Chapter 3
Brain-Computer Interfaces in Contemporary Art: A State of the Art and Taxonomy

Mirjana Prpa and Philippe Pasquier

Abstract In this chapter, we present a state of the art on Brain-Computer Interface (BCI) use in contemporary art. We analyzed sixty-one artworks that employ BCI dating from 1965 to 2018, and present a taxonomy with five categories guiding the discussion of specific BCI artworks: input, mapping, output, format, and the presence of an audience. Moreover, we briefly present and discuss key points about BCI devices used in some of the artworks that are available on the market. Finally, we present insights from nineteen artists that we surveyed about their BCI art practices, experiences with BCI devices and peculiarities of working with brain activity as a resource for art creation. We then conclude with our summary of challenges and potentials for BCI art in the future.

Keywords State of the art · BCI · EEG · Taxonomy · Contemporary art

3.1 Introduction

Revealing the intricacies of the human brain and its functioning is a source of intrigue and a subject of study for various disciplines with the same goal: to understand how we behave and experience the world. One of these disciplines, that of art, has been providing a unique perspective on understanding the human brain. Through their practices, artists' contribution to this understanding requires rigorous involvement in the process of discovery: "*...the artist is in a sense, a neuroscientist, exploring the potentials and capacities of the brain, though with different tools... How such creations can arouse aesthetic experiences can only be fully understood in neural terms*." (Shimamura and Palmer 2012).

M. Prpa (✉) · P. Pasquier
School of Interactive Arts + Technology, Simon Fraser University,
Surrey, Canada
e-mail: mprpa@sfu.ca

P. Pasquier
e-mail: pasquier@sfu.ca

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Although the modes of artistic exploration of the brain can take upon various forms (such as metaphorical), in this chapter, we are concerned with the utilization of neurophysiological brain data through artistic processes and into a creative output. For this inquiry, we identified two historically significant events: the first took place in 1924 when German psychiatrist Hans Berger recorded the electrical activity of the human brain for the first time in history. The recording of *Berger's wave* or what is known today as "*Alpha rhythm*" marked the beginning of electroencephalography (EEG), a neuroimaging technique that has since been utilized in the context of art. The second event, following Berger's work, was when two leading physiologists from Cambridge's Physiological Lab, Edgar Douglas Adrian, and Bryan Matthews, mapped Alpha waves into audio signals in 1934 (Adrian et al. 1934; Rosenboom and Number 1990). While the first event made the utilization of brainwaves possible, the second event naively marked the beginning of creative explorations of brain activity that advanced outside of science labs into the world of contemporary art.

In the early days of artistic experimentation with brain sensing, due to the complexity of early EEG apparatus, collaborations between scientists and artists were common. Alvin Lucier was initially introduced to "brain-music" by his friend, physicist Edmond Dewan. With the assistance of Dewan and support from John Cage, Lucier performed *Music for Solo Performer* at the Rose Art Museum (Waltham, Massachusetts) in 1965 which constitutes the first recorded brainwave music performance. Moreover, Lucier's sonification of Alpha waves laid the foundation for what we refer to in this chapter as **brain-computer-interface art (BCI art)**.

The term brain-computer interface (BCI) was coined by Jacques Vidal, UCLA's[1] professor and pioneer in this field (Vidal 1977, 1973). BCI is a system that senses and utilizes brain activity in one-way communication from a brain to a computer. BCI definitions vary though, depending on how BCI is utilized. For example, (Wolpaw and Wolpaw 2012) define BCI as "*a system that measures central nervous system (CNS) activity and converts it into artificial output that replaces, restores, enhances, supplements, or improves natural CNS output, and thereby changes the ongoing interactions between the CNS and its external or internal environment*".[2] However, Wolpaw and Wolpaw's definition describes one approach to utilizing BCI (active BCI, Sect. 3.2.2.2) that Zander et al. (2010) recognize as *Direct BCI*, in which mental activity is consciously controlled and directed in order to change the output of the system. The same authors also juxtapose *Direct BCI* with *Indirect BCI*, as the latter collects and utilizes passive, spontaneous brain activity that is not consciously controlled (this will be expanded on in Sect. 3.2.2.2).

While early BCI devices emerged within the context of medical research, recent interest in ubiquitous computing, wearable technologies, body interfaces, affective computing, and a movement towards the "quantified self" emphasize the potential impact that commercial BCI devices could have on the market. Since the first International Meeting on BCI in New York in 1999 (Wolpaw et al. 2000), the expansion

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[1] University of California, Los Angeles.

[2] An example of this definition is a participant with impaired motor neurons who utilizes BCI input to control their wheelchair.

of BCI devices on the market resulted in a large number of open source as well as proprietary devices that are non-invasive, affordable and user-friendly. Following these technological advances in BCI technologies and their diverse uses beyond laboratories and into the wild of the consumer market, the corpus of BCI art has grown extensively. However, the lack of a systematic overview of ideas, concepts, implemented approaches, and typologies prevents us from a comprehensive understanding of the BCI art landscape.

To that end, with this chapter, we aim to contribute to understanding the complex landscape of BCI art. Our research process was as follows: first, we surveyed EEG-based BCI devices with a focus on EEG approaches and related control paradigms. Then we analyzed 61 BCI artworks (see Table 3.3 in Sect. 3.7) based upon which we created a taxonomy (see Fig. 3.1b in Sect. 3.2.1 and Table 3.4 in Sect. 3.7) that we present here. Following the logic of our research process, we begin this chapter by introducing the field of brain-computer interface and laying out the landscape of EEG-based BCI devices and types of brain data. Second, we group, combine, analyze, and categorize the work that has been done in BCI art so far. Within each taxonomy category and their subcategories, we provide background knowledge and concepts necessary for understanding the nuances of that category, illustrated with examples from BCI art. A comprehensive list and video/images of BCI artworks that we analyzed can be found in the online database that we created at https://bci-art.tumblr.com/. Finally, in addition to the taxonomy, we discuss challenges and potentials of the exploitation of brain activity in art, based on the insights gained through our practice, analyzed examples, and direct correspondence with nineteen authors. Our aim is to provide a clear framework as guidance for artists and researchers in all future creation and discussion of BCI artworks.

3.2 Categories for BCI Art Analysis

In this section, we present the complex landscape of BCI art (Fig. 3.1) by looking at the characteristics of EEG-based BCI devices used in an art context (Fig. 3.1a), and BCI artworks (Fig. 3.1b). First, in Sect. 3.2.1 we present the main characteristics of EEG-based BCI devices (Table 3.1). Then we introduce 61 artworks starting from the mid-1960s until 2018 (Table 3.3) through the categories of the **Taxonomy of BCI art** (Table 3.4). The proposed taxonomy consists of 5 main dimensions that guided our comparison and analysis of the artworks. In *Input dimension*—Sect. 3.2.2—we discuss different types of brain data, detailing EEG classification approaches, control paradigms, timeliness of input, and finally we discuss modality of BCI artworks because some of the analyzed artworks combine EEG data with other types of input data (heart rate, electrodermal activity, etc.). Then in Sect. 3.2.3—*mapping*—we discuss the different ways that input is transposed to output in BCI artworks. This is followed by a discussion of the *Output dimension* in which we present a variety of outputs that BCI artworks have, including visual, sound, audio-visual, moving images, immersive, and control of a physical object (Sect. 3.2.4). Output is

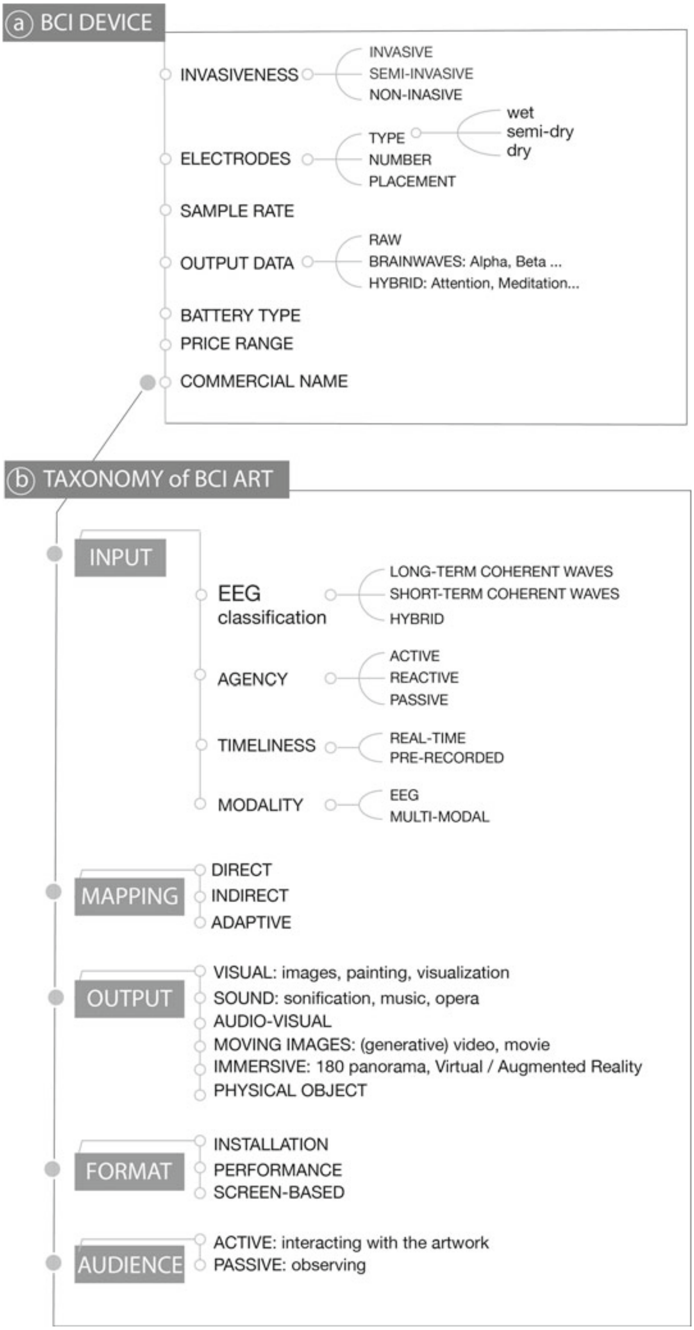

Fig. 3.1 Taxonomy of BCI devices (**a**) and BCI artworks (**b**). Image by the authors

closely related to *presentation format* that we discuss in Sect. 3.2.5, which is then followed by a discussion of the presence and the role of the audience in BCI artworks (Sect. 3.2.6).[3] The descriptions of the taxonomy categories are illustrated with some artwork examples and a brief description of their features. More details about the artworks can be found by following the number indicated in ⓧ in the survey Tables 3.3 and 3.4 (Sect. 3.7).

3.2.1 EEG-Based BCI Devices

Brains are complex systems within which dynamic electrochemical processes take place. Neuroimaging (brain-imaging) techniques provide insights into *structural* and *functional* properties of the nervous system. While structural imaging allows for a better understanding of brain structures, functional imaging provides recordings of the activity across different brain areas. The practical application of brain-imaging in artworks discussed in this chapter is concerned with electroencephalography (EEG), an approach to the understanding of brain functioning through measuring electrical activity in the brain by multiple electrodes that are placed on the skull's surface. Available today are various other techniques for neuroimaging, such as: *magnetoencephalography*—records magnetic fields produced by electrical currents occurring in the brain (Panoulas et al. 2010), *functional Near-Infrared Spectroscopy*—measures hemodynamic (the flow of blood in the brain) responses associated with neuron behavior (Coyle et al. 2007), *Event-related optical signal*—measures changes in the optical properties of active areas of the cerebral cortex (Nam et al. 2018). These techniques provide higher spatiotemporal resolution of recordings compared to EEG. However, the majority of consumer-grade BCI devices utilize EEG only. Just recently there has been a push towards hybrid BCIs that combine EEG (high temporal, low spatial accuracy) and fNIR (low temporal, high spatial accuracy) (Naseer and Hong 2015; von Luhmann and Muller 2017), however, our query yielded one artwork that utilizes hybrid BCI approach. We are certain that we are very close to embracing hybrid BCIs, or even solely fNIR-based BCI (NIRSIT 2018) in the art field. The push towards the development and proliferation of ergonomic and aesthetically pleasing headsets spanning beyond EEG into more precise (higher spatial-temporal resolution), reliable, and wireless, headsets opens many possibilities for art applications in the future.

