+Reviews, 2019, pp.24-25, www.computermusic.org/media/documents/array/ array_special_ICMC2019.pdf

Crick, Francis, and Koch, Christof. “A Framework for Consciousness.” *Nature Neuroscience*, vol. 6, no. 2, 2003, pp. 119–126.

Deoksun, Park. *E.A.T.(Experiments in Art and Technology): Open-ended*, National Museum of Modern and Contemporary Art, 2018. pp.13

Finger, Stanley. Origins of Neuroscience: a History of Explorations into Brain Function. Oxford University Press, 1994.

Gombrich, E. H. *Art and Illusion; a Study in the Psychology of Pictorial Representation*. Pantheon Books, 1960.

Hoggett, Reuben. "Robots in Art." *1964 – Robot K-456 – Nam June Paik (Korean) & Shuya Abe (Japanese),* 1 September 2010, cyberneticzoo.com/robots-in-art/1964-robot-k-456-nam-june-paik-korean-shuya-abe-japanese/

Kameron R. Christopher, et al. "A History of Emerging Paradigms in EEG for Music." *International Computer Music Conference Proceedings: Vol. 2014*, 2014, pp. International Computer Music Conference Proceedings: vol. 2014, 2014.

Koch, Christof. *Consciousness: Confessions of a Romantic Reductionist.* MIT Press, 2012.

Koch, Christof. *The Quest for Consciousness : a Neurobiological Approach*. Roberts and Co., 2004.

LEE, Sooyoung, ed. NJP Reader #7 *Coevolution: Cybernetics to Posthuman*. Yongin: Nam June Paik Art Center, 2017.

Lokhorst, Gert-Jan, "Descartes and the Pineal Gland." *The Stanford Encyclopedia of Philosophy*, Stanford University, 2018, plato.stanford.edu/archives/win2018/entries/pineal-gland/.

Lucier, Alvin, et al. *Reflections : Interviews, Scores, Writings 1965-1994 = Reflexionen : Interviews, Notationen, Texte* 1965-1994. Zweite erweiterte und überarbeitete Auflage. ed., MusikTexte, 2005.

Lusted, Hugh S, and Knapp, R. Benjamin. "Biomuse: Musical Performance Generated by Human Bioelectric Signals." *The Journal of the Acoustical Society of America*, vol. 84, no. S1, 1988, p. S179, asa.scitation.org/doi/10.1121/1.2025994.

McCulloch, Warren, and S. Pitts. "A Logical Calculus of the Ideas Immanent in Nervous Activity." *The Bulletin of Mathematical Biophysics*, vol. 5, no. 4, 1943, pp. 115–133.

Millet, David. *The Origins of EEG*, 3 June 2002, www.bri.ucla.edu/nha/ishn/ab24-2002.htm

Mullen, Tim, et al. "MindMusic: Playful and Social Installations at the Interface Between Music and the Brain." *More Playful User Interfaces*, Springer Singapore, Singapore, 2015, pp. 197–229. Gaming Media and Social Effects.

Nayak, Chetan S., et al. “EEG Normal Waveforms.” *StatPearls Publishing*, 2020, www.ncbi.nlm.nih.gov/books/NBK539805/

Newman, Eric A., et al. *The Beautiful Brain : the Drawings of Santiago Ramón y Cajal*. Abrams, 2017.

Niedermeyer, E. “Alpha Rhythms as Physiological and Abnormal Phenomena.” *International Journal of Psychophysiology*, vol. 26, no. 1-3, 1997, pp. 31–49.

Niedermeyer, Ernst, et al. *Niedermeyer's Electroencephalography : Basic Principles, Clinical Applications, and Related Fields*. 6th ed., Wolters Kluwer/Lippincott Williams & Wilkins Health, 2011.

Nijholt, Anton. *Brain Art: Brian-Computer Interfaces for Artistic Expression*. Springer, 2019.

Partch, Harry. *Genesis of a Music : an Account of a Creative Work, Its Roots and Its Fulfillments*. 2d ed., enl. ed., Da Capo Press, 1979.

Rao, Rajesh P. N. *Brain-Computer Interfacing : an Introduction*. Cambridge University Press, 2013.

Robinson, Howard. “Dualism.” *Stanford Encyclopedia of Philosophy*, Stanford University, Fall 2017, Edward N. Zalta (ed.) plato.stanford.edu/archives/fall2017/entries/dualism/.

Rosenblueth, Arturo, et al. “Behavior, Purpose and Teleology.” *Philosophy of Science*, vol. 10, no. 1, 1943, pp. 18–24.

Rosenboom, David. *Biofeedback and the Arts, Results of Early Experiments*. 2d ed., Aesthetic Research Centre of Canada, 1976.

Shanken, Edward A. *Art and Electronic Media*. Phaidon Press, 2009.

Singh, Harsimrat, and Daly, Ian. “Translational Algorithms: The Heart of a Brain Computer Interface.” *Brain-Computer Interfaces*, Springer International Publishing, Cham, 2014, pp. 97–121. Intelligent Systems Reference Library.

Solso, Robert L. *Cognitive Psychology*. 3rd ed., Allyn and Bacon, 1991

Straebel, Volker, and Thoben, Wilm. “Alvin Lucier's Music for Solo Performer: Experimental Music beyond Sonification.” *Organised Sound : an International Journal of Music Technology*, vol. 19, no. 1, 2014, pp. 17–29.

Tallon-Baudry, Catherine, et al. “Oscillatory γ-Band (30–70 Hz) Activity Induced by a Visual Search Task in Humans.” *The Journal of Neuroscience*, vol. 17, no. 2, 1997, pp. 722–734.

Tye, Michael, “Qualia.” *The Stanford Encyclopedia of Philosophy, Stanford University,* Summer 2018, Edward N. Zalta (ed.), plato.stanford.edu/archives/sum2018/entries/qualia/.

Weimar, Jörg R. “Boundary Conditions.” *Modeling with Cellular Automata*, Technical University Braunschweig, 2002, www.jcasim.de/main/node6.html

Weisstein, Eric W. “Elementary Cellular Automaton.” *MathWorld*, mathworld.wolfram.com/ElementaryCellularAutomaton.html

Wiener, Norbert. *Cybernetics; or, Control and Communication in the Animal and the Machine*. 2nd ed., M.I.T. Press, 1961.

Wiener, Norbert. *The Human Use of Human Beings : Cybernetics and Society*. Da Capo Press, 1988.

Wittgenstein, Ludwig. *Philosophical Investigations*. Basil Blackwell, 1968, pp. 365-377

Wolf, Daniel James. “NO IDEAS BUT IN THINGS - Music For Solo Performer (1965).” 1 Jul. 2013, www.alvin-lucier-film.com/solo_performer.html.

Wolfram, Stephen. “Statistical Mechanics of Cellular Automata.” Reviews of Modern Physics, vol. 55, no. 3, 1983, pp. 601–644, www.stephenwolfram.com/publications/academic/statistical-mechanics-cellular-automata.pdf

Ziolecki, Austin. “Forebrain.” *Structures of the Brain*, thebrainstructure.weebly.com/forebrain.