EEG-Based BCI Devices Used in Art Contexts are Non-invasive—From the early days of Berger recording brain activity by inserting electrodes into a patient's skull until today, the advancement of BCIs and underlying technologies is undeniable. The devices available today are capable of detecting electrical signals of the smallest magnitude from the electrodes placed on the surface of the skull. Compared to Berger's rudimentary and invasive approach, the degree of invasiveness of BCI devices on the participant has decreased significantly. Overall, regarding the inva-

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[3] In this chapter we use word "participant" to differentiate between an audience at large and a person—a participant—whose EEG data is utilized in an artwork.

siveness, BCI devices are classified into three classes: invasive, partially invasive, and non-invasive (Nicolas-Alonso and Gomez-Gil 2012). Both *Invasive BCI* and *Semi-invasive BCI* require the surgical placement of microelectrodes inside gray matter to record brain activity and are used exclusively for medical applications. While we have no knowledge of these devices being widely employed in an artistic context at the time of writing, interest in a cyborg movement (Harbisson and Ribas 2010) has offered some perspectives on how these interfaces could be used in the future. Neil Harbisson, a color blind artist, became the first cyborg known for an invasive implant in his skull—an eyeborg antenna—that translates colors to sound to overcome color blindness (Eyeborg 2019). In a performance set in two locations in New York, Haribsson "perceives" the colors from a canvas painted by volunteers on Times Square via Skype connection and projections at his location. Without looking at the projection, his implanted antenna translates the projected colors into sound frequencies that he then paints on a canvas (Pearlman 2014, 2015). To our knowledge, the use of invasive brain implants is tied only to the cyborg art movement and the work of Haribsson, compared to non-invasive BCI devices that are widely employed in an art context and therefore will be the focus of this chapter.

The use of *non-invasive* BCI spans beyond medical into various everyday applications, from gaming, meditation, to utilization in art. One of the main differences among consumer EEG-based BCI devices is in the type of electrodes: wet, semi-dry, and dry. Wet electrodes require the application of a gel to secure the connectivity between the skull and the electrode. In the past, all non-invasive EEG-based BCIs used wet electrodes. However, due to the inconvenience of the gel residues, devices with wet electrodes are now used mainly in a medical context. *Semi-dry* electrodes partially overcome the residue problem by replacing the conductive gel with a saline solution. However, the saline solution on the electrodes' felt pads tends to dry quickly, so these electrodes need moistening more often than gel-based electrodes. Compared to gel-based electrodes that can hold high conductivity for up to eight hours, semi-dry compromise the endurance for comfort. *Dry* electrodes require reduced set-up time and no need for gel/paste application. However, this type of sensor requires firm pressure on the head. Devices with dry electrodes must penetrate through hair and achieve solid scalp contact which is often experienced by the participants as uncomfortable. Finally, focus and high expectations are on a new generation of dry electrodes (Lin et al. 2011) moisturized by human perspiration (for example, the hydrophilic polymer electrodes built in devices such as Emotiv's Insight (Emotiv n.d.)). This type of dry electrodes do not require firm pressure on the skull. However, their price is higher than the price of gel-based electrodes.

Range of EEG-Based BCI Devices on the Market—Table 3.1 presents the range of BCI devices available on the market at the time of writing. Since the end of the 1990s, the number of low-cost EEG BCI devices on the market has rapidly increased, resulting in head-mounted devices such as Emotiv EPOC and Emotiv Insight (n.d.), Muse (n.d), and NeuroSky Mindwave (n.d.-b). These devices vary in the type, number, and placement of electrodes, output signal, sample rate, as well as price (Table 3.1). It is expected that the number of head-mounted BCI devices will continue to increase, however the most recent direction for BCI is towards in-ear

Table 3.1 EEG-BCI devices – continued from previous page

Device	Electrode # : type	Electrode placement	Sample rate/resolution	Output data	Battery/run time	Price (USD)
ABM X10 (B-Alert X series mobile EEG 2018)	9+1*: dry	F3, Fz, F4, C3, Cz, C4, P3, POz, P4	256 Hz/16-bit	Delta, Theta, Alpha, Beta, Gamma, and High Gamma	Lithium Ion/11 h	—
ABM X24 (B-Alert X series mobile EEG 2018)	20+4*: dry	Fz, Fp1, Fp2, F3, F4, F7, F8, Cz, C3, C4, Pz, P3, P4, POz, T3, T4, T5, T6, O1, O2	256 Hz/16-bit	Delta, Theta, Alpha, Beta, Gamma, and High Gamma	Lithium Ion/6 h	—
Cognionics Quick-20 (Quick20 n.d.)	8/20 +2*: dry	Fz, Fp1, Fp2, F3, F4, F7, F8, Cz, C3, C4, Pz, P3, P4, P7, P8, T3, O1, O2	0–131/262/524 Hz/24-bit	Raw data, 3-axis accelerometer	Lithium-ion/up to 12 h	6,000–15,000
Cognionics Quick-30 (Quick30 n.d.)	30 +2*: dry	Af3, Af4, Fz, Fp1, Fp2, F3, F4, F7, Fc5, Fc6, F8, Cz, C3, C4, Cp5, Cp6, Pz, Po7, Po3, Po4, Po8, P3, P4, P7, P8, T3, O1, O2	0-131/262/524 Hz/24-bit	Raw data, 3-axis accelerometer	Lithium-ion/up to 12 h	22,000
Cognionics Mobile-128 (Quick30 n.d.)	64/128 +2*: wet	128 electrodes, 10–20 placement	0–131/262 Hz/24-bit	Raw data, 6-axis IMU (Acc+Gyro)	Lithium-ion/up to 8 h	38,000–50,000
Emotiv EPOC (Emotiv n.d.)	14+2*: semi-dry	10–20: AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, AF42: P3*,P4*	128 or 256 Hz/ 14-bit per channel	Raw data, gyroscope, accelerometer, magnetometer (with EmotivPro licence); MyEmotiv app: focus, stress, excitement, relaxation, interest and engagement	Lithium Polymer battery 640mAh/12 h	800
Emotiv Insight (Emotiv n.d.)	5 + 2*: dry	10–20:AF3, AF4, T7, T8, Pz: P3*, P4*	128 Hz/: 14-bit per channel	Raw data, gyroscope, accelerometer, magnetometer (EmotivPro licence); MyEmotiv app: focus, stress, excitement, relaxation, interest and engagement	Lithium Polymer battery 480mAh/4 h	300

(continued)

Table 3.1 (continued)

Device	Electrode # : type	Electrode placement	Sample rate/resolution	Output data	Battery/run time	Price (USD)
IMEC (wireless 2018)	8: dry	—	512 Hz/—	Raw data (0.5–100 Hz)	—	—
Interaxon Muse (Muse n.d.)	4+1*: dry	10–20: TP9, AF7, AF8, TP10: FPz*	256 Hz/12-bit per channel	Raw data, calm score, accelerometer, gyroscope	Lithium Ion/5 h	250
MyndBand EEG Brainwave Headset (MindPlay n.d.)	1+2*: dry	10–20: FP1	512 Hz/—	Raw data (3–100 Hz), Attention, Meditation, Eye blink	Lithium Ion/10 h	300–600
Neuro- electrics Enobio (Neuroelectrics ENOBIO n.d.)	8/20/32: wet/dry	10–10: a cap with 39 possible positions	500 Hz /24-bit per channel	Raw data	—/up to 16 h	4,000–17,000
Neurosky MindWave Mobile (NeuroSky Mind-Wave n.d.-a)	4: dry	10–20: TP9, FP1, FP2, TP10	512 Hz/12-bit per channel	Attention, Meditation, Eyeblinks, Brainwave Bands, raw Output	1 AAA/8 h	100
Neurosky MindSet (NeuroSky n.d.)	1: dry	FP1	128Hz or 512Hz/—	Raw data (0–50Hz), Attention, Relaxation, Blink detection	Lithium Ion/—	Obsolete
OpenBCI (OpenBCI n.d.)	8/16: dry	10–20: (for 8) Fp1, Fp2, C3, C4, P7, P8, O1, O2; (16): add F7, F3, F8, F4, T7, T8, P3, P4	—	Raw data	Lithium Ion 500 mAh/—	Open source

EEG BCI devices (Looney et al. 2012; Mikkelsen et al. 2015; Ear EEG demo 2018; Ear EEG project 2018).

3.2.2 Input of BCI Artworks

In this section, we cover four subcategories of the input dimension: EEG classification approaches, agency paradigms, timeliness of the input, and modality of input, illustrating them with BCI art examples.

3.2.2.1 Input: EEG Classification Approaches

EEG is a functional neuroimaging technique for recording the electric component of the brain's electrochemical processes. EEG captures "neural oscillations" —a synced electrical activity of the clusters of neurons across the brain that are constantly firing electrical discharges. While a large number of the neurons fire simultaneously across the brain, the activation of the neuron clusters in particular regions of the brain indicates specific actions or processes. For example, brainwaves associated with cognitive processing are most prominent in the occipital region of the brain (back and lower part of the skull). To capture brain activity across various brain regions, one of the most widely accepted approaches to electrode placement on the skull is the *10–20 International System of Electrode Placement* (Silva and Niedermeyer 2012) developed by Dr. Herbert Jasper in the 1950s (Fig.3.2) (Szafir 2010). For higher density electrode setting, the 10–10 system has been used for placement of up to 81 electrodes, and beyond that the 10–5 system is used for placing up to 320 electrodes (Jurcak et al. 2007).

Recorded brainwaves are classified by their frequencies, amplitudes, location, and shape (Kumar and Bhuvaneswari 2012). Regarding frequency, spontaneous neural activity shows fast cortical potentials (FCP) that range from 0.5 Hz to 100 Hz (Moss 2003). Raw, unprocessed data of electrical activity of the brain exposes background noise which is mixed with brainwaves. Therefore, to understand the relationship between brainwaves and the presented stimulus or cognitive processes better, two distinct approaches are discussed in the literature. The first approach is the recording and analysis of *Long-Term Coherent Waves* (LTCW), and second, *Short-Term Transient Waves* (STCW) (Rosenboom and Number 1990). The third approach, **Hybrid**, emerged due to the progress in machine learning and artificial intelligence, and builds upon LTCW and STCW, using all possible data combinations to train artificial models for high-level prediction.

Long-Term Coherent Waves (LTCW)—In this approach, also known as **neurofeedback**, captured EEG activity is classified based on brainwave frequencies in the range from 1 to 30 Hz. According to some authors, different brainwaves are more prominent in some parts of the brain than in others, and the probability of capturing a particular brainwave can be increased by positioning electrodes in the regions of the brain associated with it. For capturing slow brainwaves (0.5–2 Hz), the electrodes

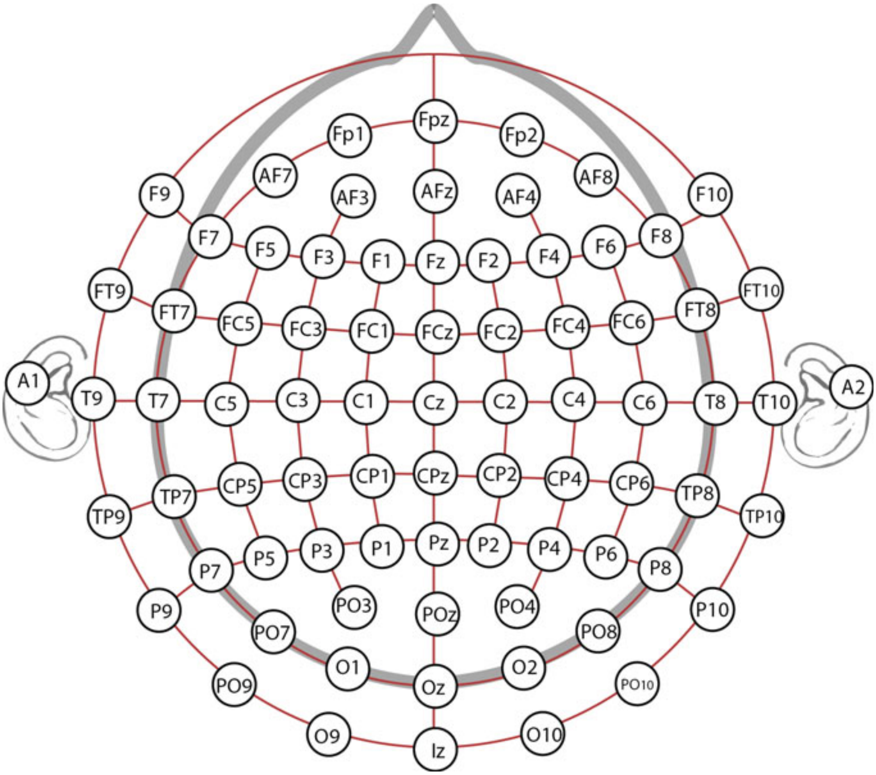

Fig. 3.2 Electrode Placement according to the International 10–20 System. Letters correspond to the lobes –F(rontal), T(emporal), P(arietal), and O(ccipital). C stands for Central position. Image by the authors

should be placed in F4-A1 positions (see Fig. 3.2), for brainwaves in the frequencies between 11 and 16 Hz in C4-A1 position, and finally, for Alpha wave (8–13 Hz) in 02-A1 positions (Morley et al. 2013). However, further classification of brainwave

Table 3.2 EEG waves, their frequencies and features

Name	Frequency range (Hz)	Associated features
Delta	0.5–4	Fatigue, sleep, severe slowing of mental processes, possible to occur in meditation by very experienced practitioners able to maintain consciousness in delta state
Theta	4–7	Deep meditation, reduced consciousness, hypnosis, attention lapses, slowed processing, stage 1 of sleep, memory consolidation
Alpha	8–14	Relaxed wakefulness, readiness, inactive cognitive processing, most prominent during meditation
Slow Beta	15–20	Intense focus, cognitive enhancement
Medium Beta	20–30	Anxiety, distractibility
Fast Beta (Gamma)	30–70	Hyper-alertness, processing of various attended stimuli (tactile, visual, auditory), stress

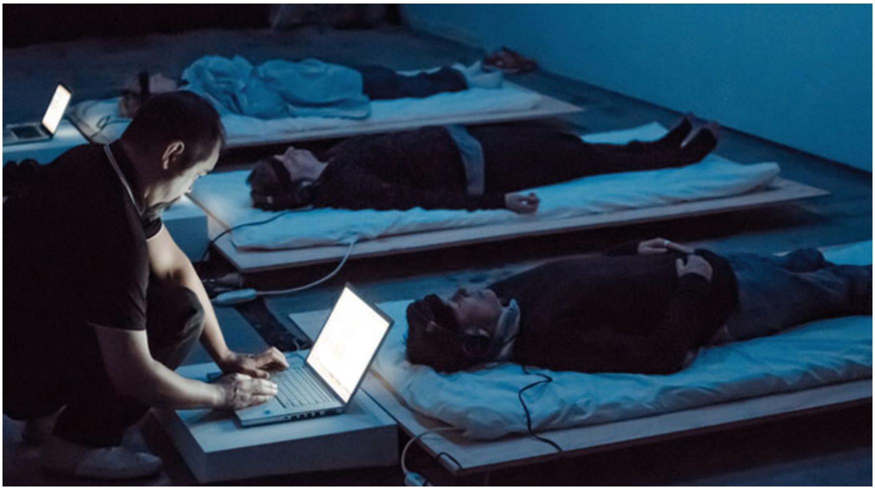

Fig. 3.3 George P. Khut and James P. Brown, *Alpha Lab*, 2013. *Alpha Lab. 2013. George P. Khut, James P. Brown*. With the permission of George P. Khut

frequencies into brainwave bands is a subject of disagreement. While in some literature brainwaves can be found divided into five bands: Alpha, Beta, Gamma, Delta, and Theta, the majority follows the guidelines provided by the *International Federation of Electrophysiology and Clinical Neurophysiology* (Steriade et al. 1990). Based on this classification, brainwaves are classified into six bands with associated features, as presented in Table 3.2.

In our survey, the majority of the artworks (43/61) utilized LTCW. However, the documentation of only fifteen artworks specified which brainwaves were utilized. For example, Khut's **Alpha Lab** (37) is built upon the activity of the Alpha brainwave. This installation (Fig. 3.3) invites its audience to explore their consciousness through an immersive soundscape generated in real-time by Alpha brainwave activity. The installation takes place in a dark chamber in which three participants lay comfortably. Each participant wears headphones and a BCI device that reads the levels of Alpha waves and translates them into a soundscape. While there is no "desired result," the experience takes the form of lucid dreaming supported by a soundscape that reacts to fluctuations in Alpha waves, which naturally occur during meditation or just before falling asleep.

Short-Term Transient Waves (STTW)—SSTWs are the brain's response to sensory, cognitive or motor stimuli, and are also known as *slow cortical potentials* (SCP). SCP last between 300 ms to several seconds (Psychophysiological 2000) and are observable as shifts in cortical electrical activity after the stimulus. These event-related potentials (ERP) are time-locked EEG activity which means that they occur (only temporarily) after a specific time following the sensory stimuli or cognitive processes. For example, P300 stands for an ERP that occurs around 300 ms after the triggering event that can be a visual or audio stimulus, or even a thought (Panoulas et al. 2010).

Besides ERP, the other approach to input EEG classification builds upon Steady-State Evoked Potentials (SSEP) that are elicited by the repetitive external stimulus. SSEP can be visual (Steady-State Visual Evoked Potentials-SSVEP), auditory (Steady-State Auditory Evoked Potentials-SSAEP) or tactile (Steady-State Somatosensory Evoked Potentials-SSSEPs). The premise behind these methods is that external stimuli at specific frequencies can stimulate brain activity. For example, Steady-State Visual Evoked Potentials are visually induced brain responses at frequencies ranging from 3.5 to 75 Hz. When the retina is visually stimulated, the brain generates an electrical response at the same frequency as the frequency of visual stimuli. A wide range of SSVEP frequencies allows for a wide range of utilization of this paradigm in creative endeavors. Exposing the audience to visual stimulation of a particular frequency at the same time opens a design possibility to utilize as many input points as there are audience members, whose now altered brainwaves are synchronized. Moreover, SSVEP's relative immunity to the artifacts (e.g., muscle potentials) makes them desirable and widely used. Lastly, motor-related activities can be captured in the brain as a *sensorimotor rhythm* (SMR) or μ-rhythm. SMR is a recording of brain activity in ranges between 12 and 15 Hz over sensory-motor areas on the skull during a motor task (movement) or even motor imagery (imagined movement) (Thompson and Thompson 2003).

In our analysis, we came across seven artworks that employ various STTWs. One of the artworks, **The Gender Generator** (58) by Josh Urban Davis, utilizes a modified P300 paradigm (n250 ERP) in an exploration of gender expression and dysphoria. First, flashing characters on a screen (Fig. 3.4) are presented to the participant who is then prompted with the question "Which Is You?" Second, after the question the participant makes a mental selection of the character and they count the appearance of the same character as it repeats in random order several times on the screen. This

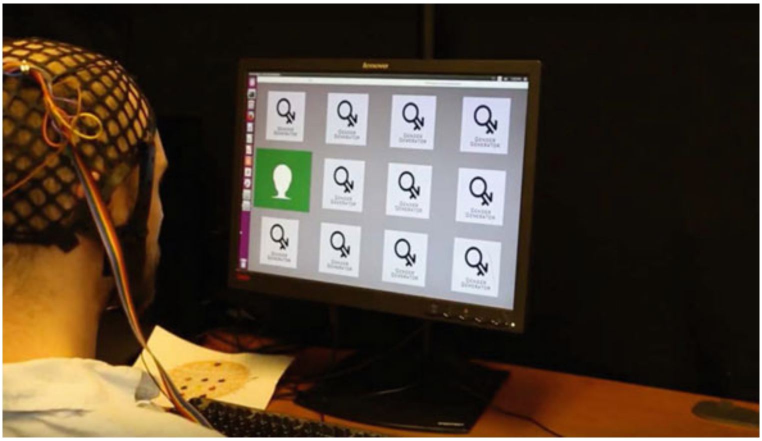

Fig. 3.4 Josh Urban Davis, *The Gender Generator*, 2017. *The Gender Generator. 2017*. Josh Urban Davis. A video still from a technical evaluation of the Gender Generator. With the permission of Josh Urban Davis

procedure is then repeated for various questions about one's physical appearance: body type, hair, etc. until the "complete" representation of the gender of a person is displayed on the screen.

Finally, the third and most recent approach allowed by the progress in machine learning is what we termed here: **hybrid**. In the hybrid approach, the device's proprietary software employs machine learning models to captured EEG data in order to detect complex categories of affective or cognitive functioning. One example of such hybrid classification is Emotive's *MyEmotive suite* (previously known as EPOC Affectiv Suite) that allows participants to measure six cognitive metrics: interest, excitement, relaxation, engagement, stress, and focus (Emotiv n.d.). Other headsets provide different categories, such as Interaxon's Muse that outputs levels of meditation only or NeuroSky that provides scores for: attention, meditation, blink detection, mental effort (engagement), familiarity, appreciation (enjoyment), cognitive preparedness, creativity, alertness, and emotional spectrum (intensity, and pleasantness) (NeuroSky Algorithms n.d.). While we speculate that these algorithms employ machine learning models on complex EEG data, none of these commercial software provide insights into how these levels are measured or extracted from the raw data, and these procedures are therefore subject to speculation and ambiguity.

In our survey, we identified nine artworks that employed the hybrid approach in EEG classification. All of these artworks utilize device proprietary software to extract participants' states and employ the information in various outputs. For example, Ramchurn's brain-controlled movie—**The Moment** (61) utilizes the participant's attention levels to alter the narrative of the movie. When the participant's attention levels drop, the movie changes from the initial narrative to show scenes from a secondary narrative. The movie then unfolds dynamically, driven by the changes in attention levels, leaving room for “101 trillion ways to view the content” (Ramchurn 2018).

3.2.2.2 Input: BCI Agency Paradigms

In this section, we describe three BCI agency paradigms and present a few examples for each. For this input category, we prefer to use the word “agency” over “control” for a few reasons. First, in the context of BCI artworks, the participant-artwork interaction is not always built upon the control of creative output. Often, a participant’s brain activity is utilized in the creative output without the participant’s awareness of their explicit “control” over the artwork. Second, the agency in our taxonomy is concerned with the degree of impact that the participant’s brain activity has within the artwork, revealing “the capacity, condition, or state of acting or of exerting power” (Agency n.d.). In this sense, an artist has creative control over the final output, by choosing interaction paradigms that restrict or support the degree of the impact that the participant’s brain activity can have on the creative output. A somewhat different perspective on creative control is presented by Wadeson et al. who discuss four categories of a participant’s *creative control*: passive, selective, direct, and collaborative (Wadeson et al. 2015). However, we find that the first three categories of Wadeson et al.’s classification relate to input agency and mapping, while the fourth, collaborative, refers to the number of participants in the artwork.

While we find the use of the word “agency” more suitable in our classification, we borrowed two categories from existing BCI input paradigm literature: *active*, and *passive*. The third category: *reactive* was borrowed from a classification by (Zander et al. 2010). While active and reactive inputs require a participant to train the system, passive does not require any training (Zander et al. 2010).

Active Input Agency—The initial development of BCI as assistive technology allowed people with sensory-motor or cognitive impairments to perform actions that were otherwise inaccessible (Millán et al. 2010). For example, BCI-controlled wheelchairs allow people with motor difficulties to move in physical space. Similarly, BCI-controlled cursors and pointers on screen enable impaired participants to use computers, communicate, and participate in activities that were otherwise inaccessible (Lebedev and Nicolelis 2006). In both examples, the participant has active control over the performed task; however, the drawback of this approach is the long and demanding training process that the participant must undertake before performing a task. Another drawback is mental fatigue that occurs after a certain period of BCI usage.

In our analysis, we identified twelve artworks that utilize active input agency. The participant’s active control is used to control the behavior or physical characteristics of the artwork. Duenyas’ installation **Ascent** ㉕ is an example of active input agency. This brain-controlled levitation performance defies gravity, as the participant, suspended in a flying harness, starts to meditate (see Fig. 3.5). The higher

Fig. 3.5 Yehuda Duenyas, *Ascent*, 2011. *Ascent. 2011.* Yehuda Duenyas. Image credit: Andrew Federman.With the permission of Yehuda Duenyas

the meditation levels are, the higher the participant ascends. Also, meditation levels control the sound and light of the installation.

Reactive Input Agency—employs brain activity that is altered by an external stimulus. The participant is simply attending to the stimulus. The participant's short-term transient waves then reveal the presence of the stimulus with an onset time (using, for example, P300 paradigm) and those fluctuations in brainwaves are then employed as a reactive input control (Zander and Kothe 2011).

Reactive input agency is often found in artworks that employ some form of short-term transient waves (see Sect. 3.2.2.1), such as **The Multimodal Brain Orchestra** ⑲. The orchestra members equipped with BCIs, attend to a range of flashing stimuli (in this case, to a visual representation of music excerpts). They change the piece by making a mental selection of one of the flashing stimuli and then count the number of its occurrences (similar to the interaction in *The Gender Generator* (58)). Another example, Batoh's live performance **Brain Pulse Music** ㉛, illustrates how reactive agency input can be utilized in a stage performance to create a relationship between the participant and the performer. In this collaborative piece between the artist and the

Fig. 3.6 Masaki Batoh, *Brain Pulse Music*, 2012. A video still from performance. Image credit: Masaki Batoh. With the permission of Masaki Batoh

audience member (see Fig. 3.6), the participant wears goggles, and a custom-made headset with EEG electrodes and flickering LED lights which affect the participant's brain activity (VEP). The participant's brain data is then sent to Batoh who maps it to sound in his on-stage performance. While this is an appealing approach to influencing brainwaves via external stimulus, it remains unclear what impact these LED lights have on the brain activity if at all, and whether the participant is instructed on how to attend to the LED lights.

Passive Input Agency—Opposite to active, passive input does not require the participants to perform any particular task to change or influence their brain activity explicitly. Referring to the shortcoming of active BCI, some authors advocate for the development and use of passive BCI. Passive BCI has been advocated as an adequate technology for open monitoring of ongoing processes in the brain that are not always easy to otherwise capture and translate. To that end, (George and Lècuyer 2010) presented a few applications of passive BCI: adaptive automation (when the participant's engagement levels decrease, the system takes control over driving), multimedia classification, video games (control of aesthetics and game mechanics based on the participant's engagement), and error detection.

Artworks that employ passive control rely on the changes and fluctuations in either brainwaves (Long Term Coherent Waves) or the participant's states (Hybrid classification) that are utilized in the artwork. **The Magic of Mutual Gaze** ㉙ is an installation/performance piece for two participants who are seated across from each other. While the participants are directing their gaze towards each other (Fig. 3.7), their brainwaves are captured and analyzed for synchronicity. The synchronous functioning of two brains generate visuals that show the connection. In this case, the participants are not instructed what to do, and the experience emerges from the moment-to-moment synchronicity of their brains oscillating at the same frequencies.

Fig. 3.7 Suzzane Dikker, Marina Abramovic, Matthias Oostrik, Jason Zevin, *The Magic of Mutual Gaze*, 2011–2014. *Measuring the Magic of Mutual Gaze. 2011*. Marina Abramovic, Suzanne Dikker, Matthias Oostrik and participants of the Annual Water mill Art and Science: Insights into Consciousness Workshop. Photo by Maxim Lubimov, Garage Center for Contemporary Culture. With the permission of Abramovic LLC

Finally, in our survey we faced a situation in which one artwork can be defined as active or passive, depending on the information disclosed to the participant. For example, in our taxonomy we list a number of artworks with passive input agency, such as: **Mind Pool** ㉑, **Solaris** ㊼, and **UFO wave** ⑰. What is common for the artworks with passive agency is that the nuances and details behind the interaction are usually undisclosed to the participant. However, once the participant becomes aware, for example, that their meditation levels have a particular impact on the artwork, they might purposefully try to alter their brain activity by focusing on the practice of meditation. In that case, passive BCI is utilized as an active BCI as long as the participant is engaged in performing actions that alter brain activity and therefore, the final output. Similarly, we classify **PrayStation** ㉚ and **Eunoia** ㊳ as active, but if their participants do not perform the required task of meditating/praying, the piece becomes passive.

3.2.2.3 Input: Timeliness of Input Data

Timeliness of input data refers to the time when data is captured. Our analysis encompasses artworks that employ real-time EEG data capture and mapping into the artwork. However, we came across two pieces that utilize pre-recorded data, and we include them in the Taxonomy. Casey's *Dream Zone* ㉝ is a generative video showing patterns and mandalas that respond to changes in pre-recorded data. The artist records the participants' brain activity while meditating "on the morphing hexagon kaleidoscope", which is then used to generate the video, with the hope that such imagery will stimulate viewers' Theta wave activity, associated with the profound states of consciousness otherwise normally reached only through meditation.

3.2.2.4 Input: Modality

The majority of the artworks reviewed in this chapter are mono-modal (54/61) in that they employ EEG-data only. Multimodality stands for an approach in which EEG data is combined with other physiological data such as EKG (electrocardiography), EMG (electromyography), or GSR (galvanic skin response). One of the multimodal projects analyzed here is **Naos** (see ⑱ in Table 3.4), an installation and platform for "sensing" the participant. Built upon the *Biometric Tendency Recognition and Classification System* (Castellanos et al. 2008), this system presents the participant with visual stimuli carrying affective content. Based on the physiological response of the participant (EEG, EMG, GSR) the system determines in real-time what next image should be displayed. This process creates an affective loop between the participant and the system. The ultimate goal of the system, according to the authors, is to reach "equilibrium" in which the image's expected physiological response, and the participant's actual response and classification are the same.

For further analysis of multi-modal artworks, it is critical that we delve into a comprehensive understanding of how data of other input modalities are used in these artworks. However, we came across an obstacle: a lack of documentation regarding how different data contributed to the overall experience of the artworks, besides EEG data. This is one of the few limitations that is mentioned in the Discussion (Sect. 3.4).

3.2.3 Mapping Strategies

The analysis of how EEG data is mapped to the parameters and interaction nuances of the artworks revealed a severe challenge similar to the one above, that is a lack of documentation about mapping details. Most of the artwork documentation we came across did not disclose mapping details, making the analysis of it difficult without speculation. However, we identify three possible mapping situations: direct, indirect, and adaptive.

Direct Mapping is the simplest of the three, in which the input EEG data is always mapped to the same parameters of the artwork and the output is somewhat predictable. For example, **The SubConch** ⑳ is an installation consisting of a lit conch sculpture in which direct mapping is realized by calibrating the lighting levels to brain activity. The participant's brainwaves are mapped to the sounds and control the brightness of the light through a passive agency (Fig. 3.8). Therefore, the participant passively creates the audio-visual installation by utilizing the direct mapping between brain activity on one side, and the sounds and lighting levels on the other, resulting in a somewhat predictable outcome.

Indirect Mapping is found in artworks that map EEG data to one set of parameters and then influence the values of another set of parameters. An example of indirect mapping is Ulrike Gabriel's **Terrain 01** (04), a piece that reveals the artist's intention to show a failure in our attempts to keep the role of mere observers. In **Terrain 01**, Gabriel puts the participant in the position of a robot's "brain" that controls their behavior. A few tiny robots that resemble roaches, with photovoltaic cells and proximity electrodes attached to their backs, are placed on an oval plate. The participant's Alpha waves indirectly control the robots by regulating the lightning in the installation; the more relaxed the participant is, their Alpha waves would be more prominent, which finally results in the lights shining brighter, giving the robots more energy for moving.

Finally, **adaptive mapping** arose from artificial intelligence and models capable of listening and changing how and to what EEG data is mapped, following the programmed logic. This type of mapping could contribute to the ever-changing nature of the piece (anywhere between random and predictable), or could adjust to the participant-specific EEG activity. In the latter, the artwork with adaptive mapping could "listen" to the participant and gradually lead the interaction, keeping participant engagement levels at the optimum for flow experience (Nakamura and Csikszentmihalyi 2014). One of the artworks with adaptive mapping is **Naos** (18), previously described in Sect. 3.2.2.4.

Fig. 3.8 Mats J. Sivertsen, *The SubConch*, 2009. With the permission of Mats J. Sivertsen

3.2.4 Diversity of the Output Types of BCI Art

We classify all analyzed artworks into six categories regarding their type of output, as per Fig. 3.1b. First we discuss artworks with *visual output* such as BCI images, painting, and visualization in Sect. 3.2.4.1. This is followed by a discussion of *sound output* of BCI artworks spanning from sonification, orchestral compositions, and opera (Sect 3.2.4.2). Then we discuss artworks with *audio-visual output* in Sect. 3.2.4.3. Following the discussion on visuals, we continue by presenting more recent work in *moving images*, discussing BCI-based generative video artwork and a BCI movie in Sect. 3.2.4.4. Then we expand the discussion to encompass *immersive*, computer-generated environments (Virtual and Augmented Reality) and head-mounted 180 panorama in Sect. 3.2.4.5. Finally, we conclude the output section by discussing built BCI-based physical objects, installations, and instruments in Sect. 3.2.4.6.

3.2.4.1 Visual-Based Output of BCI Artworks

The examples that follow are classified into the visual category for two reasons. First, the media used in these artworks convey visual information. Second, the artworks are not context dependent, they do not occupy the space beyond a canvas or a screen, and do not create a sense of spatial immersion (such as in the case of immersive virtual environments presented on head-mounted displays). Thematically, it appears the majority of the artworks in this category are centered around searching for an answer to how we visually represent something that is invisible to our eyes; What are our thoughts like, and do they have a shape or a color?

In attempts to demystify the brain and find answers to these questions, many artists capture brain activity and translate brainwaves into paintings and digital prints. **The Shapes of Thought** ⑫ is a visual representation of EEG recorded during the participants' evocation of traumatic events. While participants alter between hypnotic and sleeping state, the system captures participants' brain activity and generates complex 3D meshes in real-time. These 3D forms are then printed as images and presented as a collection of traumatic experiences. Similarly, **Brain Art: Abstract Visualization of Sleeping Brain** ㉘ utilizes pre-recorded instead of real-time data of the brain during sleep. An interesting departure from printed images are systems that allow an audience to create EEG-driven digital paintings like **Cerebral Interaction and Painting** ㊱, or the commercial application **Braintone art** (Braintone 2019).

While the artworks above visualize brain activity of one participant at a time, one of the pioneers of BCI art, Nina Sobell, explores the synchronicity and non-verbal communication between two participants. In her **BrainWave Drawings** (02), a real-time video portrait of two participants is augmented by the drawing of a Lissajous curve on the screen when their brain activity is synced (Fig. 3.9). As Sobell shares "*a circular configuration or Lissajous figure forms on an oscilloscope, when both are emitting the same brainwave frequency simultaneously. The pattern distorts horizontally or vertically, indicating a person is plugged into the X-axis and which*

Fig. 3.9 Nina Sobell, *BrainWave Drawing*, 1973–2008. *BrainWave Drawing. 1973-2008*. Nina Sobell. With the permission of Nina Sobell

person is on the Y-axis. The people have been informed which axis, X or Y, they have been plugged into. So, when the pattern distorts horizontally (x-axis) or vertically (Y-axis) they can see immediately who is in the process of diverging."

3.2.4.2 Sonic Output: Brain Sonification, Music and Opera

Cerebral Music, a sonification of the brainwaves performed during a radio interview in 1961 by Grey Walter, has been speculated to be the first brain music (Haill n.d.). However, the lack of recordings of that event overshadows that claim. The first recorded performance of brain music is Alvin Lucier's **Music for Solo Performer** (01) from 1965. In this piece, Lucier, who was introduced to EEG by his friend, the scientist Edmond Dewan, used fairly simple equipment that consisted of one to three EEG electrodes placed on his forehead while performing. For the premiere on May 5th, 1965, he sent amplified Alpha waves to "16 loud speaker-percussion pairs deployed around the museum" (Straebel and Thoben 2014). These amplified Alpha waves required continuous distribution and redirection to the instruments in the room, and for this reason, Lucier was not the only one to perform that night. Lucier's assistant was John Cage, who took part in creating the piece as "an invisible performer, who raised and lowered the stereo amplifiers' volume controls, channeling the Alpha signal to various instruments around the room." (Straebel and Thoben 2014)

The interest in EEG sonification performances in contemporary music has not swayed since 1965. Some contemporary artists perform solo while others engage the audience on stage (like the previously mentioned Batoh's *Brain Pulse Music*). In solo performances, self-reflection through the sonification of brainwaves seems to be a reoccurring theme. In **Sitting.Breathing.Beating.NOT Thinking** (16) Adam Overton maps not only his brainwaves but changes in heartbeat and breathing rate to influence sound while performing *a meditative brain concert*. In this piece, Overton explores different mappings of the input, creating a unique performance each day for 7 days. As described by the author, the projected sound is generated by the software that plays data files as sound files, resulting in a purely digital, noise-like sound achieved in a process known as "data-bending."

Next, beyond sonification is brain-controlled music pioneered by David Rosenboom. As defined by Rosenboom, his piece **On Being Invisible** (03) is an "attention–dependent sonic environment". The sonic environment is generated by a brain-controlled set of electronic sound modules obtained from several inputs: small instruments, voice, and brainwaves. The brain signals are analyzed by applying pattern recognition to the brainwave frequencies. When a match between a new and one of the previous frequencies is found, the rhythm and the sound are affected by the same set of the rules previously applied to the matching pattern. In 1994, inspired by progress in physics, brain-science, and cosmology, Rosenboom returned to some of the ideas of **On Being Invisible** to realize them in a new piece, the self-organized opera **On Being Invisible II (Hypatia Speaks to Jefferson in a Dream)** (06). Even though some of the early technical solutions in Rosenboom's pieces were limited to the technology available at the time, his work has had a strong influence on contemporary practice. Beside Rosenboom, Richard Teitelbaum is yet another pioneer in the sonification of brainwaves, as seen in his work with an improvisational group –*Musica Elettronica Viva* (Holmes 2016).

The artworks presented so far relied on LTCW (neurofeedback) paradigm and direct EEG mapping of brain activity to sounds. A different approach is found in **The Multimodal Brain Orchestra** ⑲ that is performed by a quartet, a multimodal interactive system, and a conductor. In this concert, music is generated from a previously recorded tape. Quartet members voluntarily create a performance through two different stimulation approaches used to trigger sound events:

- P300 speller paradigm: in a matrix of 6 × 6 symbols, a symbol, a column or a row of symbols flashes. To trigger discrete sounds in real time, an orchestra member focuses on the flashing symbol and counts the number of times it flashed,
- Steady-State Visual Evoked potential: Four different light sources flicker at different frequencies and provoke the retina that causes the brain to generate activity at the same frequency triggered by the flickering light (see Sect. 3.2.2.1).

Both of these BCI approaches require a training period for the participants/ performers. The conductor directs the piece by giving cues to the performers, after which the performers focus on a specific row or column to ignite the desired brain activity, and consequently play the desired scores. Unlike the performance mentioned above, Eduardo Miranda's **Activating Memory** ㊹ does not have one central figure/conductor to direct the performance. Instead, the orchestra consists of a string quartet and the Brain-Computer Music Interface (BCMI) quartet. Each of the four performers in this BCMI quartet wears a cap with attached EEG electrodes and are seated in front of a screen. Four possible scores are displayed on the screen to each BCMI member out of which they choose only one at a time by gazing at it. The whole process relies on the approach of visually evoked potentials (VEP) and measured brain activity in the visual cortex, similar to the approach used in **Multimodal Brain Orchestra**. After the selection is made, one of the four string performers receives the score and performs it. In this case, all of the performers with EEG-caps are the creators of the collaborative piece in real time. For further reading about BCI and music, Eduardo Miranda and Julien Castet's book "Guide to Brain-Computer Music Interfacing" (Miranda and Castet 2014), and Rosenboom's "Extended Musical Interface Human Nervous System: Assessment and Prospectus" (Rosenboom and Number 1990) are significant resources.

Finally, our analysis includes one opera. *Noor* (56) is an opera performance concerned with the theme of surveillance. The performer's affective states are obtained from their brain activity. Then those affective states such as excitement, interest, meditation, and frustration, are mapped to one of the four databases containing prerecorded sound, libretto, and videos. Through real-time feedback between changes in the performer's affective states and corresponding audio-visuals, the performer controls the libretto, music, and videos and creates the multi-media opera.

Fig. 3.10 Dmitry Morozov ::Vtol::, *eeg_deer*, 2014. *eeg-deer. 2014*. Dmitry Morozov.With the permission of Dmitry Morozov

3.2.4.3 Audio-Visual Output of BCI Artworks

In this section, we discuss two formats of audio-visual BCI artworks: BCI audio-visual installations, and BCI audio-visual performances.

Audio-Visual Installations—In "**Behind Your Eyes, Between Your Ears**" (54), the participants, one at the time, explore the states between "thinking and being" while their Alpha wave activity is mapped to interactive soundscape and visuals. Visuals are then projected on each participant's face, creating a dreamy portrait for the audience to enjoy (Khut 2015). Another example of audio-visual installation is **State.Scape** (51), a virtual environment exposing a flock of birds whose behavior depends on the participant's excitement, engagement, and meditation levels as obtained from Emotiv's *Affectiv Suite*. Changes in the EEG data controls the flock's position, birds' speed, and their number. Apart from controlling the flock properties, EEG states are mapped to control the volumes of different audio tracks, creating a dynamic atmosphere that changes in real-time. With this piece, the authors aim to create an intimate experience in an enclosed space that allows for self-reflection and ultimately, meditation. Immersive virtual environments presented on head-mounted displays are discussed in Sect. 3.2.4.5.

Audio-Visual Performances—In audio-visual performances, the agency and presence of a performer can vary significantly from one piece to other. For instance, performance can be merely brainwave-generated music and visuals projected on the screen in which the performer's presence is minimal, such as in Dmitry Morozov's **eeg_deer** (46) (Fig. 3.10).

On the contrary, in Novello's performance titled **Fragmentation,** (49) the performer's presence on the stage has a crucial part in creating the experience. The

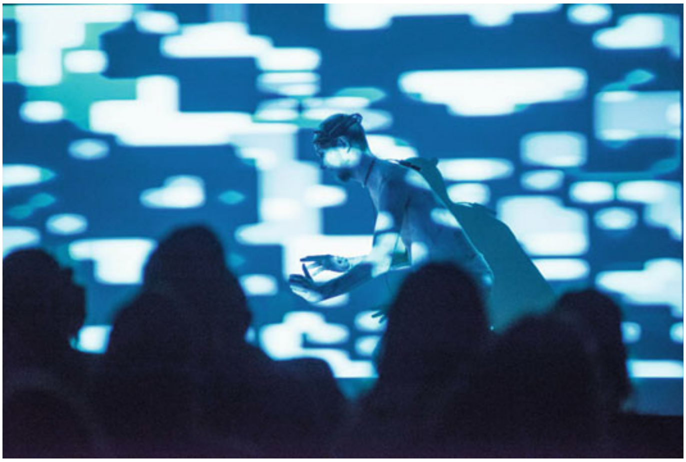

Fig. 3.11 Alberto Novello, *Fragmentation*, 2014. *Fragmentation. 2014*. Alberto Novello. Image credits: Erin McKinney. With the permission of Alberto Novello

experience starts with the performer—a Butoh dancer—sleeping on the stage. Once awake, the performer practices a concentration task and finally jogs while their brainwaves generate the soundscape and the visuals projected on the wall behind the artist (Fig. 3.11). The performer's EEG controls an avatar in a virtual 3D maze project on the wall, that then controls the sounds and visuals as the avatar moves. In this complex piece, Novello challenges himself as a performer from "outside" and"inside" of his body, to create a performance through particular mental and physical tasks. Another piece with a strong presence of a performer is **The Escalation of Mind** ㉜. An artist seated on the stage is reading Herman Hesse's "The Glass Bead Game" while his facial expressions and brain activity control audio-visual sequences and their duration.

3.2.4.4 Moving Images as Output

In our analysis, we included three kinds of moving images: live video footage, brain-controlled movie, and screen-based virtual environments. The **Chromatographic Orchestra** by Ursula Damm ㊵ is an interactive BCI-controlled live video footage. In Damm's work, the participant's neural activity manipulates the software that, as a result of the interaction, defines the degree of abstraction of the displayed video from nearby cameras. Two other examples in this category are *The Moment* (61), a brain-controlled movie, and *Dream Zone* ㉝, a generative video piece; both are described previously.

3.2.4.5 Immersive Output of BCI Artworks

Immersive Virtual Environments—Our research of virtual reality artworks presented exclusively on head-mounted displays (HMD) resulted in four artworks. **The Hidden Rooms** ㉔ is a panorama (180° image) from 2011 presented on head-mounted display. This piece, according to the author, represents the metaphor for the unconscious side of the brain. In this piece, the participant equipped with the *QBIC Belt Integrated Computer* (Amft et al. 2004) wanders through the panoramic environment defined by the author as "a brain-controlled panoramic experience using photography and spatiality".

The Einstein's Brain Project by Alan Dunning and Paul Woodrow resulted in a rich corpus of artworks presented on HMD that very often expand beyond HMD into a physical space. The overarching theme of the project examined "the idea of the world as a construct sustained through neurological processes contained within the brain" (Dunning et al. 2001). In **The Errant Eye** ⑪ the authors explore perception, consciousness and the constructs of reality in the virtual reality medium while focusing on the brain as the main operator in handling this process. The participant, immersed in a virtual environment through HMD, and equipped with the *Interactive Brain Wave Visual Analyzer* [4] and a gesture recognition glove, explores the virtual environment. This environment is not stable; it changes according to the changes in the participant's EEG activity, distorting the images of "reality". A discrepancy in the images of the world as it is and the world as it is perceived (manipulated by EEG) creates a thought-provoking space for negotiation and exploration.

Immersive BCI Virtual Worlds Projected in Physical Space—Expanding beyond virtual environments, **The Mnemonic Body** (07), brings together virtual and physical space. The installation is composed of a life-sized mannequin of the human body equipped with electrodes. The participant interacts with it by touching, stroking, or breathing on the body covered with thermochromic paint that changes color when touched. An image of a field of stars is projected on four walls around the mannequin. The participant wears the *Heads Up Display* (HUD), a head-mounted display with attached electrodes for EEG recording, and haptic gloves. As described by the authors, the installation depends on the participant's affective states: calming states trigger a projection of fluid, slow-paced and smooth environments, whereas discomfort results in more startled, fast-paced environments. Similar work by the same authors are: **The Madhouse** ⑧, **Derive** ⑩, and **Pandaemonium** (09).

Lastly, **Conductar** ㊺ is somewhere between a virtual environment and augmented reality. Inspired by **Derive** ⑩, this audio-visual application is location dependent: it depends on the GPS location in the physical environment. Audio and a generated world visible on the screen of a mobile phone (Fig. 3.12) are generated through movement and EEG data as the participant is moving and exploring the city of Asheville (USA).

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[4] http://www.ibva.co.uk/.

Fig. 3.12 Jeff Crouse, Gary Gunn, Aramique, *Conductar*, 2014. *Conductar. 2014*. Jeff Crouse, Gary Gunn, Aramique. With the permission of Aramique

3.2.4.6 Installations of Physical Objects

In this section, we present artworks that employ brain activity to manipulate properties or states of physical objects directly. Most of these artworks are installations and designed for a single participant. One noticeable similarity among these installations is in the position of the participant, who is usually centrally positioned in the installation, or in a position that allows for easy monitoring of changes caused by their brainwaves.

In **Mind Pool** ㉑ the participant's brainwaves are reflected in ferrofluid in the form of concentric circles, accompanied by sound. Brainwave frequencies trigger the electromagnets positioned under the surface of the dish filled with ferrofluid. Depending on the most prominent brainwaves, different electromagnets are activated which change the appearance of the circles on the surface. A similar project to **Mind Pool** is **Solaris** ㊼. While **Mind Pool** has more of a meditative character to it, **Solaris** creates a darker, experientially more stimulating experience through the choice of colors and sounds. Similarly, Lisa Park's **Eunoia II** ㊸ (Fig. 3.13) expands on her previous work **Eunoia** ㊳ by adding more physical elements—dishes installed on top of the speakers. Each of the dishes, half filled with water, represents one particular emotion. Once the real-time analysis of the participant's brainwaves (via proprietary software) reveals the participant's current emotion, the system generates a sound corresponding to the emotion which then causes the water to resonate in concentric circles on the surface. In both of these pieces, introspection and reflection through physical objects are apparent whereas the mapping is undisclosed and ambiguous.

While the projects mentioned above are single-participant, our survey encompasses a few multi-participant installations in the category of controlled objects such as Mariko Mori's **UFO wave** ⑰. Three participants enter a futuristic oval sculpture and lay on one of the pods while wearing EEG electrodes on their foreheads. The spherical ceiling projects six abstract shapes/blobs that represent the left and right lobes of the participants' brains. Shapes and colors of the blobs change based on the participants' Alpha, Beta and Theta levels. As explained by the author, the intention is to evoke "a deeper consciousness in which the self and the universe become interconnected."

Fig. 3.13 Lisa Park *Eunoia II*, 2014. *Eunoia II. 2014*. Lisa Park. With the permission of Lisa Park

Fig. 3.14 Justin Love, Philippe Pasquier, *Praystation*, 2012. *Praystation. 2012*. Justin Love, Philippe Pasquier. A video still. With the permission of Philippe Pasquier

Barriere (05), another piece by Ulrike Gabriel, employs thirty robots controlled by two participants on each side of a five-meter-long tray. The sync between the activity of the participants' brains controls the level of the lightning. More light on the tray results in robots moving freely across the whole tray. In case of inconsistent and mismatching brainwave patterns, the tray is partially lit, which makes the robots "negotiate" their movement. Gabriel uses robots as a medium for displaying participants' inner states and the synergy between them.

The installations we analyzed often unfold around one central object, an instrument for controlling other elements of the installation. **PrayStation** (30) unfolds around a custom built instrument (prayer dial) (see Fig. 3.14). This piece is a commentary on "technology-as-placebo", combining ideas of religion and human thoughts in a unique and tangible experience. In this installation, the participant picks one out of the eight most popular religions on a custom designed prayer dial to pray to. After the choice is made, the system analyzes EEG data and associates it with a prayer and meditative states which then trigger the system to release virtual agents to create visual feedback on the canvas in front of the participant. Other examples of BCI-controlled instruments are: Dmitry Morozov's **Turbo-gusli** ㊽, a customized traditional instrument played by a participant's brainwaves; Jamie Gillett's **Neuro-Harp**, and Greg Kress' **The Brain Noise Machine** ㉒.

Lastly, the power of the mind to change the appearance or position of physical objects was the purpose of early applications of BCI in restoring movement limitations. Jody Xiong in their piece **Mind Art** ㊿, addresses the body's limitations through a series of paintings created by people with motor disabilities. The installation consists of four large canvases attached to form a box shape. A balloon, filled with a color that is picked by the participant, is placed in the center of the box, connected to detonators that are activated by the brainwaves of the participant. The explosion of the balloon results in the abstract paintings on canvases. Even though the idea of creating with the mind is not new (for example, see **Cerebral Painting** ㊱), **Mind Art** expanded the 2-D canvas into space, transforming the intimate act of creating mind-painting into a collective event. Even though the final output is a painting, due to its spatial display, we included it in this section rather than in the visual BCI art category.

3.2.5 Presentation Format of BCI Artworks

So far in the descriptions of the artworks above, we have mentioned three *presentation formats*. *Screen-based* BCI artworks encompass mobile or desktop applications. The other two formats, *installation* and *performance*, are similar in that the artworks in both categories need human input, either real-time or recorded for the complete presentation. What distinguishes these two formats is that in performances the author/performer(s) generate(s) the output while the audience is in the role of passive observer. Performances, compared to installations, are usually rehearsed in advance and articulated in artistic expression. This is because the artist, the creator of the piece, takes part in it as a performer. However, while installations have open ends for their users/audience members to explore, sometimes with guidance but more often without, performances are more deterministic in what and how the author/performer wants to show. In most cases, performers know precisely how to use the device or how to trigger specific brainwave patterns to achieve a somewhat predicted result which is then consciously utilized or avoided.

EEG KISS (55) by Lancel/Maat (Figs. 3.15 and 3.16) is an artwork presented in both formats: as an installation and as a performance as well. It explores the act and intimacy of kissing through real-time collected EEG data—"a portrait of a kiss" that

Fig. 3.15 Karen Lancel, Herman Maat, *EEG KISS*, 2016. *EEG KISS*. 2016. Karen Lancel, Herman Maat. With the permission of Karen Lancel

Fig. 3.16 Karen Lancel, Herman Maat, *EEG KISS*, 2016. EEG KISS. 2016. Karen Lancel, Herman Maat. With the permission of Karen Lancel

generates the audio and visuals. Participants are invited to de-mystify E.E.G data through their own sense-making processes and to take part in co-creation by evoking their own experiences of kissing.

3.2.6 Audience of BCI Artworks

This category in our taxonomy describes two roles that the audience can take. The first role is of **an active audience member** who wears BCI equipment and whose brainwaves are actively fed into the artwork. The second role is of **a passive observer**, a spectator of the performance or installation.

Regarding the number of active audience members, the majority of BCI artworks allow only one person at a time to interact with the artwork. However, some artworks utilize two or more inputs, and this exploration started early on. According to Nijholt (2015), one of the first multi-brain artworks was *Alpha Garden* by Jacqueline Humbert in 1973. Among more recent artworks, our survey includes fifteen that utilized the brain activity of a minimum two and maximum of 48 participants. **Mood Mixer** ㉖ utilizes input from two audience members, reading their relaxation and sustained attention levels to create an audio-visual experience. **DECONcert series** ㉗ by Steve Mann, James Fung and Ariel Garten utilized the brainwaves of 48 visitors to create the sonic environment. Collective brain activity is analyzed and used to change real-time sonification through a continuous feedback loop between the sonic environment and the participants' brainwaves.

Regarding artworks with the presence of an audience as spectators (passive audience), most are open to a larger audience. However, some installations aim to create an intimate ambiance for those interacting with the artwork and limit the number of participants who can be present at the same time. For example, in Khut's **Alpha Lab**, ㊲ only those who wear BCI devices are part of the experience. In the case of screen-based applications, the presence of the audience depends on the context in which the artwork is experienced (home vs. gallery).

We conclude here our analysis of the artworks. We aimed to provide these descriptions of the selected artworks to serve as examples in the presented taxonomy. Moreover, we hope that this work will ignite the discussion and help identify a larger body of BCI artworks that we are yet to discover. Finally, due to our curiosity to learn more about the artworks beyond the documentation that was available to us, we established contact with nineteen of the authors and asked them to share their experiences of working on the presented artworks, from challenges to technical details. We present their insights below.

3.3 Artists' Insights on Creating BCI Art: Survey Responses

During the process of conducting the presented research, we succeeded in establishing contact via emails/social media with nineteen out of thirty artists that we initially contacted. We asked these artists to share the nuances of their artworks via survey, mainly because some of the documentation available to us lacked details and precision. Our findings from the survey (and a few personal email exchanges with the artists) revealed valuable insights into their processes of creating BCI artworks and also the challenges and limitations they encountered while working in the field of brain-computer interface art. From these insights, we unfolded themes that relate to working with BCI devices and present them here through three categories: design of the devices, conceptual limitations, and the potentials recognized within the technological shortcomings of BCI.

Design of Devices The design of devices is critical when it comes to the reliability of the data readings. One artist reported that one of the BCI devices they used "*doesn't lay flat on people with a large brow and thus does not work for all head shapes and types"* [A7]. Along the same lines, [A3] reported that it was *"very difficult and time-consuming to attach electrodes and maintain contact limiting its use for multiple participant installations*" and continued to discuss the "*hygiene issues for multiple participants*".

In real-time performances, the sample rate is crucial for maintaining feedback loops. However, one of the artists reported issues with Bluetooth transfer of data between the BCI device and a computer, causing a very slow sample rate of 0.8 Hz. This issue, according to the artist "*made neurofeedback very challenging, given the lag between samples*" [A1]. Due to software issues and failure in noise filtering [A3] "*stopped using this because data was not trustworthy*". [A4] reported that overall the device they were using was more complex than needed; however, the biggest shortcoming was false positives "*especially since the sensors pick up much muscular activity in the face and scalp.*" Finally, two artists reported on the attractiveness of the device as a critical factor in making decisions related to the overall aesthetics of the artwork: "*ABM is the scientifically highest quality device we experimented with, ability to monitor evoked potentials, etc.; however the form factor was impractical for audience throughout of installation experience. Also, unattractive which was a factor in our design.*"[A17]

Conceptual Limitations The design of the devices, their hardware and software limitations, as well as human factors such as the presence of the audience, and the psycho-physical endurance of a performer all contribute to the articulation of the concept. These factors pose conceptual challenges and determine how the piece will evolve in space and over the exhibition's time-span.

One of the main conceptual challenges is how to make a long-lasting, engaging artwork if the technology is the core of it? [A4]'s observation is that "*because the BCI is the core of the whole concept the piece runs the risk of being a one-trick-pony. Still, I think both the contextualization that happens in the piece as well as the unique aesthetic experience offered to the viewer/user, makes it something more than a science-fair encounter*". What distinguishes an artwork from "a science-fair encounter", as suggested by [A4], is the artist's intent, and their sensibility regarding aesthetics, interaction, as well as the context in which the artwork is presented. However, the presence of a BCI headset and its visibility, aesthetics, or perceived gadgetry influences how the audience will experience the artwork. [A9] disclosed that "*the theatric costuming or the scientific instrumentation adds to deflecting audience members' glances and obscuring the body through its unique gadgetry*" that can take the audience away from the other, less immediate values of the artwork.

Another device-related conceptual limitation lies in the sometimes unpredictable quality of the signal from BCI devices in natural, real-world settings (outside the lab). The majority of BCI artworks presented in this chapter rely on real-time data and are at risk of failing to achieve the prescribed outcome should there be a disconnect in the data transmission between the BCI device and the artwork's architecture. The artists face the question of whether all interaction and the outcome should be prescribed, planned, and programmed to account for the unpredictability of the signal. While we have no definite answer, [A19] presented an interesting perspective on the role of data, which they consider as co-Actors in the piece, emphasizing the beauty of its agency and ambiguity over prescribed outcomes. To that end, [A19] states that "*in a participatory process of sense-making, we invite participants to give meaning to the very abstract, sometimes mystifying E.E.G. data-visualization of their kisses. Instead of scientific interpretation and validation, people who kissed interpret the data-visualization based on their shared memories of kissing and on imagination. Often the kisses are remembered as intimate processes of 'co-creation' and the data are perceived as 'A portrait of our kiss'.*"

Regarding human-factors, fluctuations in the performer's attention or mood directly translate into the final output of the piece and pose conceptual considerations about how those should be handled. If not accounted for through the design of the piece, this might be detrimental for the artwork. For example, artworks that require its participants to reach meditative states can be challenging if the performer is surrounded by the audience. As [A10] emphasizes "*when I had to perform in front of hundreds of audience members, it made me feel vulnerable by presenting myself, brainwave data translated in to sound*". On the other side, there are pieces in which "*the BCI performers had to practice to stay focused in a concert (theatrical) environment. These pieces also investigate a state of being in which the performers ride a very thin line separating learning to consciously control their attention shifts and focus –(as represented in ERP P300 activity)—and being a part of a system larger than themselves. In other words, they had to make subtle decisions about when to try to be an initiator of action and when to be an active, imaginative listening processor in the larger system*" [A3]. Employing more than one BCI input allows more room for potential distraction and unwanted brain activity to be masked by the activity of others who are in the right state (more on multi-brain BCI input can be found in (Nijholt 2015).

Finally, some artists shared that public showing of their artworks often required an assistant that helps the audience with the headsets [A16]. Having to have an assistant can introduce conceptual considerations around their role, the meaning behind the assistance, and how the process of assisting is performed so that it becomes an organic part of the artwork.

Limitations seen as potential Even though the artists who responded to our survey prioritized discussing potentials over limitations, a few shared that shortcomings of the device or approach can be effectively employed as a potential. [A8] pointed out that they were trying to *"limit the effect of the BCI to the minimum due to the huge noise that the data has. The signal is translated into a laser pattern which beautifully shows the variability and noise. So again as in the last piece I use the limitation of this technology aesthetically"*. This account demonstrates that while not perfect, emerging technologies can be a fertile ground for exploration and meaning-making of EEG data and that interpretation does not always rely on precision of the device when it comes to creative processes.

3.4 Challenges and Potentials

In our search for BCI artworks, we did an extensive review of online sources, catalogs, books, journals and conference papers. In this process, we identified two main challenges to further the development and advancement of the BCI art field. The first main challenge we encountered is limited documentation of the artworks. In our process of collecting the information and analyzing the artworks, the documentation was crucial for understanding the specifics of particular works in order to analyze them through a lens of proposed categories in the taxonomy (Table 3.4). However, a large number of pieces we included here haven't been documented in great detail. Nevertheless, despite this challenge, we aimed to provide the reader with a bigger picture of BCI art based on the landscape of the pieces that we found, focusing on their shared features rather than on specificity of a particular concept.

The other challenge concerns work on BCI artworks itself and can be broken down into technical and experiential challenges.

3.4.1 Technical Challenges in BCI Art

Irreplicability—The challenges of this in-flux field are many. Lack of documentation can lead to not just misunderstood concepts and ideas but to failed attempts to replicate the project. Unlike in science, in which each step of inquiry is rigorously documented, in art-making that is not the case for the majority of the artworks we found. Lack of documentation makes the artworks irreplicable. While we can argue that unique artworks do not need or aim to be replicable, an overview of their technical nuances, approaches, and solutions adds value to the whole field of BCI art. Well-documented artworks help the field grow by breaking through the unknown into new possibilities for creative output.

The majority of the artworks we analyzed are documented in the form of a portfolio or a website presentation, with a brief description of the concept. Some artists use their websites to provide more conceptual and philosophical insights about the work, also outlining technical details about the artwork's setup, as was done in the documentation by Lancel/Maat www.lancelmaat.nl or David Rosenboom http://www.davidrosenboom.com. Finally, the most detailed technical descriptions can be found in published books and papers, often including a description of the artwork's hardware and software to a precise detail that would allow for replicability, as done by Rosenboom in multiple publications (Rosenboom 1976; Rosenboom and Number 1990).

Recently a positive shift came with the popularization and growth of a DIY culture that seems to reflect on the documentation practices within the BCI art field positively. Open-source EEG hardware and software enthusiasts, engineers, artists, and researchers that have been sharing knowledge, hacks and best practices via communities such as *Sourceforge*, *Open BCI* or *Brain Control Club*. These communities offer, besides documentation and project descriptions on their websites, workshops and hackathons. Similarly, some artists like Ursula Gastfall, Pascale Gustin and Gérard Paresys longitudinally documented their EEG artwork *In-Between* by posting the iterations of code, pure data patches, project documentation such as sketches and videos in the form of a web project diary (Gastfall et al. 2018). These examples of BCI artwork documentation offer a starting point that we wish more artists would embrace as a part of their practice.

Reliability—The other type of technical challenges relate to the shortcomings of the technology used in the artworks we discussed. Despite the advances of dry electrodes over wet electrodes, the latter is still in use mainly in research labs as they require wired connection and gel/paste application. However, addressing the drawbacks of hybrid electrodes (such as pressure and price) is crucial for the democratization of affordable and reliable measuring tools (Davis et al. 2013) that are easy to set up outside of labs. Even though there is no perfect solution to any of the imposed problems, the development of semi-dry and dry electrodes is directing the development of BCI devices that are more portable and affordable, compact and easy to use, making these devices appealing to the consumer market. Only then will BCI devices contribute to the shift of focus from medical applications (e.g., assistive technologies) towards various applications in art, gaming, and the entertainment industry.

While new generations of electrodes have improved reliability and signal quality, the field of EEG based BCI still has a few obstacles to overcome before it can be considered a completely reliable tool. For this to happen, some of the issues to be addressed are a change of EEG signals during BCI sessions, and noise and low output rate (Millán et al. 2010). The change of signals, or signal non-stationarity, during BCI sessions is discussed in papers such as (Schlögl 2000; Shenoy et al. 2006; Vidaurre et al. 2009). Some solutions to this problem involved the rejection of the signal change and maintaining levels of the stationary signal as proposed by (Kawanabe et al. 2009). The other approach—*adaptation*, is to choose EEG features that are stable over time (Galán et al. 2007) and feed the data of these features into the artwork. However, no instant solutions are available for any of these issues, and what works for one of the artworks might not work for others. These issues are even amplified if the participants are moving, which makes the use of BCI devices close to impossible. Decisions about which approach to take will depend on the nature of the artwork itself. However, while data artifacts usually present an obstacle for precise observation of brain functioning, these artifacts are a source of unpredictability that can add value to artistic explorations. We are looking forward to seeing these issues addressed with more variety of BCI devices and approaches employed in generating BCI-based performing art such as dance and theater.

Lastly, our analysis is bound to the artworks that employ EEG-based BCI devices to record brain activity. Only one artwork **E.E.G Kiss**, to our best knowledge, combined EEG BCI with an IMEC headset that utilizes fNIRS approach. While other non-invasive approaches in BCIs are more reliable, they are either robust or costly. Even though consumer-BCI have been considered somewhat reliable and potent for revealing humans' feelings and cognitive processes, these devices have severe limitations. Panoulas (Panoulas et al. 2010) mentioned that “all EEG-based BCI classes have to face the problem of separating the control signal from interfering noise signals that have two sources: non-EEG artifacts, such as recording noise, power line interference, eye movement, eye blinking, EMG and ECG; and EEG signals that are not used as control signals.” An additional drawback lays in the fact that BCI devices cannot provide a complete picture of processes in the brain, as the brain produces electrochemical signals from which only electrical are recorded. Other challenges recognized by Panoulas are technically oriented and relate to the calibration that has to be done before every use, which is cumbersome and requires additional time. We expect that by solving these issues, low-cost BCI devices will be able to provide a reliable overview of cortical activity in real time, without long and demanding training time or complicated pre-use procedures. If these devices succeed in doing so, we speculate that BCI devices will have a broader range of applications as well as more applications in art.

Compatibility, transparency and open-sourcing—Finally, the last two limitations discussed here are the compatibility of BCI systems across platforms and the transparency of data. The majority of the applications for BCI devices are created for desktops exclusively. If those applications were included on smartphones/tablets as well (Millán et al. 2010) a broader range of applications that require greater mobility would be possible. Mobility is an especially important aspect to consider when creating performances and spatial installations, and artists’ hacks are sometimes geared towards ensuring the compatibility of BCI setups across various platforms (desktop, tablets, mobile).

Regarding transparency, many of the BCI devices available on the market (Sect. 3.2.1) do not provide their EEG classifying software and raw data to its users. Therefore the artists are presented with two options. One option is to use the available devices and trust their algorithms in how they sort out raw data. The other option depends on the artists’ knowledge of hardware/software hacks if they aim to use raw data and apply open-source algorithms. Our analysis yielded only five artists who used custom-made BCI. One of them, [A9] worked on the piece that involved a significant amount of time spent on the setup itself: “*about 50% of that time involved composition or circuit-building...and the other 50% was spent testing to see how many zillions of ways the software or circuit was likely to crash during performance*”. [A9]’s experience poses new questions: is the lack of skill to hack custom BCI setup, or the trust in stability and reliability of consumer BCI over custom-made devices, deterring artists from customizing and hacking BCIs in their work at a larger scale?

3.4.2 Experiential Challenges

The fascination and curiosity to understand the invisible processes of the brain often leads an audience to wish for more than is achievable with the current technology used in BCI artworks. Some of the common questions that regularly emerge from interaction with the audience are questions around *mind reading* and *privacy*. While it is certainly not possible to read one's mind (at least not to our best knowledge), lack of understanding of what BCI can and cannot do leads to confusion, fear, resentment, and often rejection of the artwork. One way to prevent this from happening is to inform the audience about what the artwork does, what it collects regarding physiological data, where it stores the data, and if recordings of brain activity are made, who will have access to them in the future.

However, this approach of disclosing all the details of the artwork to the audience poses the risk of undermining the audience's curiosity, exploration, and meaning-making in the moment of experiencing the artwork. What should be disclosed to the audience, to what level of detail, and should the disclosure be done prior, during, or after the experience? One of our interviewees shared that, compared to other biofeedback such as breathing and heartbeat which the audience can immediately relate to through feeling of their heartbeat or breath at the moment, *"brainwaves however are mystical, need to be explained in ways that are hard to avoid using confusing terminology, and almost always lend a glare of scientific endeavor"* [A9]. The lack of available information about how the artists listed in our taxonomy dealt with this challenge when they show their BCI artworks prevents us from looking at the best practices or even proposing some solutions. However, we recognize that this chapter would have benefited from such a discussion, and we leave it for future work.

Lastly, a challenge that emerges from a lack of understanding of the nuances of the artwork is: how to utilize real-time brain activity in the artwork in such a way that it does not appear superficial or fake? In other words, how should artists demonstrate that the EEG of brain activity obtained from the audience member/performer via the headset is utilized in the presentation of the final output of the artwork (Millán et al. 2010)? Unless the audience is familiar with the algorithms, mapping, and interaction design of the artwork, there might always be questions about the truthfulness of data lingering in the air. This is not necessarily a defect of the artwork, but rather a design opportunity that welcomes ambiguity in a meaning-making process that adds to the beauty of the unknown to be explored and discovered individually.

3.4.3 Potentials Within BCI Art

Despite the challenges we encountered, we recognized many potentials of BCI that can be explored further in BCI art. So far, many of the pieces we analyzed are focused on the meditational (self-reflective) aspect of one's experience. To our knowledge, it is mostly because BCI devices easily detect when the participants are meditating not just by recording brain activity from particular parts on the skull, but by recording the muscle activity that occurs while they keep their eyes closed. By acquiring more reliable devices that can give us more detailed insights into brain processes, it is to be expected that the main focus will shift from meditation towards many other conceptually different directions that include various states of altered consciousness.

Agency is yet another aspect that has much potential for further exploitation in BCI art. The current category of input control can be further expanded beyond passive, active and reactive input types. Including semi-active BCI could complement the previous input types by introducing the concept of *controlled unpredictability*. This approach to a participant's agency falls somewhere between boredom (predictability) and chaos (complete unpredictability) and is achievable with current BCI devices. This could be a crucial point for further exploration of BCI applications in art. This effect could even be amplified in the case of a few simultaneously employed BCI devices within the same piece, such as a collaboration between an artist and a few participants simultaneously generating the outcome. Thinking even further, by adding an artificial intelligence component, the possibilities for the evolution of BCI art are unlimited. However, while the possibilities are many, their materialization depends on the technological progress in the BCI field and adoption from creative minds.

Lastly, on that note, even Alvin Lucier recognized the potential of agency in real-time performances over pre-recorded sessions: *"I let the structure go, let the continuity of the Alpha pulses, as they flowed out of my head, determine the moment-by-moment form of the performance. Somebody suggested to record the Alpha waves and compose the piece, but then I decided to do it live, and that is a risk because it is not sure you can get them, the more you try, the less likely is to succeed. So the task of performing without intending to give the work an irony it would not have had on a tape"* (Lucier and Simon 1980).

3.5 Conclusion

We presented a structured overview of the expanding field of BCI art, with utilized approaches and BCI devices, and proposed a systematic way of categorizing artworks based on their similarities in the presented taxonomy. The presented taxonomy encompasses sixty-one artworks; however this list is not exhaustive. Our goal was to offer a list of artworks to serve as examples that illustrate nuances of the categories in the presented taxonomy. Finally, our contribution is in the proposed categories of the taxonomy and gathered insights from the artists. With this chapter we aimed to provide an overview and analysis of the BCI art landscape from the 1960s until 2018, and we suggest that this work should be seen as an open invitation to a discourse on not only present practices but what can be done differently in the future.

3.6 Additional Materials

Illustrations of presented artworks, links to the artists and artworks, and other resources can be found here: https://bci-art.tumblr.com/.

3.7 Taxonomy

The taxonomy consists of two tables. Table 3.3 introduces sixty-one artworks by their titles, year, authors' names and provides references. Table 3.4 details each artwork across taxonomy categories.

Table 3.3 BCI artworks

#	Title	Year	Author(s)	References
①	Music for Solo Performer	1965	Alvin Lucier	Straebel and Thoben (2014), Novello (2014b)
②	BrainWave Drawings	1973–2008	Nina Sobell	Sobell (2008)
③	On Being Invisible	1976–1977	David Rosenboom	Rosenboom and Number (1990)
④	Terrain 01	1993	Ulrike Gabriel	Whitelaw (2004)
⑤	Barriere	1993	Ulrike Gabriel	Whitelaw (2004)
⑥	On Being Invisible II	1994	David Rosenboom	Rosenboom and Number (1990)
⑦	The Mnemonic Body	1995–2001	Alan Dunning, Paul Woodrow	Dunning et al. (2001)
⑧	The Madhouse	1995–2001	Alan Dunning, Paul Woodrow	Dunning et al. (2001)
⑨	Pandaemonium	1995–2001	Alan Dunning, Paul Woodrow	Dunning et al. (2001)
⑩	Derive	1995–2001	Alan Dunning, Paul Woodrow	Dunning et al. (2001)
⑪	The Errant Eye	1995–2001	Alan Dunning, Paul Woodrow	Dunning et al. (2001)
⑫	The Shapes of Thought	1995–2001	Alan Dunning, Paul Woodrow	Dunning et al. (2001)
⑬	Body Degree Zero	1995–2001	Alan Dunning, Paul Woodrow	Dunning et al. (2001)
⑭	Terrain 02	1997	Ulrike Gabriel	Gabriel (1997)
⑮	BIOS	2002	Thomas Tirel, Sven Hahne, Jaanis Garancs, Norman Muller	Tirel et al. (2002)
⑯	Sitting.Breathing. Beating. [NOT] Thinking	2004	Adam Overton	Overton (2004)
⑰	UFO wave	2005	Mariko Mori	Mori (2005)
⑱	Naos	2008	Carlso Castellanos, Philippe Pasquier, Luther Thie, Kyu Che	Castellanos et al. (2008)
⑲	The Multimodal Brain Orchestra	2009	Sylvain Le Groux, Jonatas Manzolli, Paul F.M.J Verschure	Le Groux et al. (2010)
⑳	The subConch	2009	Mats J. Sivertsen	Sivertsen (2014)
㉑	Mind Pool	2010	Kiel Long, John Vines	Long and Vines (2013)
㉒	The Brain Noise Machine	2010	Greg Kress	Kress (2010)
㉓	Staalhemel	2010	Christoph De Boeck	Boeck (2010)
㉔	Hidden Rooms	2011	Marie-France Bojanowski	Bojanowski (2014)
㉕	Ascent	2011	Yehuda Duenyas	Duenyas (2012)
㉖	MoodMixer	2011	Grace Leslie, Tim Mullen	Leslie and Mullen (2011)
㉗	DECONcert series	2011	Steve Mann, James Fung, Ariel Garten	Mann et al. (2007)
㉘	BrainArt	2011	Daria Migotina, Carlos Isidoro, Agostinho Rosa	Migotina et al. (2011)
㉙	The Magic of Mutual Gaze	2011–2014	Suzzane Dikker, Marina Abramović, Matthias Oostrik, Jason Zevin	Dikker and Oostrik (2014)
㉚	Praystation	2012	Justin Love, Philippe Pasquier	Love and Pasquier (2011)
㉛	Brain Pulse Music	2012	Masaki Batoh	Batoh (2012)
㉜	The Escalation of Mind	2012	Dmitry Morozov	Morozov (2012)

(continued)

Table 3.3 (continued)

#	Title	Year	Author(s)	References
(33)	Dream Zone	2012	Karen Casey	Casey (2012)
(34)	Clasp Together (beta)	2012	Harry Whalley, Panos Mavros, Peter Furniss	Whalley et al. (2015)
(35)	Compatibility Racer	2012	Lauren Silbert, Jennifer Silbert, Suzzane Dikker, Mattias Oostrik, Oliver Hess	Silbert et al. (2012)
(36)	Cerebral Interaction and Painting	2013	Yiyuan Huang, Alain Lioret	Huang and Lioret (2013)
(37)	Alpha Lab	2013	George Khut, James P. Brown	Khut and Brown (2014)
(38)	Eunoia	2013	Lisa Park	Park (2013)
(39)	The Creation with Strobes	2013	Luciana Haill	Haill (2013)
(40)	Chromatographic Ballads	2013	Ursula Damm	Damm (2013)
(41)	The Mutual Wave machine	2013	Suzanne Dikker, Matthias Oostrik	Dikker and Oostrik (2013)
(42)	(un)Focused	2013	Alberto Novello	Novello (2013)
(43)	Eunoia II	2014	Lisa Park	Park (2014)
(44)	Activating Memory	2014	Eduardo Miranda	Miranda (2014)
(45)	Conductar	2014	Jeff Crouse, Gary Gunn, Aramique	Aramique (2014)
(46)	eeg–deer	2014	Dmitry Morozov	Morozov (2014)
(47)	Solaris	2014	Dmitry Morozov, Julia Borovaya, Eduard Rakhmanov	Morozov et al. (2014)
(48)	Turbo-Gusli	2014	Dmitry Morozov	Morozov (nd)
(49)	Fragmentation: a brain-controlled performance	2014	Alberto Novello	Novello (2014a)
(50)	Mind Art	2014	Jody Xiong	Xiong (2014)
(51)	State.Scape	2014	Mirjana Prpa, Svetozar Miucin, Bernhard Riecke	Prpa et al. (2014)
(52)	Vessels	2015	Grace Leslie	Leslie (2015b)
(53)	Eyes Awake	2015	Grace Leslie, Carolyn Chen	Leslie (2015a)
(54)	Behind Your Eyes, Between Your Ears	2016	George Khut	Khut (2015)
(55)	E.E.G KISS	2016	Karen Lancel, Hermen Maat	Lancel and Maat (2016)
(56)	Noor: a Brain Opera	2016	Ellen Pearlman	Pearlman (2017); Fedorova (2017)
(57)	You are the Ocean	2017	Özge Samanci, Gabriel Caniglia	Samanci and Caniglia (2018)
(58)	The Gender Generator	2017	Josh Urban Davis	Davis (2018)
(59)	NeuroSnap	2017	Ryan Lieblein, Camille Hunter, Sarah Garcia, Marvin Andujar, Chris S. Crawford, Juan E. Gilbert	Lieblein et al. (2017)
(60)	Harmonic Dissonance	2018	Matthias Oostrik, Suzanne Dikker	Oostrik and Dikker (2018)
(61)	The Moment	2018	Richard Ramchurn	Ramchurn (2018)

Table 3.4 Taxonomy of BCI art

	Input				Output	Presentation	Audience
	Device	EEG classification	Agency	Modality	Type	Format	Active/Passive
(01)	Custom: 2 + 1 reference	LTCW	Passive	EEG	Sound: Sonification	Performance	1/1+
(02)	Various: EEG Grass Valley, IBVA, Brainquiry	LTCW: Alpha, Beta, Theta, Delta	Passive	EEG	Visual: Image	Installation	2/1+
(03)	Custom[a]	LTCW + STTW: ERP	Passive + reactive	EEG	Sound: Sonification, ongoing musical form	Performance	1/1+
(04)	—	LTCW	Passive	EEG	P.O: Structure + Light	Installation	1/1+
(05)	—	LTCW	Passive	EEG	P.O: Structure + Light	Installation	2/1+
(06)	Custom[b]	STTW: P300	Reactive	EEG	Sound: ongoing musical form	Performance	2/1+
(07)	IBVA	LTCW: Alpha, Beta, Theta.	Passive	EEG	Audio-Visual	Installation	1/1+
(08)	IBVA	LTCW: Alpha, Beta, Theta.	Passive	EEG	Immersive: VR + Audio-Visual	Installation	1/1+
(09)	IBVA	LTCW: Alpha, Beta, Theta.	Passive	EEG	Immersive: VR	Installation	1/0
(10)	IBVA	LTCW: Alpha, Beta, Theta.	Passive	EEG/EKG	Audio-Visual	Installation	1/1+
(11)	IBVA	LTCW: Alpha, Beta, Theta.	Passive	EEG	Immersive: VR	Installation	1/0

(continued)

Table 3.4 (continued)

	Input				Output	Presentation	Audience
	Device	EEG classification	Agency	Modality	Type	Format	Active/Passive
⑫	Contact Precision sensor + 2 amplifiers Contact (n.d.)	STTW: ERP /VEP	Reactive	EEG/EKG/GSR /HR	Visual: Image	Installation	1/0
⑬	Contact Precision sensor + 2 amplifiers Contact (n.d.)	STTW: ERP /VEP	Reactive	EEG/EMG/GSR /HR	Audio-Visual	Performance	3/1+
⑭	—	LTCW	Passive	EEG	P.O: Structure + Light	Installation	2/1+
⑮	Custom: 16 electrodes, on back of the head	STTW: VEP	Passive	EEG	Audio-Visual	Installation	1/0
⑯	Custom: based on Ciarcia (1988) and Rosenboom (1976)	LTCW	Active	EEG/ECG	Sound: Sonification	Performance	1/1+
⑰	—	LTCW	Passive	EEG	Physical Object	Installation	1–3/0
⑱	Neurosky EEG	STTW: ERP/P300	Passive	EEG/EMG/GSR	Physical Object	Installation	1/1+
⑲	g.Tech	STTW: P300/SSVEP	Active	EEG	Audio-Visual	Performance	4/1+
⑳	Emotiv EPOC	LTCW	Passive	EEG	Physical Object + Audio + Light	Installation	1/1+
㉑	Emotiv EPOC	LTCW	Passive	EEG	Physical Object + Audio	Installation	1/1+
㉒	Neurosky EEG	LTCW	Passive	EEG	Physical Object + Audio	Installation	1/1+
㉓	IMEC	LTCW: Alpha	Passive	EEG	Physical Object + Sonification	Installation	1/1+

(continued)

Table 3.4 (continued)

	Input				Output	Presentation	Audience
	Device	EEG classification	Agency	Modality	Type	Format	Active/Passive
㉔	Custom	LTCW: Alpha, Beta	Active	EEG	Immersive: 180 panorama	Installation	1/—
㉕	NeuroSky	Hybrid: NeuroSky	Active	EEG	Physical Object	Performance	1/1+
㉖	NeuroSky MindSet	Hybrid: NeuroSky: Focus, Relaxation	Passive	EEG	Audio-Visual	Installation	2/1+
㉗	ThoughtTec	LTCW: Alpha	Passive	EEG	Sound: Sonification/Music	Installation	48/1+
㉘	—	LTCW	—[c]	EEG	Visual: Visualization	Screen-Based	1+/—
㉙	Emotiv EPOC	LTCW	Passive	EEG	Visual: generative Visuals	Installation/ Performance	2/1+
㉚	Neurosky Mindset	LTCW: Alpha, Beta	Active	EEG	Physical Object + Visuals	Installation	1/—
㉛	Custom	STTW: VEP	Reactive	EEG	Sound: Music	Performance	1/1+
㉜	Emotiv EPOC	LTCW	Passive	EEG	Audio-Visual	Performance	1/1+
㉝	—	LTCW	—[d]	EEG	Moving Image: Generative Video	Installation	1/1+
㉞	Emotiv EPOC	Hybrid: Affectiv Suite: Excitement, Frustration, Engagement, Meditation; facial expressions; head movement	Active	EEG/ ECG/ gyroscope	Sound: Music	Performance	1/1+
㉟	Emotiv EPOC	LTCW	Passive	EEG	Physical Object	Installation	2/1+

(continued)

Table 3.4 (continued)

	Input				Output	Presentation	Audience
	Device	EEG classification	Agency	Modality	Type	Format	Active/Passive
㊱	Emotiv EPOC	LTCW	Active	EEG	Visual: Image	Screen-Based	1/0
㊲	Myndplay	LTCW: Alpha	Passive	EEG	Sound: Sonification	Installation	1–3/0
㊳	Neurosky Mindwave	Hybrid: NeuroSky: Attention, Meditation	Passive	EEG	Physical Object	Performance	1/1+
㊴	Custom	LTCW	Passive	EEG	Physical Object	Performance	1/1+
㊵	Emotiv EPOC	LTCW	Passive	EEG	Moving Images: Live Video footage	Installation	1/1+
㊶	Emotiv EPOC	LTCW	Passive	EEG	Physical Object	Installation	2/1+
㊷	Emotiv EPOC	LTCW	Active	EEG	Audio-Visual	Performance: Butoh	1/1+
㊸	Emotiv EPOC	Hybrid: Affective Suite: Excitement, Engagement, Meditation, Frustration	Active	EEG	Physical Object	Performance	1/–
㊹	g.Tech g.tech (n.d.)	STTW: VEP	Reactive	EEG	Sound: Music	Performance	4/1+
㊺	NeuroSky Mindwave Mobile	LTCW	Passive	EEG	Audio-Visual + Immersive: AR	Installation	1/1+
㊻	Modified Necomimi	LTCW	Passive	EEG	Audio-Visual	Performance	1/1+
㊼	Emotiv EPOC	LTCW	Passive	EEG	Physical Object	Installation	1/1+
㊽	Emotiv EPOC	LTCW	Passive	EEG	Physical Object	Installation	1/1+
㊾	Emotiv EPOC	LTCW	Active	EEG	Audio-Visual	Performance: Butoh	1/1+
㊿	—	LTCW	Active	EEG	Physical Object + Visual: Painting	Performance	1/1+

(continued)

Table 3.4 (continued)

	Input				Output	Presentation	Audience
	Device	EEG classification	Agency	Modality	Type	Format	Active/Passive
(51)	Emotiv EPOC	Hybrid: Attention, Excitement, Meditation, Boredom	Passive	EEG	Audio-Visual	Installation	1/1+
(52)	Muse	LTCW	Passive	EEG/ ECG/ EDA	Sound: Music	Performance	1/1+
(53)	Muse	LTCW: Alpha	Passive	EEG	Sound: Music	Performance	1/1+
(54)	Muse	LTCW: Alpha	Passive	EEG	Audio-Visual	Installation	1/1+
(55)	IMEC (fNIRS), Muse	LTCW: Alpha,Beta, Theta	Passive	EEG	Audio-Visual	Installation/ Performance	2/1+
(56)	Emotiv EPOC	Hybrid: Affectiv Suite: Excitement, Interest, Meditation, Frustration	Passive	EEG	Sound: Opera + Audio-Visual	Performance	1/1+
(57)	NeuroSky MindWave 2	Hybrid: eSense: Attention, Meditation	Passive	EEG	Audio-Visual	Installation	1/1+
(58)	OpenBCI with OpenVibe	STTW: n250 ERP (modified P300)	Active	EEG	Visual: Visualization	Installation	1/1+
(59)	Emotiv Insight	LTCW: Alpha, Beta	Passive	EEG	Visual: Camera Overlay	Screen-Based	1/—
(60)	Emotiv EPOC	LTCW	Passive	EEG/ HRV/ GSR	Audio-Visual	Installation	5/1+
(61)	NeuroSky	Hybrid: NeuroSky: Attention	Passive	EEG	Moving Image: Movie	Installation	1/1+

[a] 2 electrodes + EEG amplifiers made by Princeton Applied Research, model PAR 133, Pre Amp

[b] 2 electrodes at Cz for each of two performers

[c] Artworks 28 & 33 are pre-recorded

[d] Artworks 28 & 33 are pre-recorded

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